INTER-CELL INTERFERENCE COORDINATION IN OFDMA NETWORKS: TWO AUTONOMOUS-DISTRIBUTED ALGORITHMS

by

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ABSTRACT

INTER-CELL INTERFERENCE COORDINATION IN OFDMA NETWORKS: TWO AUTONOMOUS-DISTRIBUTED ALGORITHMS

In OFDMA cellular networks, inter-cell interference hinders system performance, especially for users located at the cell edges. Inter-cell interference coordination (ICIC) techniques have been investigated by both the academia and standardization communities to reduce the impact of interference and improve system performance. We first survey conventional frequency planning schemes, and classify ICIC schemes in terms of their distributivity and dynamicity. We highlight the advantages and disadvantages of these schemes using examples from the literature. We then evaluate the performances of frequency planning schemes, in particular, reuse-1, reuse-3, strict fractional frequency reuse (FFR) and soft frequency reuse (SFR). We compare their performances under different resource scheduling strategies via simulations. Based on the simulation results, we outline the design trade-offs for ICIC techniques to be used in OFDMA networks. The novel contribution of this thesis is the proposition of two autonomous-distributed ICIC algorithms. One is a dynamic algorithm based on game theory, where the base stations play a trial and error game to maximize the overall network throughput. The other is a semi-static algorithm based on cell-based measurements and aggregate feedback, whose goal is to increase the number of supportable users by optimizing FFR parameters. We evaluate the performance of the proposed algorithms against static ICIC schemes, via system simulations under a variety of scenarios. While the game-theoretic algorithm shows robust results, outperforming all static schemes under different conditions, we argue its suitability for implementation. Although the semi-static algorithm is open to implementation and still shows promising results, we indicate cases where its performance falls slightly under reuse-1. Finally, we discuss possible ways to improve our algorithms and we suggest future research directions.

ÖZET

DFBÇE AĞLARDA HÜCRELER ARASI GİRİŞİM EŞGÜDÜMÜ: İKİ ÖZERK-DAĞITIK ALGORİTMA

Dikgen frekans bölüşümlü çoklu erişim (DFBÇE) hücresel ağlarda, hücreler arası girişim, sistem başarımını, özellikle hücre kenarlarında olan kullanıcılar için olumsuz etkiler. Girişimin etkilerini azaltmak için, hücreler arası girişim eşgüdümlemesi (HAGE) yöntemleri, hem akademi hem de ölçünleme kurulları tarafından araştırılmıştır. Öncelikle, geleneksel frekans planlama yöntemlerini inceliyor ve HAGE yöntemlerini dağıtıklık ve devingenlikleri bakımından sınıflandırıyoruz. Literatürden örnekler vererek, bu yöntemlerin getirilerini ve götürülerini belirtiyoruz. Sonrasında, yeniden kullanım-1, yeniden kullanım-3, kesirli frekans yeniden kullanımı (KFYK) ve yumuşak frekans yeniden kullanımı (YFYK) olmak üzere, frekans planlama yöntemlerinin başarım değerlendirmesini yapıyoruz. Farklı özkaynak çizgeleme gengüdümleri altında, benzetimler aracılığıyla, bu yöntemlerin başarımlarını karşılaştırıyoruz. Benzetim sonuçlarına dayanarak, HAGE yöntemlerinin tasarım ödünleşimlerini anahatlarıyla belirtiyoruz. Bu tezde, iki özgün özerk-dağıtık HAGE algoritması öneriyoruz. Oyun kuramından yola çıkılarak oluşturulan devingen ilk algoritmada, üs radyoları genel ağ hızını artırmak için deneme-yanılma oyunları oynuyorlar. İkincisi yarı-devingen algoritma ise hücre-tabanlı ölçüm ve toplu geribildirimleri kullanıyor. Bu yöntemde, hücrelerin kaldırabileceği kullanıcı sayısını artırma amacıyla, KFYK parametrelerinin eniyilemesi yapılıyor. Çeşitli senaryolar altındaki sistem benzetimleriyle, önerilen algoritmaların sabit HAGE yöntemlerine göre başarım değerlendirmesi yapılıyor. Oyun kuramsal algoritma, farklı koşullar altında tüm sabit yöntemleri aşan sağlam sonuçlar gösterse de, hayata geçirme konusunda sıkıntılar olduğunu görüyoruz. Yarı-devingen algoritma gerçeklenmeye açık olduğu ve umut veren sonuçlar verdiği halde, başarımının yeniden kullanım-1'in biraz altına düştüğü durumları belirtiyoruz. Son olarak, algoritmalarımızı geliştirmek için olası yolları tartışıyor ve gelecek araştırma yönleri öneriyoruz.

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LIST OF SYMBOLS

f_i	Set of subbands in the i^{th} band
G_{xy}	Path loss between the base station and the user
h_{xy}	Channel fading coefficient between base station x and user y
$J(x)$	Fairness index
N	Reuse factor
N_{band}	Number of total subbands
N_{int}	Number of interior region subbands
N_{ext}	Number of exterior region subbands
P^*	Fixed downlink transmission power
P_{xy}	Downlink transmit power of base station x to user y
r_{xy}	Downlink transmission rate of the y^{th} user of the x^{th} cell
R_{int}	Radius of the boundary between the interior and edge regions
x	Base station index
y	User index
$\mathcal{Z}$	Set of interfering base stations
α	Path loss exponent
β	System parameter for the proposed dynamic algorithm
σ	Standard deviation of the noise

LIST OF ACRONYMS/ABBREVIATIONS

BS	Base station
CBR	Constant bit rate
CQI	Channel quality indicator
DIPA	Distributed inter-cell power allocation
ECDF	Empirical cumulative distribution function
FFR	Fractional frequency reuse
GBR	Guaranteed bit rate
ICI	Inter-Cell interference
ICIC	Inter-Cell interference coordination
LTE	Long-Term Evolution
MCS	Modulation and coding scheme
OFDMA	Orthogonal frequency-division multiple access
PRB	Physical resource blocks
QoS	Quality of service
SFR	Soft frequency reuse
SINR	Signal-to-interference plus noise ratio
UE	User Equipment

1. INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

In multicellular networks, interference is a primary factor affecting the quality of service (QoS) for users. In orthogonal frequency-division multiple access (OFDMA), which is the standard for Long-Term Evolution (LTE) systems [4], intra-cell users are orthogonal to each other, therefore the source of interference is inter-cell interference (ICI). Static and dynamic inter-cell interference coordination (ICIC) strategies have been proposed in the literature to improve the throughput of users, especially those at the cell-edges, which suffer the most from interference. In this chapter, we will review ICIC techniques, but we refer the reader to [1] for a more thorough survey.

1.2. Static Inter-cell Interference Coordination Techniques

First, we will review the basic frequency planning schemes, some of which will help reducing ICI to different extents.

1.2.1. Conventional Frequency Planning

A conventional frequency planning scheme is called reuse-1, where the total bandwidth is reused in every cell, paying no attention to reduction of ICI. Although this scheme achieves high peak data rates, it results in the worst performance for cell-edge users, as a result of the high inter-cell interference levels. In turn, this leads to a lowered spectral efficiency.

Alternatively, clusters of N cells can share the total bandwidth among themselves, such that each cell in a cluster uses non-overlapping $1/N^{th}$ subbands of the available spectrum, explained in detail in [5]. In the hexagonal cell structure, $N = 3$ is commonly used, where the subbands are allocated to neighboring cells such that they do not interfere with each other. Compared to reuse-1, while reuse-3 results in better rates for

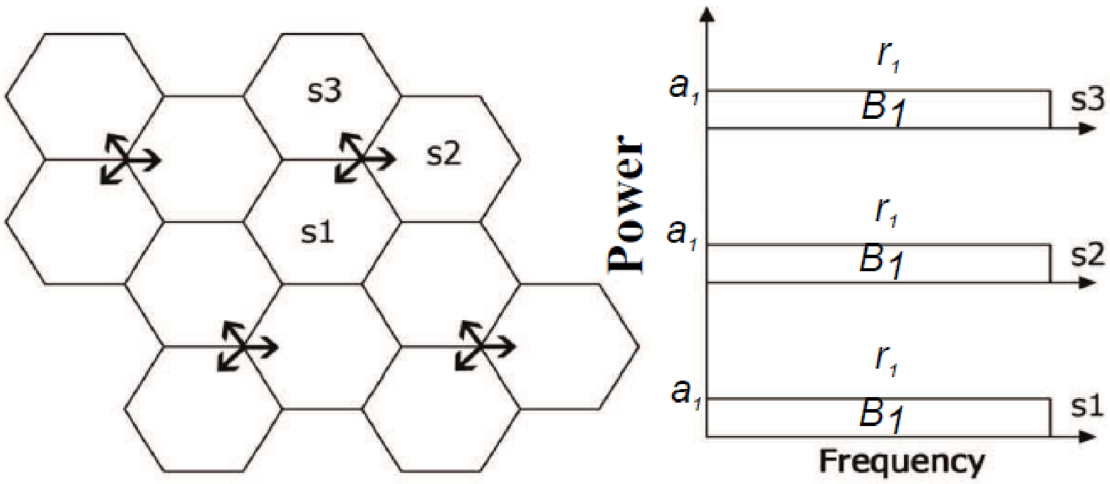


Figure 1.1. Conventional Frequency Planning: Reuse-1 [1].

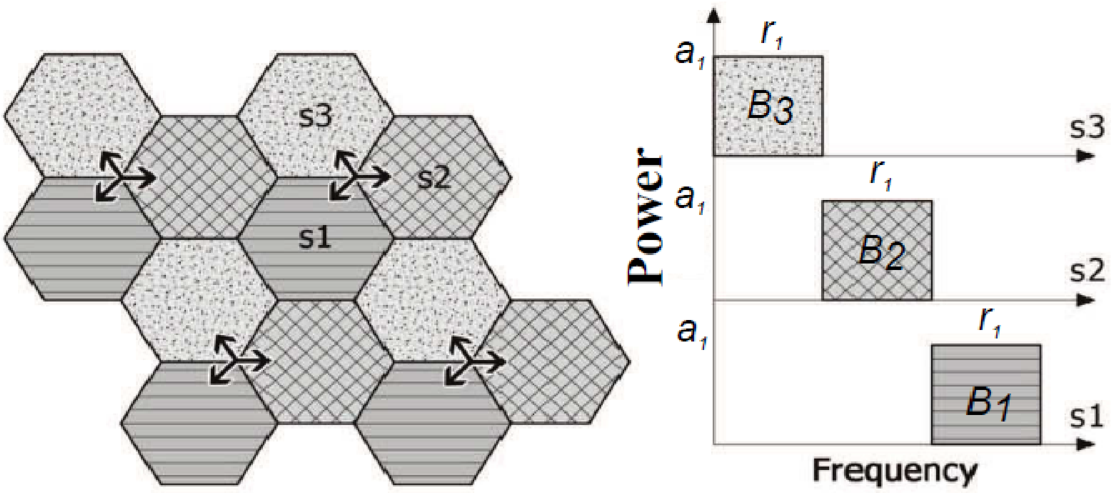


Figure 1.2. Conventional Frequency Planning: Reuse-3 [1].

edge users due to reduced ICI, it comes at a cost of low bandwidth utilization, hence low sum-rates for each cell.

While schemes with higher reuse factors are possible, such as Reuse-7, they are not practical due to even lower data rates. Therefore, in the discussion below, reuse-1 and reuse-3 schemes will be treated as the opposite ends of the spectrum of frequency allocation schemes. The former does not employ any interference avoidance or coordination at all, whereas the latter can be regarded as the extreme case of interference coordination, where no interference between neighboring cells exist, at a cost of severe bandwidth, hence throughput.

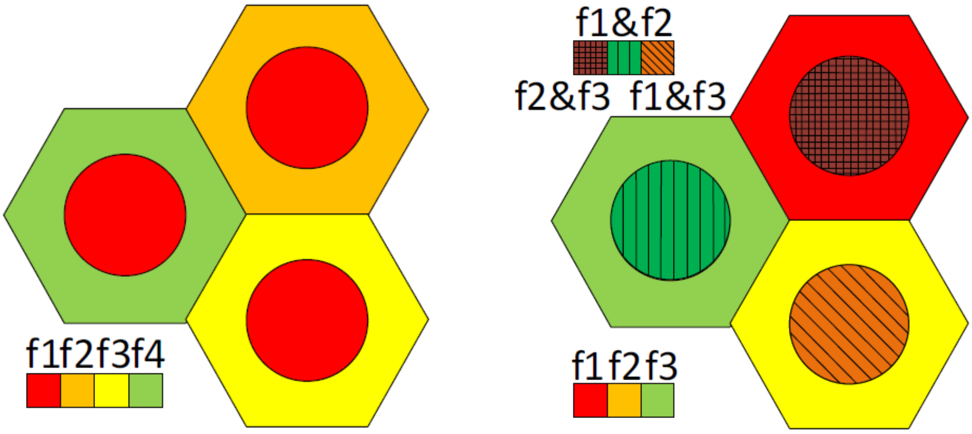
1.2.2. Fractional Frequency Reuse (FFR)

Fractional frequency reuse (FFR) is another common ICIC technique in OFDMA based wireless networks [6]. In FFR, each cell is divided into two regions, called cell-interior and cell-edge, based on the distance to the base station (BS). The bandwidth is partitioned so that cell-edge users of neighboring cells do not interfere with each other, and the interference received (and created) by cell-interior users is reduced. The use of FFR in cellular networks leads to natural tradeoffs between rate and coverage for cell-edge users, and mean throughput [7]. FFR schemes achieve reuse factors between 1 and 3, offering a compromise between the extreme shortcomings of the conventional frequency reuse schemes.

The two main types of FFR schemes are called strict FFR [8] and soft frequency reuse (SFR) [9], both of which will be considered in detail in Chapter 2. In strict FFR, the cell centers share a common band of frequencies, while the remaining spectrum is partitioned into different and mutually orthogonal frequency bands, as shown in Figure 1.3. Here, the interior users do not share any bandwidth with exterior users, reducing the interference for both interior and cell-edge users, at the expense of spectral efficiency. In SFR, the cell-edges of neighboring cells still use mutually orthogonal bands, however the cell-center of a particular cell is allowed to share the cell-edge subbands of the neighboring cells. SFR is therefore more bandwidth efficient compared to strict FFR, but the cell-edge users suffer from more interference due to sharing frequencies with neighboring interior users. To mitigate this, the downlink transmit power for interior users is typically lowered, at a cost of peak throughput.

1.3. Semi-static and Dynamic Inter-cell Interference Coordination Techniques

The aforementioned ICIC techniques are not able to adapt to changing conditions, such as user traffic or user density. Therefore, such schemes will result in performances that are far from ideal for certain cases, such as in a rush-hour scenario, where a large group of users are concentrated in specific parts of the network. To mitigate such



(a) Strict FFR (b) Soft FFR

Figure 1.3. FFR employments (Courtesy of [2]).

Table 1.1. Classification of ICIC techniques in terms of adaptability [3].

ICIC Time Scale	ICIC Adaptability	ICIC Classification
Days	Adaptive to long-term conditions	Semi-static (Adaptive)
Minutes	Cell-load adaptive	Semi-static (Adaptive)
Seconds	User-load adaptive	Semi-static (Adaptive)
Milliseconds	Fully-synchronized	Dynamic (Real-time)

problems, adaptive, or equivalently dynamic schemes that make use of cell-coordination are needed. Such cell-coordination based schemes can be categorized into two classes in terms of their adaptability, into semi-static and dynamic as shown in Table 1.3; or four classes in terms of their distributivity: Centralized, Semi-Distributed, Coordinated-Distributed, and Autonomous Distributed, as shown in Figure 1.4.

In centralized schemes, the whole network of base stations is coordinated through a single centralized server. Such systems are currently deemed to be unimplementable due to the computational complexity, as well as the large amounts of overhead and the associated scheduling delays, due to the limitations of today's backbone networks [10]. For these reasons, LTE systems have eliminated the central control unit [11]. Examples of centralized scheme can be found in [12–14].

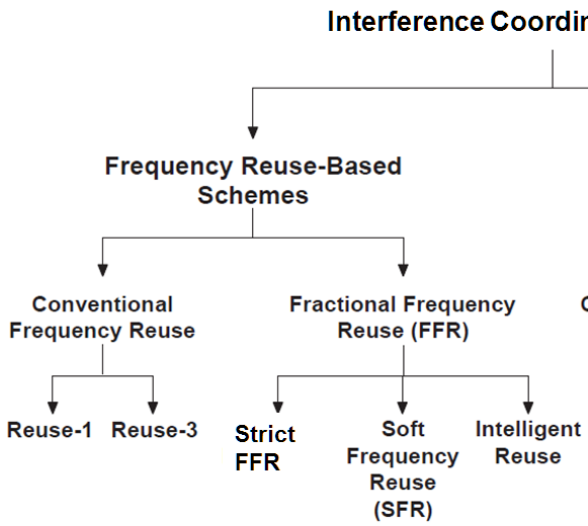


Figure 1.4. Classification of ICIC techniques in terms of distributivity [1].

Semi-distributed schemes make use of central controlling entities which control a number of base stations, rather than the whole network. These schemes also suffer from the same problems as the centralized schemes, though at a lesser extent. They also face scalability issues, which are not properly addressed in some of the proposed algorithms [15]. Other notable examples include [16–18].

In coordinated-distributed schemes, each base station performs an optimization using the information supplied by its neighbors. Because the resource allocation is performed only at the base station level, the latency associated with the scheduling is greatly lowered, making such schemes more attractive for practical implementation. However, due to constraints on the communication standards between base stations, the realization of these schemes have remained limited [19]. The LTE standard defines a few messages to be exchanged between base stations to coordinate inter-cell interference. Articles that make use of these messages include [20–22].

The autonomous-distributed schemes are similar to coordinated distributed schemes in that each station performs its own optimization, yet in the autonomous scenario, the base stations only use the local information collected from its connected users. As there is no latency associated with the signaling between the base stations, decisions can adapt faster to the instantaneous channel and traffic conditions, making such systems truly self-organizing, a key factor for the future mobile network systems [23].

1.3.1. Autonomous-Distributed Cell Coordination-Based Algorithms

In this thesis, we propose two novel autonomous-distributed algorithms, therefore we would like to familiarize the reader with a few examples of such algorithms from the literature.

One of the earlier and well-cited papers in this field was written by Stolyar *et al.* [24], who propose an algorithm dynamically allocating power to different subbands, which eventually converges to FFR-like patterns without any prior planning. Their scheme divides the bandwidth into a number bands (3 for their simulations), grouping a number of subbands together. Each BS regularly solves a selfish optimization of the assignment of the users to bands and the associated transmit powers, with the objective of minimizing its power usage. This optimization is done based on the reports on channel quality indicator (CQI) from its connected users. This optimization naturally converges to a solution, where the edge users are assigned the good channels and allocated higher transmit powers. In turn, these channels will become bad for its neighboring cells, which will assign different sets of channels to their edge-users as a result of their local power optimization. This will then result in even better channels for the cell-edge users of the original cell, hence a further improvement in performance. After a few iterations, the system therefore settles into a subband allocation pattern, resembling efficient FFR patterns. The primary limitation of the authors' work, is that they assumed constant bit rate (CBR) traffic type flows, which may not represent real-life traffic, where the users may require changing data rates.

In their later work, Stolyar *et al.* focus on best-effort traffic, instead of CBR traffic [25]. While the power allocation algorithm in this paper is similar to their earlier work, a further "proportional fair scheduling algorithm" is required for the scheduling of users, described in detail in [26].

In [19], Cicalo *et al.* propose a resource allocation algorithm, that preserves the fairness between cells, by running an offline algorithm for load balancing between cells. It is claimed this distributed scheme approaches the capacity of centralized schemes. However, the main disadvantage of this work, is that the system requires a previously planned static FFR scheme as a base, therefore it is neither fully dynamic, nor can it be used in systems with irregular cell configurations.

In [27], Ko *et al.* present a power allocation algorithm which they call distributed inter-cell power allocation (DIPA), which improves the throughput-fairness trade-off. DIPA determines the power allocation to each users by using a simplified version of the iterative water-filling scheme, and then incorporates the individual power allocations into one policy. Each user measures the average ICI level on each channel over a super-frame period of 1 second, then compares it to the interference threshold set by the BS. Users that report high interference levels choose channels with low interference levels, and send this preference information to its BS, which performs the power allocation procedure that incorporates the preferences of all the users.

A game-theoretic algorithm to solve the resource allocation problem is proposed by Duy La *et al.* in [28]. In this paper, the users, which constitute the players in the game, compete for a number of subbands by playing the "best-response" (also known as myopic) game, until the Nash equilibrium is reached. In the algorithm, each user tries to minimize its utility function, which the authors define as the the sum of the interferences generated by itself, and those that it receives from elsewhere.

1.4. Organization

The organization of the thesis is as follows: In Chapter 2 we provide a detailed performance evaluation of static frequency planning schemes. In Chapters 3 and 4, we propose one dynamic and one semi-static autonomous-coordinated ICIC scheme, evaluate their performances and discuss their advantages and shortcomings. We conclude with Chapter 5.

2. PERFORMANCE EVALUATION OF FREQUENCY PLANNING AND SCHEDULING SCHEMES

2.1. Motivation

In Chapter 1, we introduced static and dynamic ICIC techniques, and stated that we would propose two autonomous-distributed algorithms later on in the thesis. In order to evaluate and quantify the effectiveness of these algorithms, we first need to obtain benchmark results of static frequency planning techniques for comparison.

In this chapter, we therefore evaluate the performance of these frequency planning schemes, using round-robin, proportional fair, and best channel quality information (best CQI) schedulers via Monte Carlo simulations. Our contributions are as follows:

- To highlight the tradeoffs between design parameters and performance evaluation metrics
- To bring insights to the design of cellular systems
- To provide benchmark results for the development of dynamic ICIC techniques and resource scheduling methods.

The work in this chapter was published in [29].

2.2. System Model

In this work, we study the downlink traffic in OFDMA cellular systems. Furthermore, our model only considers the path loss and small scale fading effects, and we ignore shadowing and fast fading effects for simplicity. Therefore, the signal-to-interference plus noise ratio (SINR) for user y served by the base station x in our system is given as:

$$\text{SINR}_y = \frac{P_{xy} h_{xy} G_{xy}}{\sigma^2 + \sum\limits_{z \in \mathcal{Z}} P_{zy} h_{zy} G_{zy}} \tag{2.1}$$

where P_{xy} and P_{zy} are the downlink transmit powers of the serving and interfering base stations, respectively, for the subband in use by user y. h_{xy} denotes the channel fading coefficient, which is assumed to be exponentially distributed. The path loss between the base station and the user is calculated as $G_{xy} = \|\mathbf{x} - \mathbf{y}\|^{-\alpha}$, where $\mathbf{x}$ and $\mathbf{y}$ denote the coordinates of base station x and user y, and α is the path loss exponent. σ is the standard deviation of the noise and $\mathcal{Z}$ is the set of base stations interfering with user y.

2.2.1. Frequency Planning Schemes

For strict FFR (which will be referred simply as FFR for the remainder of this thesis), P_x, the downlink transmit power, is fixed for all users in all subbands, but for SFR, the transmit power can be reduced by a power control factor for center users. Typically used power control values are 2 or 4, which correspond to edge-user gains of 3 dB and 6 dB, based on heuristic results in [30].

The classification of users into interior and exterior regions is an important factor in FFR and SFR systems. This is typically achieved through time averaged SINR calculations. If the SINR is above some threshold, the user is deemed to be an interior user, otherwise an exterior, or cell-edge user. Changing this SINR threshold directly changes the radius of the interior circle (see Figure 1.3), which forms the boundary between center and edge users. The ratio of interior radius to the cell radius is therefore a design parameter for FFR and SFR systems.

Furthermore, the allocation of the total bandwidth into bands is another design factor. For FFR, given a total number of subbands N_{band} and interior region subbands N_{int} as a design parameter, the number of exterior region subbands is calculated in [9] as

$$N_{ext} = \frac{N_{band} - N_{int}}{3}. \tag{2.2}$$

Similarly, for SFR, the number of exterior region subbands is given by:

$$N_{ext} = \min\left(\frac{N_{band}}{3}, N_{band} - N_{int}\right). \tag{2.3}$$

2.2.2. Schedulers

In OFDMA systems, users are allocated a specific number of subbands for a predetermined amount of time. These are referred to as physical resource blocks (PRB) in the LTE specifications. Allocation of PRBs is handled by a scheduling function at each base station.

We consider three major scheduling schemes for the scope of our work: round-robin, proportional fair and best CQI.

Round-robin scheduling is the conventional, non-channel-aware scheduling scheme, where the users take turns in using the shared resources of time slots and subbands, without taking the instantaneous channel conditions into account. The main advantage of round-robin scheduling is its inherent fairness, in that each user in a particular region gets equal allocation of resources. However, as it ignores the channel quality information, it typically results in suboptimal throughput levels.

Best CQI scheduler assigns each resource block to the user with the best channel conditions, i.e. the best SINR. In the actual implementation of cellular systems, this is achieved through the feedback of the CQI from each user to their serving base station on a subband basis. This scheduling scheme therefore maximizes the sum-rate, at the expense of fairness. Due to the increased path loss, the cell-edge users are unlikely to be assigned any resources.

Proportional fair scheduler, proposed in [31] for OFDMA systems, achieves a good tradeoff between mean throughput and fairness among the users. This channel-aware scheduler assigns each subband to maximize the sum of logarithmic transmission rates. In our work, we use the slightly suboptimal reduced-complexity algorithm, explained in detail in [32].

2.2.3. Performance Evaluation Metrics

Plotting the empirical cumulative distribution function (ECDF) of individual user throughputs is a powerful tool to assess the performance of frequency planning schemes and schedulers. However, when testing against a family of parameters, plotting ECDFs for each combination is impractical for clarity purposes. In this case, we can examine the following metrics to summarize the distribution of user throughputs: mean throughput, edge throughput (defined as 5^{th} percentile point of user throughput ECDF), peak throughput (defined as 95^{th} percentile point of user throughput ECDF), and fairness index, proposed by Jain in [33]:

$$J(x) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n\sum_{i=1}^{n} x_i^2}, \tag{2.4}$$

where x_i are the throughputs for each of the n users. This fairness index is bounded between 0 and 1, where 1 implies full fairness, when each user is getting the same throughput.

2.3. Simulation Results

The parameters used to obtain the simulation results are given in Table 2.1. A 19-cell simulation setup was used, with two layers of interfering cells arranged around a target cell, for which the performance metrics were evaluated. The selection of FFR and SFR design parameters are provided in the figures and text.

Figures 2.1-2.3 present the performance of the schedulers under different fre-

Table 2.1. Simulation parameters for the performance evaluation of frequency planning and scheduling schemes.

Parameter	**Value / Assumption**
Cell Layout	Hexagonal - Single Sector
User Distribution	Uniform
Inter-site Distance	1 Km
Path Loss Model	$L = 100 + 35log_{10}(d)$
Cell Edge SNR	10 dB
Number of Subbands	96
Number of Users per Cell	60
Subband Bandwidth	1 MHz
Channel Model	Rayleigh Flat Fading
Frequency Planning	Reuse-1 Reuse-3 FFR SFR
Scheduler	Round Robin Best CQI Proportional Fair

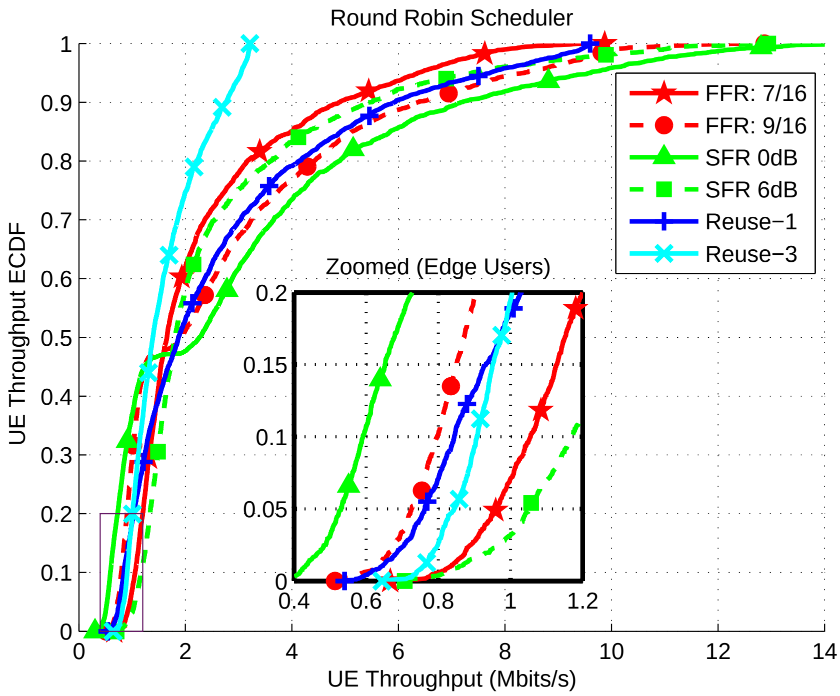


Figure 2.1. Performance of round-robin scheduler under different frequency planning schemes.

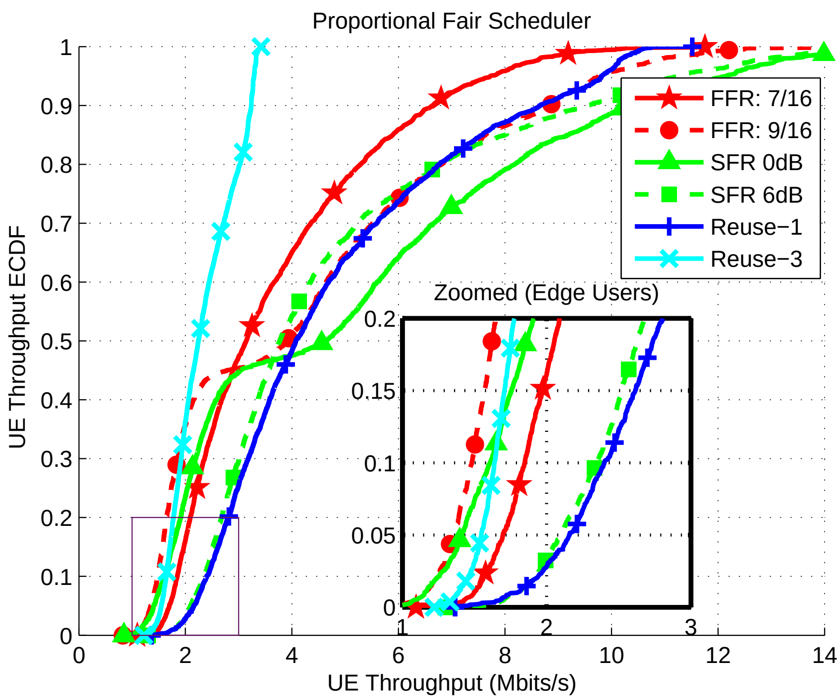


Figure 2.2. Performance of proportional fair scheduler under different frequency planning schemes.

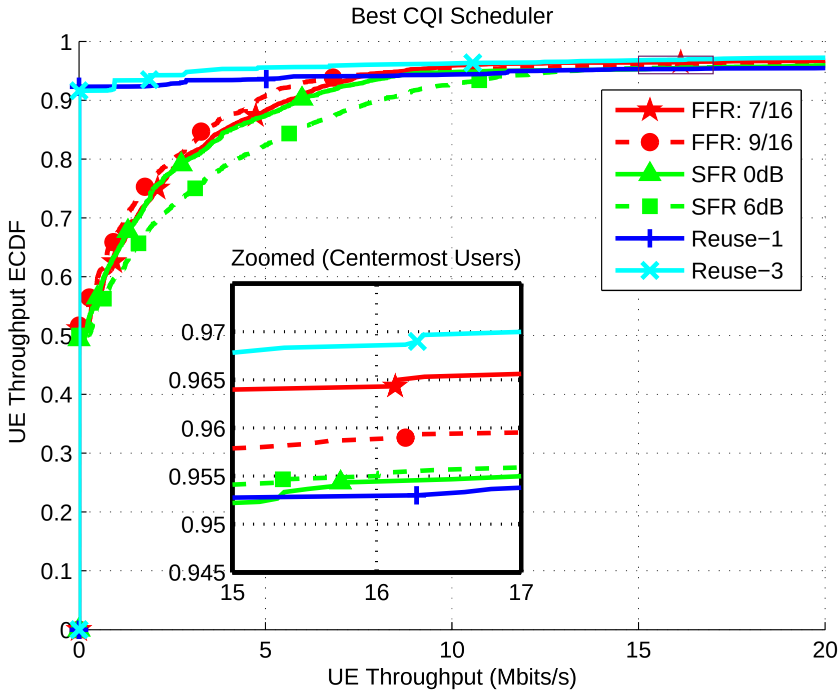


Figure 2.3. Performance of best CQI scheduler under different frequency planning schemes.

quency planning schemes. The lower tail of the ECDF is zoomed for clarity to show the cell-edge performance in the round-robin and proportional fair schedulers, and the high-throughput region is zoomed to show the peak performance for the best CQI scheduler. We compare the performance of reuse-1, reuse-3, FFR and SFR techniques, using two sets of system design parameters for the latter two. The ratio of the interior radius to the cell radius is fixed at 2/3 for all cases, but we repeat the simulations different ratios of bandwidth allocated to the interior region (7/16 and 9/16) for FFR, and different SFR power control factors for SFR (1 and 4, corresponding to edge user gains of 0 dB and 6 dB respectively).

The performance of the round-robin scheduler is shown in Figure 2.1. As expected, the reuse-3 scheme performs better than the reuse-1 scheme with regard to the cell-edge throughput, at the cost of significant peak throughput. We see that none of the users in the reuse-3 scheme get above 3 Mbits/s, whereas 20-40 per cent of users for other planning schemes are served with the same bit-rate. Despite offering better peak throughputs than reuse-3, the reuse-1 scheme still falls short of FFR 9/16 and SFR 0 dB. For the cell-edge throughputs, shown in the zoomed view, one might initially expect the reuse-1 scheme to perform worst. However, because SFR allocates only $1/3^{rd}$ of its bandwidth to its exterior users which make up about half of its total users, and does no interference mitigation at unity power control factor, it is in fact not surprising to see SFR 0dB perform worst for the edge users. On the other hand, with $2/3^{rd}$ of its bandwidth assigned to the interior users at full power, SFR 0 dB results in the best peak performance. Allocating more bandwidth to the exterior users, or increasing the SFR power control factor directly improves cell-edge performance, as we see from the FFR and SFR curves, at a cost of peak performance (i.e. interior user performance). It is worthwhile to note that SFR 6 dB outperforms FFR 7/16 for every part of the ECDF plot, indicating that there exist certain combinations of parameters or solutions which are absolutely better than others, despite the natural tradeoffs.

Figure 2.2 compares the performance of the frequency planning schemes for the proportional fair scheduler. Interestingly, the order of the cell-edge performances of the schemes is different compared to the round-robin scheduler. Reuse-1 outperforms the others in this case, despite having no inherent interference mitigation in its design. The intuition for this result is that the proportional fair scheduler dynamically allocates the resources based on the individual channel conditions, therefore it can be thought of as a basic dynamic ICIC technique. This helps every frequency planning scheme, bringing the cell-edge throughputs from $0.5 - 1$ Mbits/s in the round-robin case, to $1.2 - 2.2$ Mbits/s. The one to benefit the most is reuse-1, as it naturally allows for the bandwidth to be assigned freely to center and edge users, based on the channel conditions. FFR and SFR constrain each user to use from a limited set of frequencies, therefore the potential improvements from using the proportional fair scheduler is less.

The results for the best CQI scheduler are shown in Figure 2.3. This scheduler, which seeks to maximize the total throughput, assigns its resources to the user with the best channel conditions, often the closest users to the base station. This is why more than 90 per cent of the users are blocked for reuse-1 and reuse-3. Even though FFR and SFR ensures that some resources are allocated for edge users, 50 per cent of the users are still blocked. In all cases, the peak throughputs are very high, where a significant portion of the served users get over 20 Mbits/s. As with the proportional fair controller, the best performance improvements are observed for the reuse-1 scheme, because of the channel-aware scheduling.

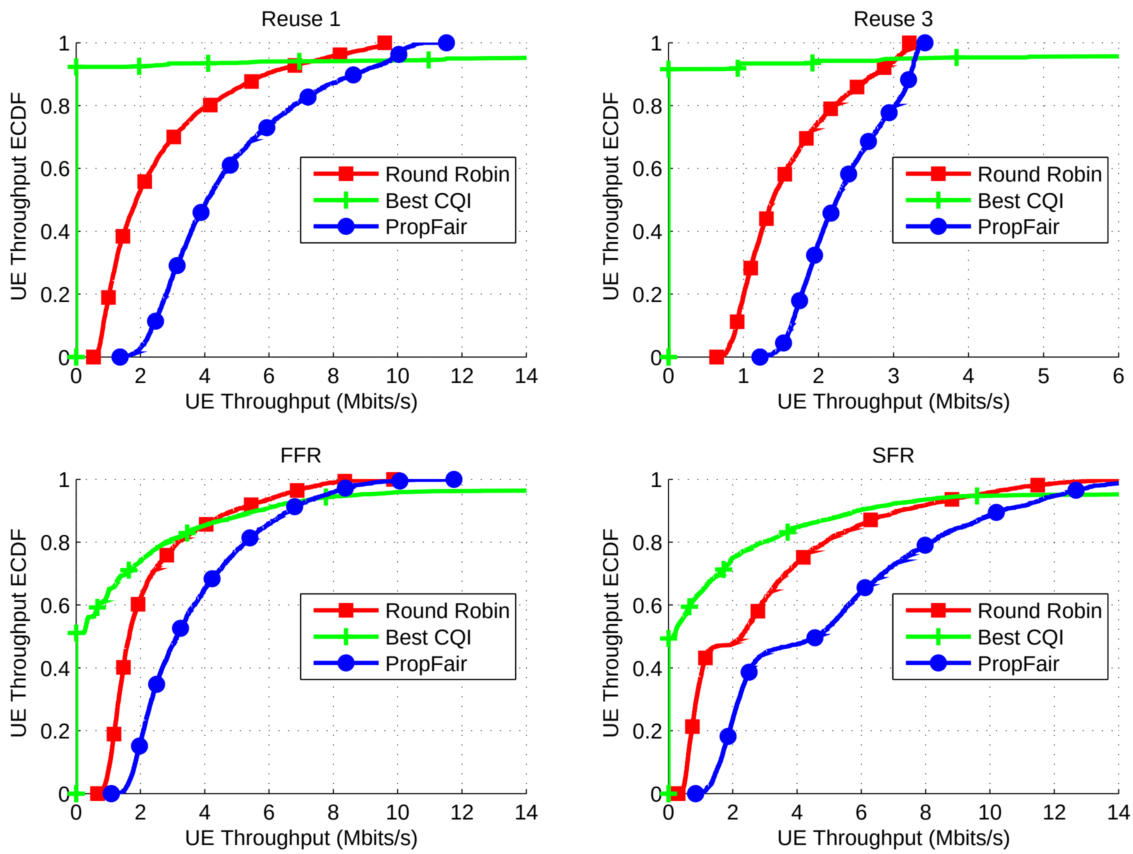


Figure 2.4. Performance of frequency planning schemes under different schedulers.

Figure 2.4 is another way of examining the previously given results, with emphasis on the schedulers. Compared with the "blind" round-robin scheduler, the channel-aware proportional fair scheduler is better for all frequency planning methods across each band of users, and the best CQI achieves its aim of maximizing total throughput at a severe cost of edge user performance and blocking.

The results presented thus far for FFR used only a fixed ratio of the interior radius to the cell radius, and two values for bandwidth allocation between the center and edge users, for clarity of presentation. As mentioned in Section 2.2, these two important parameters in the design of FFR systems can be varied independently to achieve varying

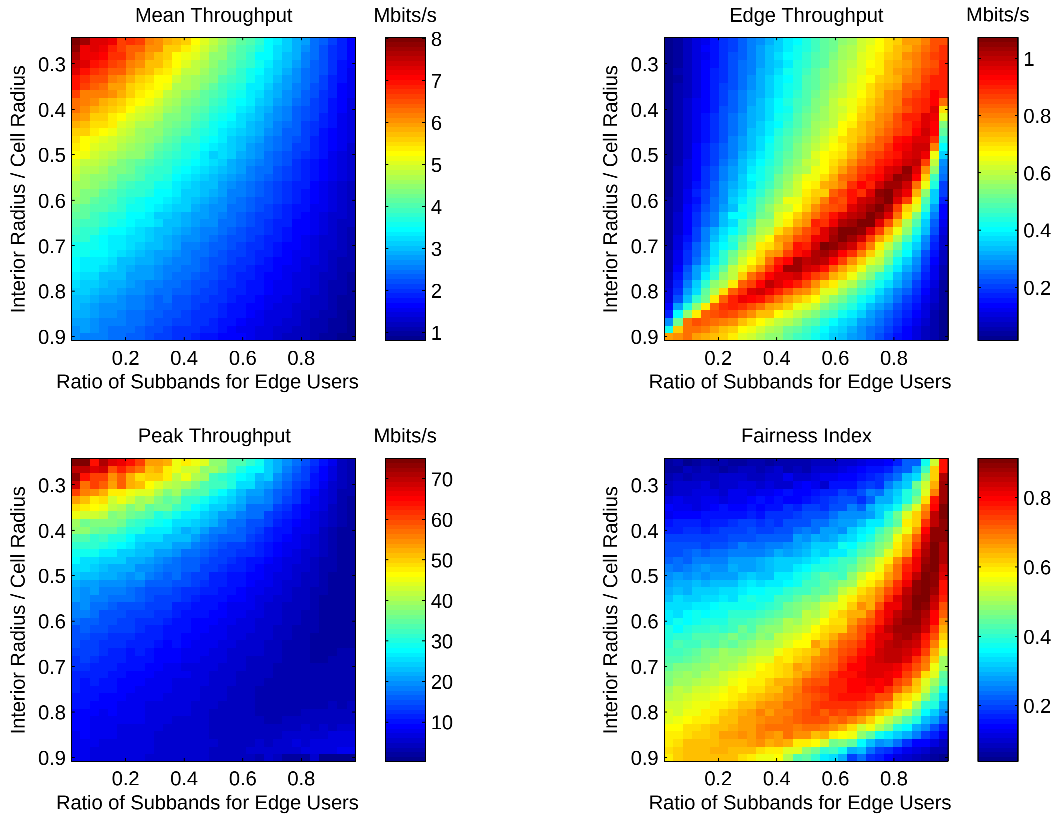


Figure 2.5. Performance of strict FFR for varying interior radii and subband allocation under round-robin scheduler.

levels of tradeoff between the peak, mean, and cell-edge throughputs and Jain's fairness index, as shown in Figure 2.5, obtained for the round-robin scheduler. As expected, when we define a smaller number of interior users and give them a larger portion of the bandwidth, the peak throughput of the system increases, at a cost of cell-edge throughput and in turn, fairness. Because the peak throughput can be two orders of magnitude larger than the cell-edge throughput, it is the dominant factor in the mean throughput. Given a fixed interior radius, as more subbands are allocated for exterior users, the cell-edge throughput naturally increases as a result of having more resources available. However, beyond a certain point, the central users are assigned so few subbands that their throughputs fall below that of edge users. Bearing our definition of edge throughput as the 5^{th} percentile point of user throughput ECDF in mind, the central users, which now constitute the low-throughput users, are effectively classified as edge users, and it is their rates which are shown in the bottom-right of the edge throughput graph. Therefore, we observe a "band" of suitable combinations of parameters to obtain high cell-edge throughput, hence better fairness, which need to be kept in mind for FFR system design.

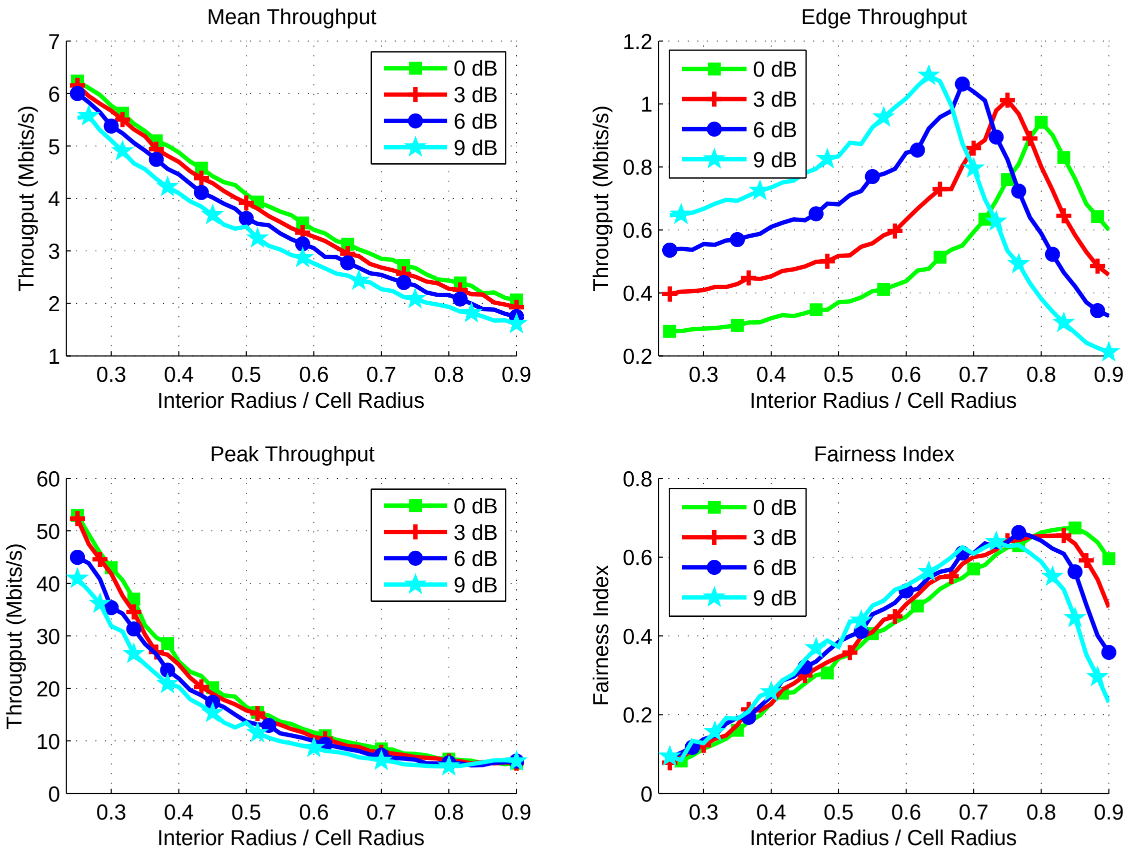


Figure 2.6. Performance of SFR for varying interior radii and power control factors under round-robin scheduler.

Similarly for SFR, the selection of important parameters of power control factor and radius ratios is investigated in Figure 2.6. As the power allocated to the interior users are decreased (power factor from 1 to 8, equivalently 0 dB to 9 dB), the peak and mean throughputs decrease as well, close to 25 per cent for a range of radius ratios. On the other hand, giving interior users less power benefits the cell-edge users due to reduced interference, up to certain radius ratios, e.g. 0.65 for SFR 9 dB. As with the FFR scheme, beyond these critical points, the central users are effectively classified as edge users because of their lower rates. As the interior radius is increased further, subbands per central user decreases even more, resulting in even lower throughput. This set of graphs therefore point out certain combinations of parameters which outperform others in terms of both peak and cell-edge throughputs.

2.4. Design Guidelines

In the design of cellular networks, the relative importance of different metrics may change under various traffic loads and channel conditions. For example, under high traffic loads, the designer may wish to optimize for total throughput, or in cases where the majority of users lie close to the cell boundaries, the designer may sacrifice peak throughput to achieve better cell-edge throughput and fairness. Because of the inherent tradeoffs observed in the results, designers may impose constraints on certain performance metrics and optimize for others. In this section, we will briefly talk about guidelines with respect to these tradeoffs.

Cell-edge user performance: For SFR, we see that the power control parameter is crucial in the cell-edge user performance from Figure 2.6. Changing this parameter from 0 dB to 9 dB increases the cell-edge throughput more than 100 per cent for a range of interior radii, at about 20 per cent reduction in the mean throughput. Changing the radius ratio also affects cell-edge throughputs significantly, at a cost of more severe mean and peak throughput performance. Therefore the designer should look to play with the power control parameter first, in order to preserve the mean throughput while improving cell-edge performance. For FFR, with edge throughput in mind, there is a favorable "band" for the selection of the two parameters shown in Figure 2.5. The ratio of the radii and the ratio of allocated subbands must be carefully chosen by the designers to achieve good edge performance, while not hurting mean throughput significantly.

For any frequency planning scheme, best CQI scheduling leads to abysmal cell-edge user performance, as all edge users are blocked, while proportional fair scheduling is better than round-robin scheduling for averaged, or asymptotic results. However, despite not being explicitly mentioned in this work, the proportional fair scheduling scheme may decide not to assign any resources to edge-users going through deep fades, in order to improve the overall system performance. The effects thereof, such as the possibility of dropped calls, or outage probabilities may need to be considered in the design of systems with CBR traffic, for which consistent scheduling may be required.

Mean throughput: For both FFR and SFR (Figures 2.5-2.6), allocating more resources for center users, and reducing the radius of the interior region improves mean throughput, at a cost of cell-edge throughput, and fairness. Compared with the round-robin scheduler, proportional fair scheduler improves mean throughput as well (Figure 2.4), and it should be preferred unless it degrades other metrics, such as queuing delay or outage probability, which were not mentioned in this work.

Peak throughput: From the results, we see that parameters that increase mean throughput result in increasing peak throughput and vice versa, albeit at different levels. The best CQI scheduler should be preferred if the only goal of design is to optimize for peak throughput, although realistic systems would most likely stay away from this choice, due to its severe impact on edge-throughput, and outage probability.

2.5. Conclusion

We have presented the tradeoffs associated with reuse-1, reuse-3, strict FFR and SFR schemes, under round-robin, proportional fair, and best CQI schedulers. Using interior radius selection, resource allocation between bands and SFR power control as design tools, it is possible to configure FFR and SFR systems to achieve desired metrics. While the best CQI scheduler maximizes peak throughput at a severe expense of edge throughput, the channel-aware proportional fair scheduler outperforms round-robin scheduling for all considered metrics. The observation of the differences in the performance of frequency planning schemes under different schedulers motivates future research on strategies that combine the two to dynamically adapt to changing channel conditions and user traffic loads in each cell.

3. A GAME-THEORETIC DYNAMIC INTER-CELL INTERFERENCE COORDINATION ALGORITHM

3.1. Motivation

In our literature survey in Chapter 1, we observed that the dynamic ICIC algorithms generally offer better and more robust results across a wide range of assumptions and problem formulations. Furthermore, we noted that schemes that are based on cell-coordination, especially centralized or semi-distributed schemes, were impractical due to scalability and latency issues. Therefore, in our research we decided to focus on developing an autonomous-distributed dynamic algorithm, where each base station will update its decisions on every time slot, independent of other base stations.

3.2. Problem Statement

We consider the downlink sum-rate maximization problem, defined as:

$$\begin{aligned} \text{maximize} \quad & \sum_{x=1}^{\#\text{cells}} \sum_{y=1}^{\#\text{users}} r_{xy} \\ \text{subject to} \quad & P_{xy} = P^* \\ & \text{Each user being assigned to a single subband,} \end{aligned} \tag{3.1}$$

where r_{xy} is the downlink transmission rate of the y^{th} user of the x^{th} cell, with a downlink transmission power of P_{xy}.

That is, given a fixed downlink transmission power P^*, we are trying to assign each user to a single subband in such a way as to maximize the sum throughput across all cells.

Even though the optimization problem given in Equation 3.1 seems simple at first glance, it is in fact extremely difficult to solve, even for a small number of users and subbands. To illustrate this point, let us consider a miniature example with 10 subbands and 5 users per cell in a 19-cell system. There exist $\binom{10}{5}$ resource assignment strategies in a cell, hence $\binom{10}{5}^{19} \approx 10^{45}$ resource assignment strategies across this relatively small network.

Moreover, the nature of the resource allocation means that the problem needs to be solved with integer programming. Coupled with the huge size of the solution space in mind, it is practically impossible to solve this problem using existing optimization software. Finally, the problem is non-convex, because terms appearing in the nominator of the SINR equation (Equation 2.1) for the calculation of rates in one cell, appear in the denominator of the SINR equation for other cells. As a result of these important issues, formal optimization methods are useless for our problem, and we require other optimization methods such as heuristic, genetic or game-theoretic algorithms.

3.3. System Model

We use a system model as described in Section 2.2, and we assume that the base stations know the instantaneous channel conditions for each user on each subband, through an uplink feedback link.

3.4. Proposed Algorithm

For our sum-rate maximization problem defined in Equation 3.1, we propose the game-theoretic algorithm in Figure 3.1, inspired by [34–36]:

The algorithm can be summarized as a series of trial-and-error games, where each base station tries to assign subbands to its users optimally. At each iteration, each base station selfishly tries to increase the data rate of a selected connected user, switching to different a different resource allocation (a different strategy) only when it will benefit the user in question. Over time, we expect that these individual selfish improvements will lead to improvement over the sum-rates of the system, and eventually settle into a Nash equilibrium, where each user content to stay with its assigned subband.

At each iteration

for $x = 1$ to $\#BSs$ **do**

BS x selects a used subband k (currently used by user y) randomly

BS x selects a free subband l (to be used by user y) randomly

if new rate>old rate for user m **then**

Change to new subband (new strategy) with probability $1 - \beta^{\Delta rate}$

end if

end for

Figure 3.1. Trial and Error Algorithm

The decision on whether the new rate of a user after the subband change is better than the old rate, is carried out by comparing the instantaneous channel conditions for the two subbands in question. The link adaptation is done in each time slot, where the rate of each user is calculated through a modulation and coding scheme (MCS) table.

The key intuition behind why this algorithm will work as intended is as follows: When a user is assigned to a new subband where it will receive a better rate, it is in fact moved to a "better" channel with less interference, which means that the neighboring cells were likely not using that channel. Therefore, with the new assignment, the user in question is taken away from a channel that the neighbor base stations possibly use, hence improving that channel for the users of the neighboring base stations. This is why selfish optimizations will point the system towards a global optimization.

In some cases, however, improving the rate of a user in a base station by a small amount may lead to significant decrease in the rates of other users in neighboring base stations. For example, if multiple neighbor cells of a target cell is using a specific subband, and we start using that subband in the target cell, then users in those neighbor cells who use that subband will suffer from lower rates because of the increased interference. In order to reduce the probability of such occurrences, we introduce the system parameter β, and have the base stations change to a different strategy with a probability of $1 - \beta^{\Delta rate}$. This means that, the smaller the additional rate from a strategy change is, the less chance that the base station will go through with that strategy change. Hence, base stations will not change their strategies for insignificant improvements, in an attempt to benefit the whole system.

It is important to note that, while trial-and-error algorithms like the one we proposed above do not guarantee reaching the global optimum, they often converge to Nash-equilibria close to the global optimum, at a small fraction of computation time. For our problem in particular, it would have been practically impossible to find optimum solutions using formal optimization tools, but using our proposed algorithm, we expect to get respectable results using real-time calculations.

3.4.1. Computational Complexity

During each iteration, the algorithm chooses two resource blocks at random, performs a single comparison of rates, and decides on the strategy based on this comparison. Therefore, the complexity per iteration per base station can be said to be $\mathcal{O}(1)$. Convergence of the algorithm and the effect of the system parameter β on the number of iterations till convergence will be investigated in Section 3.5.4.

3.5. Simulation Results

3.5.1. Sample Run of the Algorithm

Figure 3.2 shows the sum-rate progression for a sample run of the algorithm. We see that, after a number of iterations, the system finally converges to a Nash equilibrium, where no player (user) has can increase their throughput by changing only their own strategy. It should be noted that, around the 700^{th} iteration mark, we were getting a better sum-rate than the eventual Nash equilibrium, which suggests that the global optimum is not reached in the end, and that selfish optimization sometimes leads to overall system degradation as discussed in Section 3.4.

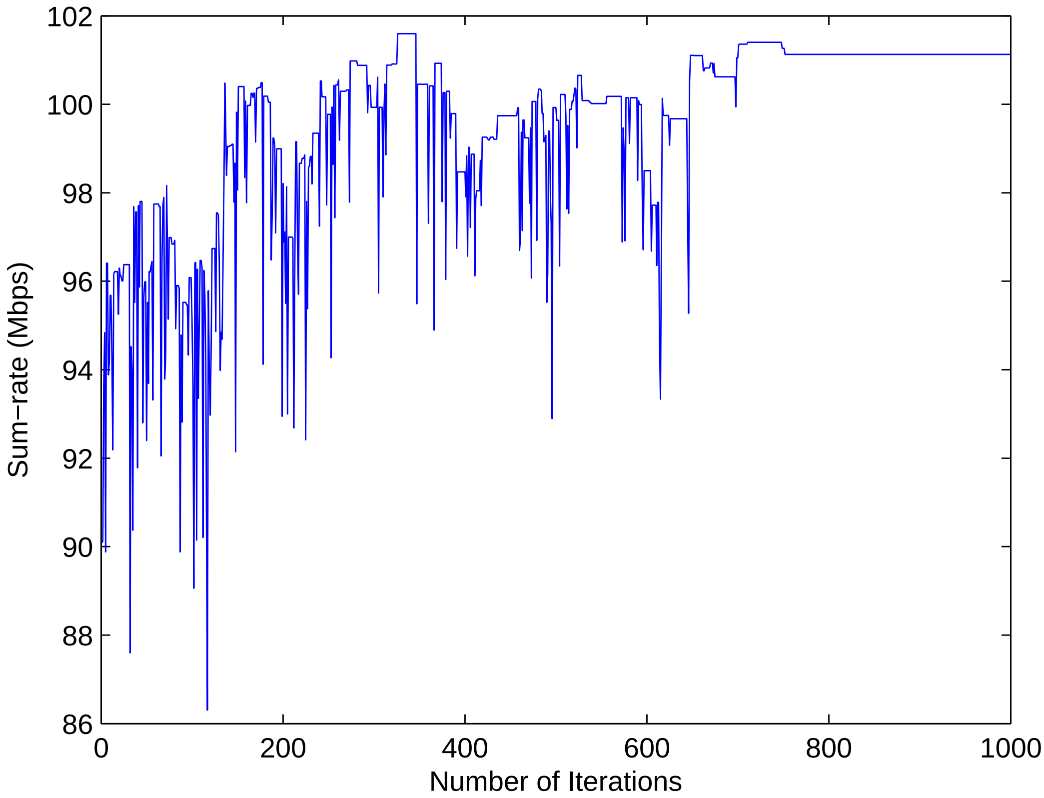


Figure 3.2. Convergence of the algorithm to Nash equilibrium.

3.5.2. Simulation Parameters

The parameters in our system can be categorized into Workload, Propagation, and System Parameters. The workload parameters consist of the number of users per base station and the number of subbands. These two factors directly affect the traffic load of each base station. Propagation parameters include the path loss factor α, downlink transmission powers and antenna gains. Finally, for we have β as our only system parameter, used in the calculations in the proposed algorithm. Please refer to Table 3.1 for a full list of system parameters in our 19-cell simulation setup, consisting of two layers of interfering cells arranged around a target cell, for which the performance metrics were evaluated.

In Section 3.5.4, we quantify the effect of Workload, Propagation and System Parameters.

Table 3.1. Simulation parameters for the performance evaluation of the dynamic algorithm.

Parameter	Value / Assumption
Cell Layout	Hexagonal - Single Sector
User Distribution	Uniform
Inter-site Distance	1 Km
Path Loss Model	$L = 100 + \{20 - 35\} log_{10}(d)$
Cell Edge SNR	$0 - 10$ dB
Number of Subbands	$8 - 16$
Number of Users per Cell	$4 - 10$
Subband Bandwidth	1 MHz
Channel Model	Rayleigh Flat Fading
Frequency Planning	Reuse-1 Reuse-3 FFR Game-Theoretic

3.5.3. Quality of Solutions

In order to evaluate the quality of our solutions, we used Statistical Quality Measure tests, as lower bounds for this problem do not exist.

Figure 3.3 was obtained using 10000 runs of random resource assignment (using reuse-1) and 6 runs of the algorithm (using random seeds). We see that the sum-rates obtained using random resource assignment fit to a Normal distribution nicely, with an average of 118.8 Mbps and a standard deviation of 2.43 Mbps. On the other hand, the solutions of the proposed algorithm lie in the range $127.5 - 129.5$ Mbps. Therefore, the algorithm leads to much better results than random assignment, around 4σ away from the mean, which indicate that the algorithm's performance can only be reached once in around 16000 random trials, hence showing its strength.

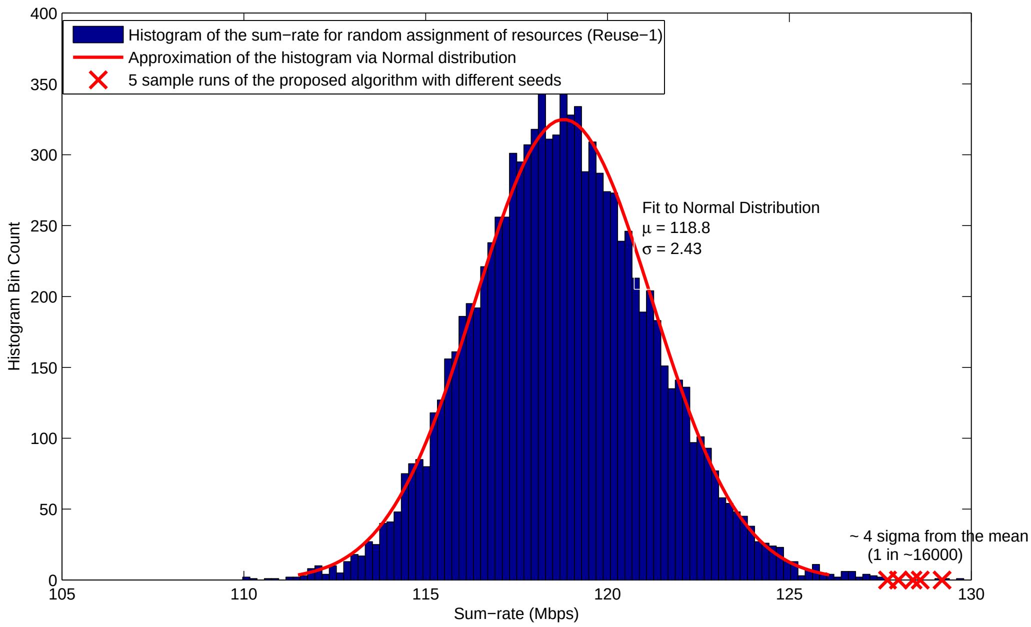


Figure 3.3. Performance of the proposed algorithm vs. random resource allocation.

In the Performance Evaluation section, we compare the performance our algorithm against random assignment of resources using not only reuse-1, but also reuse-3 and FFR frequency planning schemes. By indicating the standard deviation of each method, we further quantify the effectiveness and robustness of our algorithm under varying conditions.

3.5.4. Performance Evaluation

In this section, we show the results of our simulations, through a set of experiments where we vary one parameter at a time, using 3-4 levels for each. It would have been a more complete analysis if we could have carried out a proper 2^k factorial design. However, given our 5 workload, propagation and system parameters, the process would have been too complex, which is why we will be showing plots where we can observe the effect of a single parameter at a time, compared to a control state.

In our Monte Carlo simulations, we use different user location realizations, different resource assignment realizations (for reuse-1, reuse-3 and FFR) and different seeds for our algorithm. As stated in the previous section, by using mean and variances, we check the consistency of our results to evaluate the performance of our algorithm vs. static frequency planning schemes.

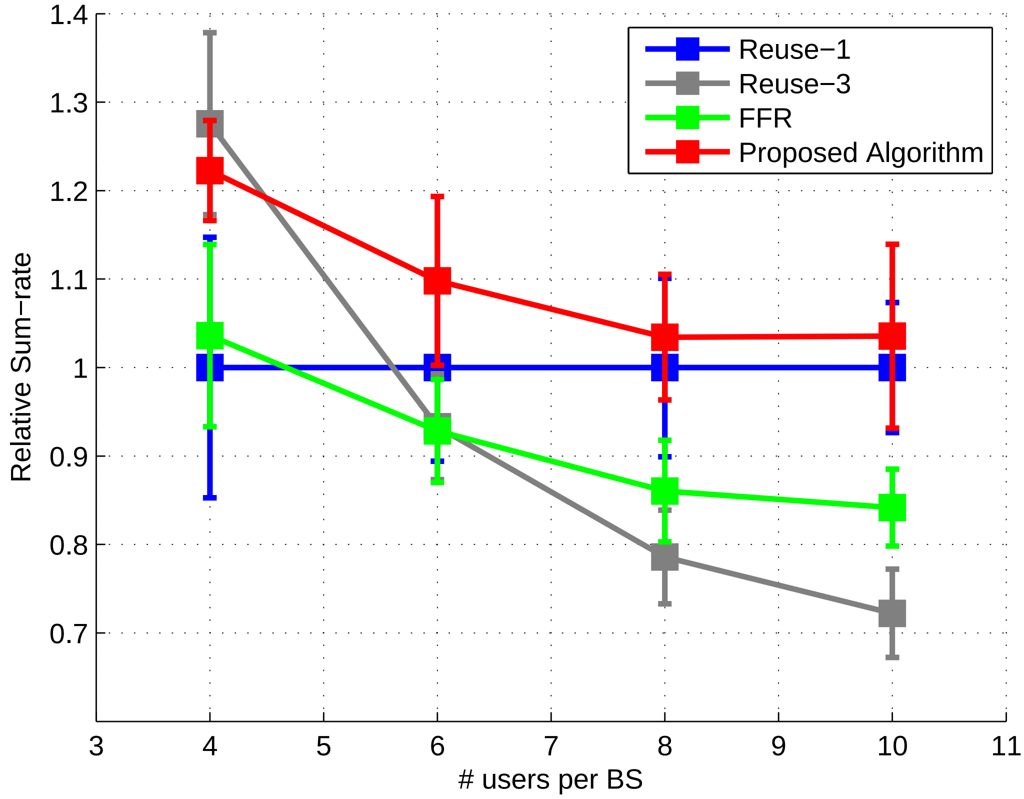


Figure 3.4. Relative sum-rate comparison for varying # users per base station, using many realizations of user locations (# subbands = 12, $\alpha = 3.5$, $\mathrm{SNR}_{edge} = 10$ dB, $\beta = 0.2$).

Figure 3.4 shows the performance of our proposed algorithm against static frequency planning schemes, when the number of users per base station is increased from 4 to 10, while keeping the other factors fixed (e.g. number of subbands is fixed at 12). In this figure and the following few figures, we plot all sum-rates relative to the sum-rates of reuse-1 in order to make fair comparisons. We see that our algorithm outperforms the other techniques across any number of users per base station, except for 4, when reuse-3 results in slightly better sum-rate. This is because reuse-3 is optimal when the number of users per BS is less than or equal to $1/3^{rd}$ of the number of subbands for our scenario. We also observe that reuse-3 falls behind of reuse-1 as the number of users are increased, as expected from the discussion in the Problem Definition section. Also, FFR's performance is between those of reuse-1 and reuse-3, as FFR forms a tradeoff between the two extreme cases.

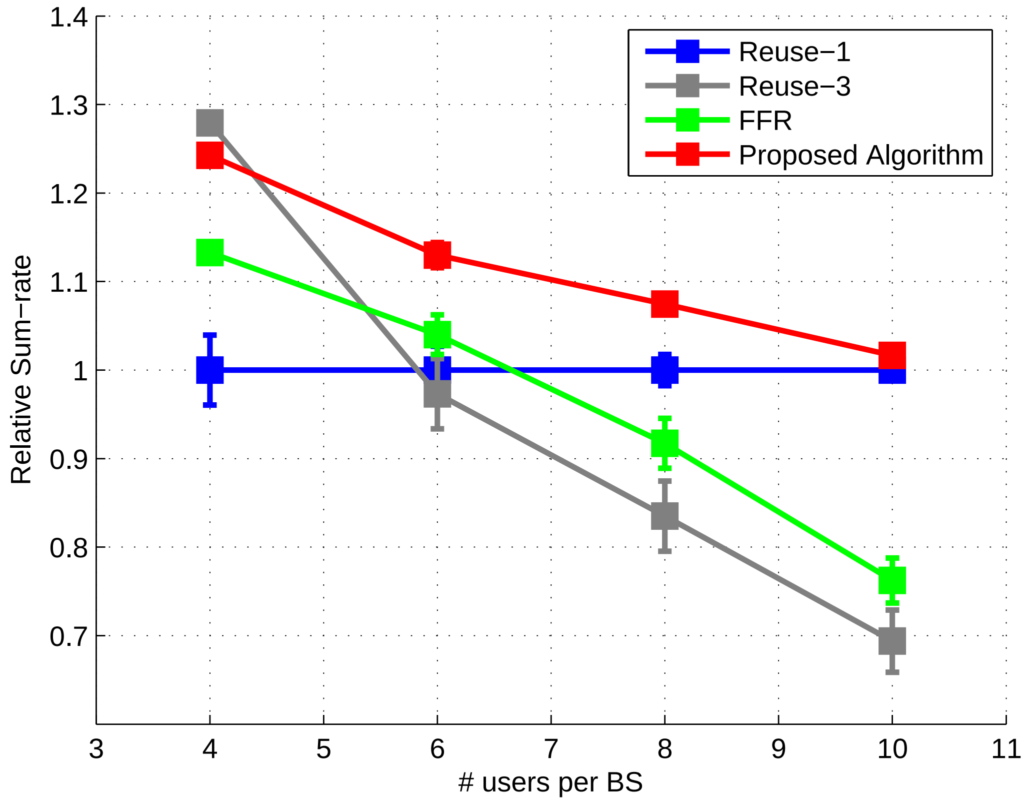


Figure 3.5. Relative sum-rate comparison for varying # users per base station, using single realizations of user locations (# subbands = 12, $\alpha = 3.5$, $\mathrm{SNR}_{edge} = 10$ dB, $\beta = 0.2$).

Carefully inspecting Figure 3.4, and observing the overlap between the standard deviations of the proposed algorithm and reuse-1 may lead us to false conclusion that our algorithm sometimes performs worse than random assignment of resources (reuse-1). To understand why this is not the case, we show the same set of results, this time using a single realization of user locations in Figure 3.5. Comparing the two figures, we see that most of the variance in the results can be attributed to changing realizations of user locations, and more importantly, that our proposed algorithm strictly performs better than reuse-1, validating its effectiveness.

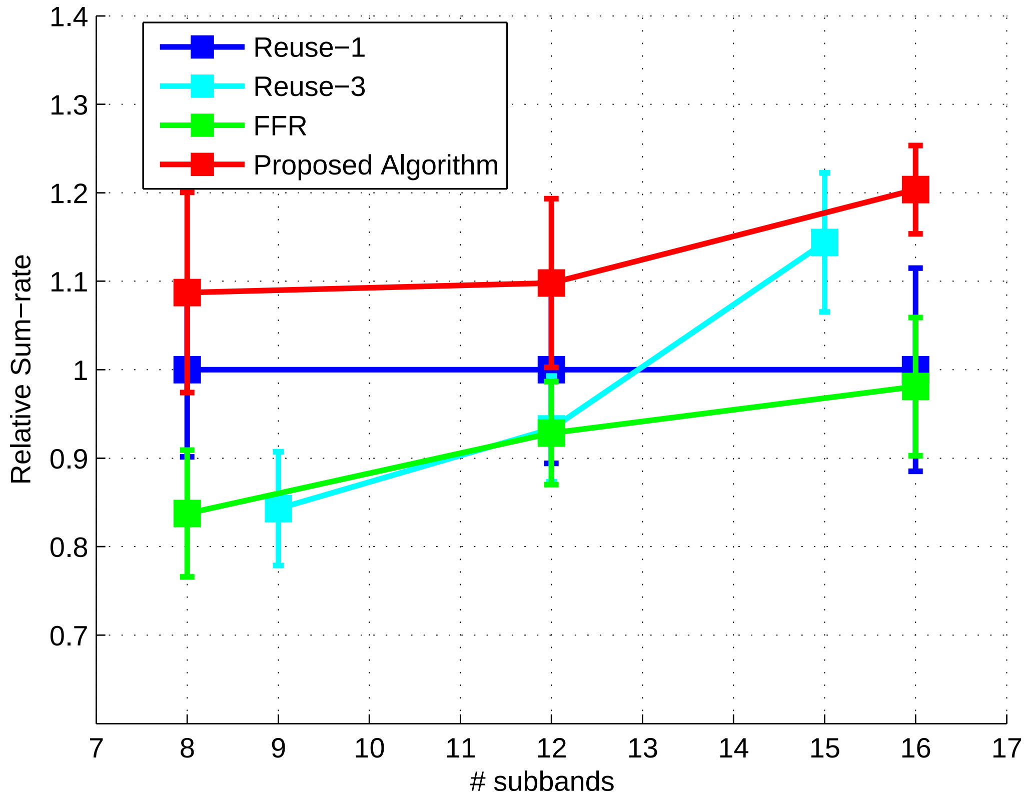


Figure 3.6. Relative sum-rate comparison for varying # subbands, using many realizations of user locations (# users per base station = 6, $\alpha = 3.5$, $\mathrm{SNR}_{edge} = 10$ dB, $\beta = 0.2$).

The effect of changing another workload parameter, number of subbands, is seen in Figure 3.6. Similar to the results in the previous two figures, as the system load is increased (number of subbands is lowered), reuse-1 gains an advantage over reuse-3, FFR shows a performance in between the two, but our algorithm outperforms all the static frequency planning techniques.

We argued in Chapter 1 that the static techniques are unable to adapt to changing conditions, including changes in user density. To test this claim, we constructed a simulation, where we increase the number of center-region users from 0 to 6, hence decrease the number of edge-region users from 6 to 0. This set of results are shown in Figure 3.7. When all users are concentrated at the center of the cell, the static methods perform similar, but the proposed algorithm brings a significant improvement. As the

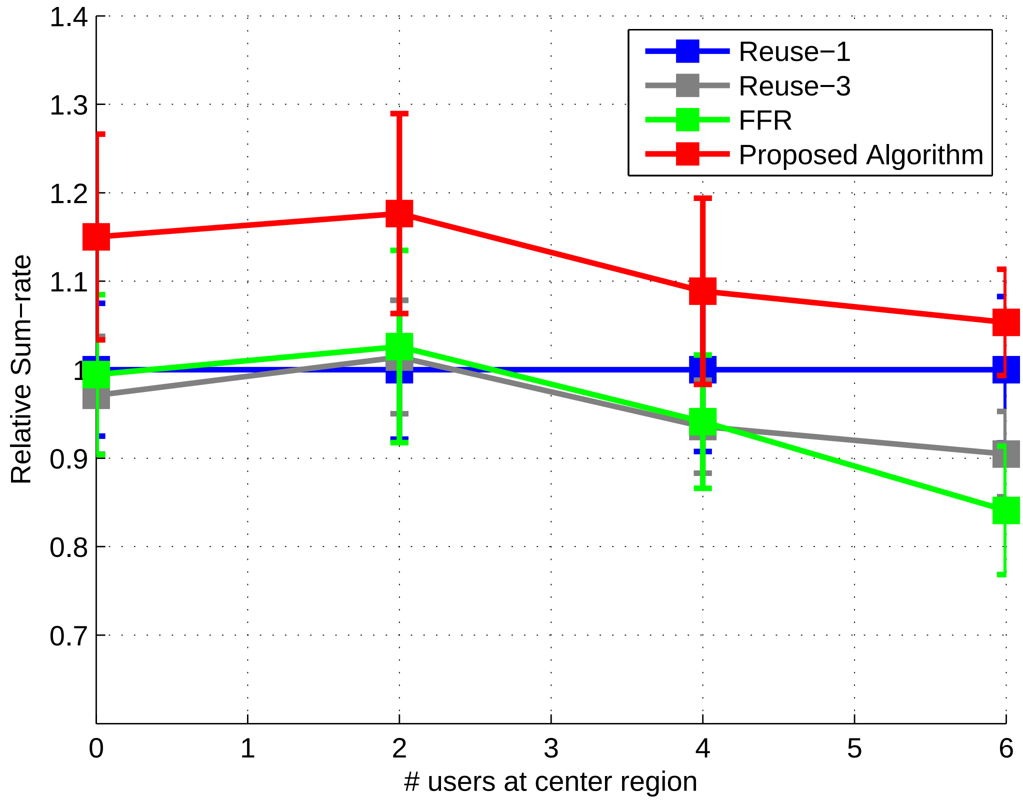


Figure 3.7. Relative sum-rate comparison for varying # users at center region, using many realizations of user locations (# users per base station = 6, # subbands = 12, $\alpha = 3.5$, $\text{SNR}_{edge} = 10$ dB, $\beta = 0.2$).

users move to the cell edge, reuse-1 shows better sum-rates than FFR and reuse-3 as expected, however, our algorithm is again better than reuse-1. This result is important in outlining the robustness of our algorithm.

Finally, we look at the effect of the system parameter β in Figure 3.8. Although the algorithm converges to very similar sum-rate values across different selections of β, how quickly we reach that equilibrium is significantly affected by the choice of it. When β is close to 1, the algorithm tends change strategies very rarely, hence increasing the number of iterations till convergence. On the other hand, when β is too close to 0, then we change the strategy even when there is a marginal improvement to be gained at a given base station, which directly influences the interference scenario for other base stations, and encourages them to change strategies as well. This leads

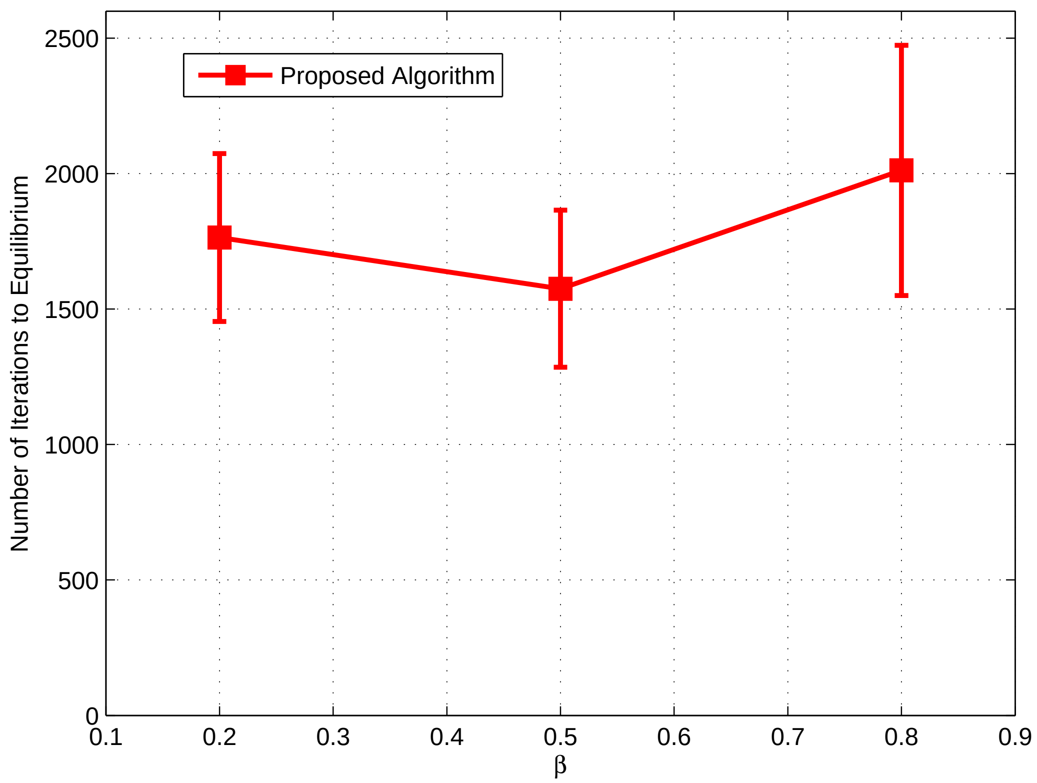


Figure 3.8. Number of iterations to reach equilibrium for varying β, using many realizations of user locations (# users per base station = 6, # subbands = 12, $\alpha = 3.5$, $\text{SNR}_{edge} = 10$ dB).

to a "ping-pong" behavior, and the number of iterations to reach an equilibrium increases significantly. Therefore, there exists a sweet-spot for the selection β for quick convergence, as supported by Figure 3.8.

3.6. Conclusion & Future Work

In this chapter, we introduced a game-theoretic algorithm for the resource allocation problem in OFDMA cellular networks in the context of ICIC. We showed via simulations, that the proposed algorithm was effective and robust, outperforming the existing static frequency planning schemes.

We also verified that the algorithm does not necessarily converge to the global optimum. In order get solutions which are closer to the global optimum, or ensure convergence to it, we may need to borrow ideas from other heuristic methods, such as Simulated Annealing.

The intuition as to why the algorithm converges to Nash equilibria was explained, however a formal proof for the existence of it will need to be provided to complete this work.

It is very important to note that our simulations were carried out using relatively small values for the number of subbands (8-16) and number of users per cell (4-10), and it took more than a thousand iterations to converge to equilibria. In a real LTE system, where there are tens to hundreds of users in a cell, with up to 100 resource blocks per base station, the algorithm will require orders of magnitude more iterations to converge, which may result in instability, as well as significant suboptimality during the process. Moreover, the feedback indicating channel conditions for each subband is likely to be done once every few slots, further increasing the time to converge. Due to these issues, our proposed algorithm is currently not suitable for implementation on a real system.

Assuming an underlying FFR structure, the proposed algorithm could be applied independently to each FFR band, each of which contain a fraction of the total number of subbands, hence reducing the number of iterations to convergence and improving stability. Alternatively, this algorithm could be used to allocate only the subbands in the f_{share} band within the structure defined in detail in Section 4.4. These two dynamic methods would be improvements over the static FFR configuration, with a smaller degree of freedom compared to the case when the algorithm would be free to use all subbands.

4. A SEMI-STATIC INTER-CELL INTERFERENCE COORDINATION ALGORITHM, BASED ON CELL-BASED MEASUREMENTS & AGGREGATE FEEDBACK

4.1. Motivation

The dynamic algorithm that we proposed in Chapter 3 was not suitable for implementation on real systems due to expected convergence issues and the requirement of excessive channel feedback. Other dynamic algorithms in the literature that we covered in Chapter 1 often exhibit high computational complexity, making them unsuitable for implementation as well. For this reason, our next focus was on developing a simpler, yet still robust semi-static autonomous-distributed ICIC algorithm, which would be applicable for implementation.

4.2. Problem Statement

Mobile users in real life either require a guaranteed bit rate (GBR), such as in VoIP or streaming video applications, or request best-effort traffic. The mobile network operators must satisfy the GBR users first, then allocate the remaining resources to the non-GBR users. In order to increase the QoS, it is of utmost importance to maximize the number of users that can be supported by a base station.

Our goal is to develop a simple and robust ICIC algorithm to increase the supportable network sum rate, hence the number of supportable users. Specifically, the algorithm should perform well when the load (or user) distribution is not uniform among cells and regions, which often happens in real life.

4.3. System Model

We use a system model as described in Section 2.2, and we assume that the base stations know the averaged channel conditions on a region (center, edge) basis, not necessarily on a subband basis, as was the case in Chapter 3.

To satisfy the GBR requirement of individual users, a proprietary scheduler is used. During each time slot, the scheduler cycles through each user in each region, by assigning them available subbands one-by-one until their GBR requirement is met, in which case it moves on to the next user. It is possible that the entire set of available subbands may be used in a time slot before satisfying the traffic requirements of each user. This reduces the satisfaction rate of the users, which is the metric that we will use to assess the performance of the algorithm.

4.4. Proposed Algorithm

The proposed semi-static, autonomous-distributed algorithm assumes that a static strict FFR configuration with 4 bands ($f_1 - f_4$) already exists. Its goal is to improve the supportable network sum rate, especially under non-uniform user distributions, by each base station independently:

- changing its radius of the boundary between the interior and edge regions (R_{int})
- changing its subband allocation of the interior and edge regions.

It is easy to understand that the first course of action may be to balance the loads in each region. If there are a lot of users in the cell interior region, but very few in the edge region, then this means a lot of users are competing for scarce resources in the interior region, whereas subbands go unused in the other. In this case, the algorithm should decrease the size of the interior region by decreasing the radius, so that some users there will be offloaded to the edge region. It is expected that this would improve the satisfaction rate of the users.

Determining how the second course of action will be carried out is a nontrivial problem. If the algorithm were to offload subbands between interior and edge regions in a given cell, it may significantly impact the interference patterns received by the neighbor cells. Specifically, if two neighboring cells were to offload some of their interior region subbands (f_1) to their edge regions (f_2 and f_3), then each base station would cause significant interference on the edge users of the other, because of the overlap between their edge subbands (f_2 and f_3). Therefore a wiser option would be to split the available spectrum into 5 bands, where an additional "f_{share}" band is added to the 4 bands (f_1, f_2, f_3, f_4) in a typical FFR assignment: f_1-f_4 would be static FFR assignments, and "f_{share}" would either stay unallocated in a cell if the load was low, or it would be allocated to the either the edge users or interior users depending upon the load distribution.

In order to decide on the course of action, each base station has access to the following reports, which may be generated every few time slots:

- Average PRB usage for the RBs allocated to interior users
- Average PRB usage for the RBs allocated to edge users
- Aggregate channel information data for the PRBs scheduled to interior users
- Aggregate channel information data for the PRBs scheduled to exterior users

The channel information feedback from the users is transmitted via uplink in the form of CQI reports, which are quantized values of SINR.

Please note that base stations only use cell-averaged data gathered every few slots, making the algorithm semi-static; and each of them makes their decisions independently without any backbone communication, making the algorithm autonomous-distributed.

In order to keep the algorithm simple and stable, we decided it should make incremental adjustments with each received feedback report. By using a threshold to indicate high PRB usage, and another threshold to differentiate between good and bad average channel conditions, we are thus left with $4^2 = 16$ states, each of which will require different actions. This list of actions that we came up with for each state is given in Table 4.1.

Table 4.1. List of actions of the semi-static algorithm.

Interior and Edge Aggr. Feedback	$\boldsymbol{R_{int}}$	$\boldsymbol{f_{share}}$
Int. PRB Usage ↓ CQI ↑		
Edge PRB Usage ↓ CQI ↑	No Action	Free
Edge PRB Usage ↓ CQI ↓	Increase	Free
Edge PRB Usage ↑ CQI ↑	Increase	If $R_{int} = R_{max}$, use for edge
Edge PRB Usage ↑ CQI ↓	Increase	If $R_{int} = R_{max}$, use for edge
Int. PRB Usage ↓ CQI ↓		
Edge PRB Usage ↓ CQI ↑	Decrease	Free
Edge PRB Usage ↓ CQI ↓	No Action	Free
Edge PRB Usage ↑ CQI ↑	Increase	If $R_{int} = R_{max}$, use for edge
Edge PRB Usage ↑ CQI ↓	Increase	If $R_{int} = R_{max}$, use for edge
Int. PRB Usage ↑ CQI ↑		
Edge PRB Usage ↓ CQI ↑	Decrease	If $R_{int} = R_{min}$, use for center
Edge PRB Usage ↓ CQI ↓	Decrease	If $R_{int} = R_{min}$, use for center
Edge PRB Usage ↑ CQI ↑	Increase	Use for center
Edge PRB Usage ↑ CQI ↓	Increase	Use for center
Int. PRB Usage ↑ CQI ↓		
Edge PRB Usage ↓ CQI ↑	Decrease	If $R_{int} = R_{min}$, use for center
Edge PRB Usage ↓ CQI ↓	Decrease	If $R_{int} = R_{min}$, use for center
Edge PRB Usage ↑ CQI ↑	Decrease	Use for edge
Edge PRB Usage ↑ CQI ↓	Increase	Use for center

It would be cumbersome to go through each of the states and their actions, but to illustrate how they were constructed, let us analyze one of them in detail. Let the interior PRB usage be low and the edge PRB usage be high, with good channel conditions throughout. In this case, it is likely that there are too many users (or too much requested rate) in the edge region. Therefore it would make sense to increase the interior radius R_{int}, in order to balance the region loads. If the radius is already at the maximum possible level and the edge PRB usage is still high, then the f_{share} subbands must be allocated to the edge users to satisfy their rate requirements. The reason we are using these extra frequencies as a last resort is to benefit the network as a whole. If the users in a particular cell can be satisfied without "borrowing" the additional frequencies, then this does not cause additional interference to the neighbors. One overloaded cell using the f_{share} band is also not an issue, but if multiple neighbor cells were to use this band at the same time, they would cause interference to each other, reducing the data rates of the users assigned to these subbands, which results in a suboptimality. The proposed algorithm therefore tries to minimize the occurrence probability of this case, while maintaining high user satisfaction rates.

4.5. Simulation Results

In our simulation environment with 19 hexagonal cells, each user is given an individual GBR requirement that needs to be met. In the simulations, we will first change the number of users uniformly across cells, then test cases when one to three cells are specifically overloaded. We will also simulate situations when there is a large crowd of users at either the center or the edge of a cell. This wide range of conditions will be an indicator of the robustness of the proposed algorithm, which will be compared with reuse-1, reuse-3, and two sets of static FFR configurations with $R_{int} = 0.5$ and $R_{int} = 0.7$. Please refer to Table 4.2 for a full list of system parameters.

In Figure 4.1, we increase the load of the network uniformly across all cells by increasing the number of users. Our proposed algorithm performs always better than reuse-3, and generally better than the FFR configurations. However, it is slightly worse when compared with reuse-1 at very high loads. In this situation, the users request more traffic than the base stations can handle, hence the algorithm dictates all base stations to use the f_{share} band, which causes severe interference in this band, eliminating the advantage of using this band in the first place. Reuse-1 suffers from the same interference issues, however it allows base stations to use the whole set of subbands instead of selected subbands, thereby resulting in higher sum-rates, and user satisfaction. In other words, we see that an FFR-based solution is not going to be

Table 4.2. Simulation parameters for performance evaluation of the semi-static algorithm.

Parameter	Value / Assumption
Cell Layout	Hexagonal - Single Sector
User Distribution	Uniform & Non-uniform
Inter-site Distance	1 Km
Path Loss Model	$L = 100 + 35log_{10}(d)$
Cell Edge SNR	10 dB
Number of Subbands	48
Number of Users per Cell	$20 - 60$
Subband Bandwidth	1 MHz
Channel Model	Rayleigh Flat Fading
Frequency Planning	Reuse-1 Reuse-3 FFR Semi-static FFR
Scheduler	GBR Scheduler

optimal if each cell is subject to very high loads, outside of their normal operating range.

In Figure 4.2, we simulate a case where only a small number of cells are overloaded in the 19-cell network. This is a more realistic case, which we expect to occur from time to time and one which we expect our algorithm to handle. We see that it is indeed superior than the static methods, which are unable to adapt to the changes between cells.

In Figure 4.3 and Figure 4.4, we test other realistic cases, where a specific region of a cell may be overloaded. In order to do this, we assign extra users to one of the regions of the target cell, while the load for other cells stay at a moderate level. While the proposed algorithm is robust against crowding of users in the edge region, it performs

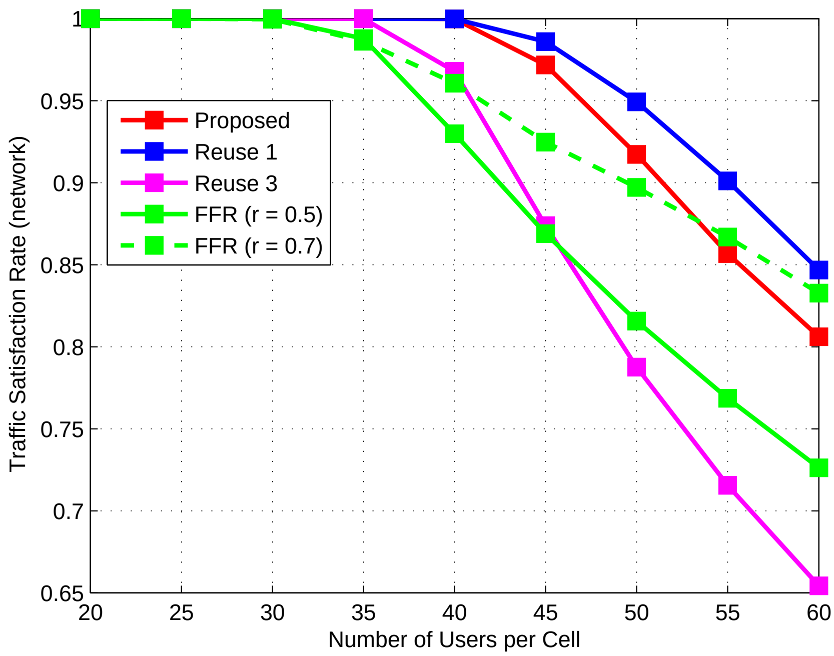


Figure 4.1. Performance of the proposed algorithm against static frequency configurations, for different cell loads uniform across the network.

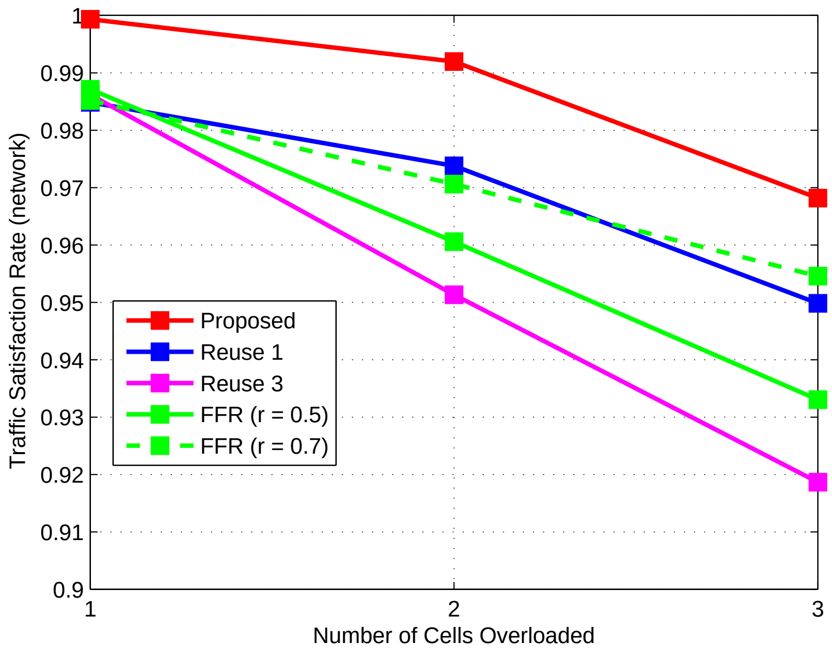


Figure 4.2. Performance of the proposed algorithm against static frequency configurations, when a number of cells in the network are specifically overloaded.

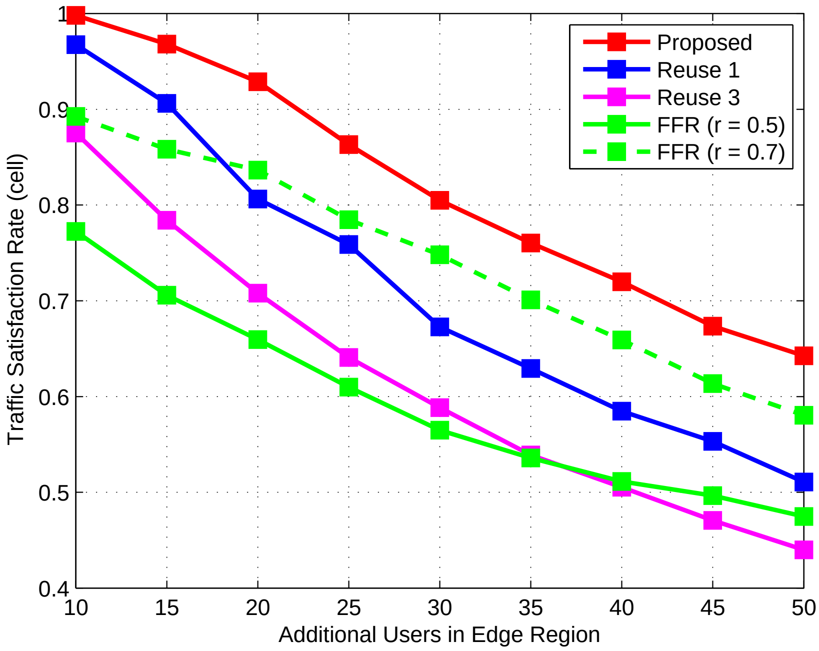


Figure 4.3. Performance of the proposed algorithm against static frequency configurations, when a given cell is overloaded with users concentrated around the cell edges.

only moderately when users are crowded close to the center of the cell. This is a direct result of not having enough available subbands in the cell center region. Specifically, for our simulations, we used 48 subbands, which are fully utilized by the reuse-1 system. In comparison, the FFR configuration with $R_{int} = 0.7$ uses 24 subbands for the center region, whereas the proposed algorithm is only allocated 12 fixed subbands for the center region plus an additional 6 subbands from the f_{share} band.

While we could have achieved better results if we used more fixed subbands for the center, it would have come at a cost of achievable edge throughput. This is therefore an important example in showing the clear limitation of using an algorithm that is tightly related to a fixed frequency configuration. Using a larger f_{share} band to increase the flexibility of the algorithm's frequency allocation and/or using backbone signaling between base stations to introduce coordination could be two possible solutions that will need to be investigated.

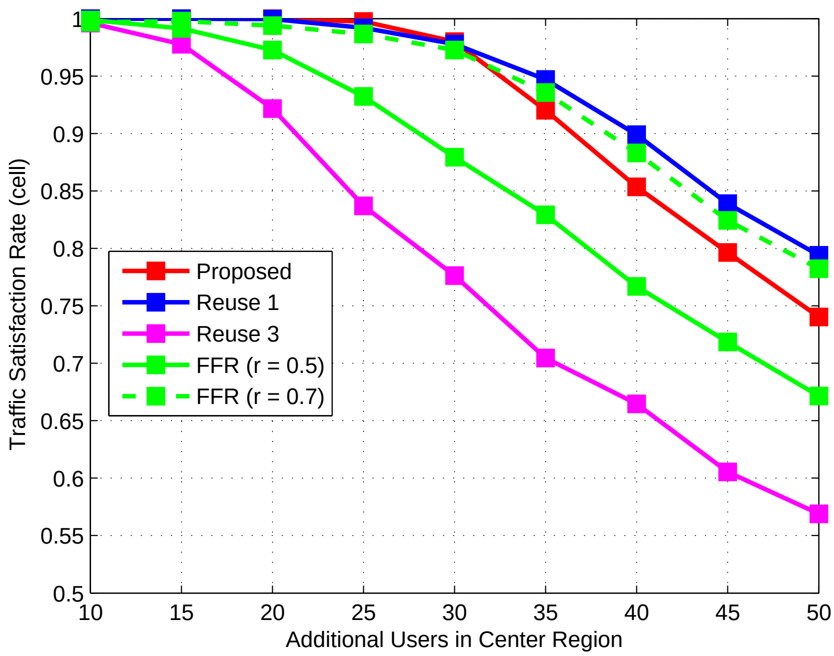


Figure 4.4. Performance of the proposed algorithm against static frequency configurations, when a given cell is overloaded with users concentrated around the cell center.

4.6. Conclusion & Future Work

We have shown that the proposed algorithm performs well under different scenarios, despite using arbitrary thresholds for PRB usage & SINR indication as well as an arbitrary FFR configuration (Number of subbands allocated to f_1-f_4). In order to make the algorithm more robust, we will need to perform extensive simulation to find optimal values, as well as figuring out how to dynamically adapt the thresholds based on the received aggregate feedback.

It is also clear that signaling between base stations through the backbone network would be useful for this ICIC algorithm, in coordinating the use of the f_{share} band. This is especially important in the cases where two (or more) neighbors may request to use this band, when the load in both cells is high. This is another open problem that needs to be considered.

In addition to the actions that our algorithm can currently take as described in the Section 4.4, shrinking or expanding the cell size, possibly through changing DL transmission powers and/or handover thresholds, could also be used to further enhance the performance. This will allow an extra degree of freedom in the algorithm design.

Furthermore, with the current structure, we have no information on the types of users, whether they are GBR or non-GBR. Getting access to such information may allow us to make more informed decisions to make sure that the GBR users are more consistently satisfied.

Finally, another important issue is to investigate the effect of reporting periods, and whether user-specific feedback can be used to improve performance.

5. CONCLUSION

We made a survey of static frequency planning schemes, and semi-static and dynamic inter-cell interference coordination algorithms in the literature. We then provided a detailed performance evaluation of static frequency planning schemes and major schedulers used in OFDMA networks, by presenting the associated tradeoffs and suggesting design guidelines. We proposed two novel autonomous-distributed ICIC algorithms and tested their performance under different scenarios, discussing their advantages over static schemes and their feasibility for implementation. Detailed conclusions were given in Section 2.5, Section 3.6 and Section 4.6.

The game-theoretic dynamic algorithm was effective and robust, outperforming all static frequency planning schemes under the tested scenarios, despite being unable to guarantee convergence to the global optimum. Due to the large required number of iterations to converge, we noted that the algorithm at its current stage may not be suitable for implementation on a real system.

We then proposed a semi-static algorithm, with the goal of making it open to implementation, while still showing robust performance. Despite using only aggregate information from users and cell-based usage reports, we showed that its performance was usually better than static techniques when users are non-uniformly distributed across the network. We suggested possible ways of improving the algorithm, especially for cases when its performance was lower than that of static techniques.

Throughout the simulations carried out in this thesis, the classification of users into either center or edge bands was done by separating users based purely on their geographic distances to base stations. In actual implementations, this classification would have been done either using wideband-SINR or reference signal received power (RSRP), both of which offer different advantages. Incorporating such measurements in the decision of classification of users is planned future work.

Furthermore, in this thesis, we investigated ICIC techniques for macrocells only. It is another challenge to reduce the impact of interference by coordination, when there are also picocells and femtocells in the network. It is a further challenge when the femtocells are moving, making not only the users mobile, but also the network. This is a promising research direction which we will be considering in the future.

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