Inter-Cell Interference Management Towards a Universal Frequency Reuse in OFDM-Based Wireless Networks

by

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Abstract

Orthogonal Frequency Division Multiplexing (OFDM) is a promising candidate for high data rate mobile communication due to its exceptional physical layer characteristics. For OFDM cellular networks, the frequency reuse factor is of high importance since the scarce frequency resource needs to be reused in as many cells as possible to enhance system's spectral efficiency. However, if frequency resources are reused aggressively, inter-cell interference is going to substantially degrade system performance. This thesis therefore proposes two techniques to combat the inter-cell interference in OFDM networks that adopt a universal frequency reuse. In the first scheme, the knowledge of users' locations is exploited in a system employing opportunistic beamforming. Simulation and analytical results show a 20% increase in the throughput of the proposed scheme compared to a traditional one. In the second scheme, the inter-cell interference has been reduced by 20 dB using an approach based on game theory.

To my parents: Yahya Al-Zahrani & Safyah Al-Zahrani

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Nomenclature

Here are the acronyms and notations.

Acronyms:

Acronym	Description
3GPP	Third generation partnership project
AMC	Adaptive modulation and coding
AWGN	Additive white gaussian noise
BER	Bit error rate
BF	Beamforming
BS	Base station
CDF	Cumulative density function
CDMA	Code division multiple access
CP	Cyclic prefix
CQI	Channel quality information
D-AMPS	Digital-advance mobile phone service

Acronym	Description
DCA	Dynamic channel allocation
DFT	Discrete Fourier transform
EDGE	Enhanced data rates for GSM evolution
FDMA	Frequency division multiple access
FEC	Forward error correction
FFT	Fast Fourier transform
FFR	Fractional frequency reuse
GPRS	General packet radio service
GSM	Global systems for mobile communication
GT	Game theory
HSPA	High-speed packet access
ICI	Inter-cell interference
IDFT	Inverse discrete Fourier transform
IEEE	Institute of electrical and electronics engineers
IFFT	Inverse fast Fourier transform
IMT-A	International mobile telecommunications-advanced
IS	Interim standard
ISI	Inter-symbol interference

Acronym	Description
ITU	International telecommunications union
LaICIC	Location-assisted inter-cell interference control
LOS	Line-of-sight
LTE	Long-term evolution
MAC	Medium access control
MIMO	Multiple input, multiple output
NE	Nash equilibrium
OBF	Opportunistic beamforming
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
PAR	Peak-to-average ratio
PF	Proportional fairness
QoS	Quality-of-service
RRM	Radio resource management
SINR	Signal-to-interference-and-noise ratio
SNR	Signal-to-noise ratio
TDMA	Time division multiple access
UE	User equipment

Acronym	Description
UMTS	Universal mobile telecommunications system
WIMAX	Worldwide interoperability for microwave access

Notation:

α	Amplitude of the antenna weight
B_c	Coherence bandwidth
T_c	Coherence time
f_d	Doppler shift
τ_d	Delay spread
ω	Marginal utility of holding the power
ψ	Marginal utility of SINR
ν	Path loss exponent
θ	Phase of the antenna weight
σ^2	Power of the additive white Gaussian noise
d_0	Reference distance for the antenna far field
B_s	Signal bandwidth
T_s	Signal duration
γ	Signal-to-interference-and-noise ratio
λ	Wavelength of the transmitted signal

Chapter 1

Introduction

Wireless technology is a truly revolutionary paradigm shift, enabling multimedia communication between people and devices from any location. Although commercially available mobile communication originated only 30 years ago, the mobile phone penetration is approaching 100 percent in most countries. Moreover, the wireless services is ubiquitous to the point that you can reach anyone almost everywhere, yet the demand for a more sophisticated wireless services is still increasing rapidly. That's why the International Telecommunications Union (ITU) is taking global initiatives to cope with a such exponentially increasing market.

From the deployment of the first generation analog networks (1G) in the early 1980s, development moved to digital technology with second generation systems (2G) such as Global Systems for Mobile Communication (GSM) in Europe and Digital-Advance Mobile Phone Service (D-AMPS¹) and Interim Standard-95 (IS-95) in US. The 2G systems set an enormous expansion of mobile telephony around the world and were gradually evolved to support packet data services and increasingly higher bit rates. The GSM system was, for example, enhanced with the General Packet Radio Service (GPRS), supporting up to 171 kbits/s and then it was enhanced even

¹D-AMPS represents both IS-54 and IS-136, where IS-136 is the evolution of the older IS-54 standard. Both of them are TDMA-based.

more by the Enhanced Data rates for GSM Evolution (EDGE), which supports up to 384 kbits/s.

In 1997, ITU set and approved the specifications of third generation (3G) system which provoked a huge competition between two prominent standards: Universal Mobile Telecommunications System (UMTS) developed by third generation partnership project (3GPP) groups, and CDMA2000 standard developed by Third Generation Partnership Project 2 (3GPP2).

Today, 3G systems and their evolutions² are supporting even higher bit rates and more services than previous generations. Nowadays, demand have grown for broadband mobile services comparable to their wired equivalents. For example, 3G systems support Internet browsing, sending multimedia messages, downloading music and much more at bit rates of up to 2 Mbits/s. While the 1G and the 2G systems changed our view of telephony from fixed to mobile, the services of the new 3G systems are indeed changing what mobile phones are used for.

Recently, ITU has set the specifications of the fourth generation (4G) system which is known as International Mobile Telecommunications-Advanced (IMT-A). According to IMT-A specifications, the throughput of 4th generation cellular systems has to reach 100 Mbit/s for high mobility and 1 Gbit/s for low mobility [4]. Moreover, one of the key features of IMT-Advanced is to reduce the delay to less than 5 ms [4] which in turn is going to raise - along with the throughput issue - the problem of coverage.

To achieve these targets, different techniques have been proposed and investigated. For example, orthogonal frequency division multiplexing (OFDM) has been chosen by 3GPP-Long Term Evolution standard (LTE) for its provision of orthogonal sub-carriers and its robustness against frequency-selective fading which is the nature of the spatial channel in mobile networks. However, OFDM is not going to increase the

²The recent evolution of 3G UMTS is the High Data Packet Access (HSPA), while the latest evolution of 3G CDMA2000 is EV-DO (Evolution-Data Optimized)

data rates of the system by itself, but rather it has some attributes that could be exploited in such a way to enhance the system's spectral efficiency.

Parallel to that development in cellular networks, the pure IP-based data networks were standardized by IEEE groups. Depending on the distance of the wireless communication, IEEE (Institute of Electrical and Electronics Engineers) set standards like IEEE802.11 for short distances (10 to 100 meters) and for metropolitan cities they set the IEEE802.16 standard, which is known commercially as WiMax (World-wide Interoperability for Microwave Access). WiMax is considered a 4th generation system, and similar to LTE, WiMax's physical layer is OFDM-based.

1.1 Research Motivation

The success of 4th Generation wireless systems which are currently either standardized (e.g. LTE) or deployed (e.g. WiMax) depends on how far they adhere to the specifications of IMT-A. In such challenging condition, it is convenient to look again at the Shannon equation and find out which part of it should be exploited:

$$C = B \cdot \min(M_T, M_R) \cdot \log_2(1 + SINR) \quad (1.1)$$

where M_T and M_R are the number of transmitting antennas and receiving antennas respectively.

1. The bandwidth (B) cannot be increased as it is a fixed portion granted by the government. In fact, in each cell the bandwidth is usually reduced (sometimes to 1/3) due to frequency reuse planning for **interference** avoidance.
2. MIMO is theoretically a brilliant and promising technology which enhances both the efficiency and performance of the system. However, from practical point of view, its performance can be severely degraded by **interference** [5].

3. Increasing SINR in a wireless system requires either increasing the signal power or reducing the **interference**. Increasing the transmit power would certainly increase the interference in the other cells and affect the whole system performance including the current cell since the other cells will employ the same strategy.

From the above brief discussion, it is clear that **interference** is the serious problem that holds all the above parameters from a good contribution to the channel capacity and then to the system capacity. Mitigating the interference or reducing it significantly is surely going to lead to a successful ubiquitous high data rate system that meets the IMT-advance specifications. So, this thesis covers how users can efficiently share the bandwidth in OFDM-based networks, without extensively interfering with each other.

1.2 Problem Statement

Intra-cell interference in an OFDM network may under certain conditions be eliminated due to the orthogonality between the available subchannels. However, users in different cells might still interfere with each other, depending on the resource allocation strategy. If the available resources are allocated too conservatively, spectrum will be wasted, causing low system performance. On the other hand, if users try to share the resources too aggressively, system performance will go down due to significant inter-cell interference. The purpose of this thesis is to propose alternative schemes and evaluate their performance for handling inter-cell interference in an OFDM-based network.

1.3 Contributions

In this thesis, we propose two different schemes for controlling inter-cell interference in high data rate OFDM-based networks. In the first scheme, the OFDM network is assumed to employ opportunistic beamforming where more and faster fluctuations are induced in the wireless channel, which also mean more null instants in the view of neighboring cells. The scheduler of the neighboring cell uses the knowledge of the users' locations and benefits from inter-base station coordination to fairly schedule the optimum user by exploiting the null instants of the signal coming from adjacent cells. Some distinct features of the proposed scheme include:

- All radio resources can be available at every cell with full power (i.e. frequency reuse factor is 1).
- The required information from users is only the overall SINR (i.e. minimal overhead signaling).
- The proposed scheme does not require inter-cell synchronization.

The performance analysis as well as simulation results showed the effectiveness of the proposed scheme where a throughput increase of 20% has been achieved compared to a system without our scheme. Moreover, to the best of my knowledge, no existing scheme available in the literature is having such improvement while maintaining all the above mentioned features.

Inter-cell interference (or co-channel interference) in its essence is a kind of contention for access to the media. For such a conflict, game theory is considered a potential solution. So, the second proposed inter-cell interference scheme utilizes game theory results to reduce the level of interference in the network. In this scheme, the game model has been characterized by specifying the game players, their sets of actions, and their payoff. Game players are the co-channel users located at adjacent

cells and their action is to choose the level of the transmit power. Utility function (or payoff) has been designed based on an economical model to assure minimal interference as well as acceptable fairness among users. Simulation results showed a 20 dB reduction in the interference level experienced by the receivers and an obvious improvement not only in the aggregate throughput but also in the cell edge users' throughput.

There are very few papers³ used game theory to control ICI in OFDM network. However, our proposed scheme is a different solution since it implements game theory results in a different way.

1.3.1 Accepted and submitted papers

Based on this work. the following papers have been accepted and submitted.

- Ali Y. Al-Zahrani, F.R. Yu and I. Lambadaris, "Location-Assisted Inter-cell Interference Management Scheme in Next Generation Wireless Networks Using Opportunistic Beamforming," *to be presented at IEEE VTC10F*, Ottawa, ON, Canada, Sept. 2010.
- Ali Y. Al-Zahrani and F.R. Yu, "Intercell Interference Management Schemes in Next Generation Wireless Networks Using Opportunistic Beamforming," *submitted to IEEE Trans. Wireless Communications*, Aug. 2010.
- Ali Y. Al-Zahrani and F.R. Yu, "A Game Theory approach for Inter-cell Interference Management in OFDM Networks," *to be submitted to IEEE Trans. Wireless Communications*.

³They will be discussed in chapter 3

1.4 Thesis Outline

A theoretical background to wireless communication systems and a detail description of OFDM are given in Chapter 2. This chapter assumes a general understanding of communications, but not of wireless communications. Related work on inter-cell interference management is described in Chapter 3. The text goes through different proposed schemes which are basically of the signal processing type or frequency planning type. Chapter 4 introduces the first proposed scheme in this thesis which is based on opportunistic beamforming. In this scheme, the knowledge of users' locations along with inter-base station coordination are exploited to control co-channel interference. The second proposed scheme which is based on game theory approach is introduced in chapter 5. The conclusion of this thesis can be found in Chapter 6, which also includes a discussion of possible continuation of this work.

Chapter 2

Background

This chapter reviews the basic characteristics of wireless communication systems followed by a deep overview of orthogonal frequency division multiplexing (OFDM).

2.1 Channel Impairments

In communication systems, the communication channels can be classified in different ways. In terms of signal strength, communication channels can be generally divided into additive white Gaussian noise (AWGN) channel and faded channel. In the AWGN channel, the received power of the desired signal is almost as powerful as the transmitted power (e.g. fiber optic) whereas in the faded channel, the received power of the desired signal is away below the transmitted power (e.g. wireless radio channel). Although they both are affected by the additive noise, faded channel is more difficult to tackle.

In terms of users, communication channels can be further classified into noise limited channel, where the channel is used by only one user, and interference limited channel where multiple users share the same channel (e.g. wireless channel in cellular network).

The wireless channel in a multi user communication system is categorized as faded

and interference limited channel. Such channel has difficult challenges if it used as a medium for reliable high data rate communication. In addition to the noise, there are other time variant impairments which are affected by user movement as well as environment dynamics. This thesis will only consider statistical models, which are typically used in wireless system design. Such models often split the effects of propagation impairments into path loss due to distance, shadow fading or shadowing and multipath fading. In the following subsections, these time variant impediments are explained in more details.

2.1.1 Path Loss

Path loss (or attenuation) is the decline in power density of an electromagnetic wave as it propagates through space. Such reduction could be due to free-space loss, diffraction, reflection and scattering. In free space, path loss is generally assumed to be fixed at a given transmit-receive distance. In addition to the transmitter-receiver distance, path loss is influenced by environment (urban or rural), propagation medium (dry or moist air), transmission frequency, and the height and location of antennas. The following simplified path loss model which captures the essence of signal propagation is commonly used for system design:

$$PL = \left(\frac{4\pi d_0}{\lambda}\right)^2 \cdot \left(\frac{d}{d_0}\right)^\nu \quad (2.1)$$

where d_0 is a reference distance for the antenna far field and assumed to be 1-10 m for indoors and 10-100 m for outdoors [6]. because of scattering phenomena in the antenna near field, the model (2.1) is generally valid when $d > d_0$. Moreover, λ is the wavelength of the transmitted signal and d is the transmitter-receiver distance. ν is the path loss exponent which indicates the rate at which the path loss increases with distance. The value of ν depends on the specific propagation environment. For

instance, in free space, ν equals to 2 whereas in urban area it ranges from 2.7 to 3.5 [7].

Depending on the velocity of the user, path loss is changing relatively slow with the time and distance. However, its effect on the signal power is tremendous comparing to the other impairments.

Other than the simplified path loss model mentioned above, there are many different path loss models¹ which have been derived using a combination of analytical and empirical methods. This thesis is adopting the following path loss model which is used by Nortel for 2 GHz fourth generation network.

$$PL = 128.1 + 35.2 \log(d) \quad (2.2)$$

where PL is in dB scale, and d is in Km.

2.1.2 Shadowing Effect

In addition to path loss due to distance, a transmitted signal will be attenuated by objects blocking the line-of-sight (LOS) path between transmitter and receiver. This attenuation is referred to as shadow fading and is usually modeled as a Gaussian distribution in dB scale and a lognormal distribution in linear scale. In this thesis we consider lognormal distribution for modeling shadow fading although there are other different models available in the literature such as gamma distribution.

The signal power variation due to shadowing occurs over distances that are proportional to the length of the obstructing objects. This fact makes the shadowing process spatially correlated. However, the shadowing autocorrelation function decays faster than that of path loss.

¹See for example chapter 2 in [6] and chapter 4 in [7]

2.1.3 Multipath Effect

Multipath fading describes the received power variations and rapid fluctuations of the amplitudes and phases due to constructive and destructive addition of multipath signal components. Such variations and fluctuations occurs over a much shorter period of time or distance comparing to path loss and shadowing. That is why multipath fading is sometimes referred as *small scale fading* while path loss and shadowing are referred as *large scale fading*. Generally, multipath fading is influenced by spatial (physical) channel, speed of the mobile user, speed of the surrounding objects and the bandwidth of the transmitted signal [7].

Spatial channel effect happens due to the physical characteristic of the environment (i.e. scatterers and reflecting objects) and can be characterized by the *delay spread* τ_d . Delay spread is defined as the difference between the time of arrival of the first multipath component and the time of arrival of the last multipath component. Moreover spatial channel can be also described by the *coherence bandwidth* B_c which is the frequency band over which the channel can be considered flat². In general, the delay spread and coherence bandwidth are inversely proportional to one another [7].

Delay spread and coherence bandwidth describe the spatial channel at a given instant. However, they do not provide information about how fast the channel is varying due to the motion of the mobile user and the surrounding objects. In small scale fading, *Doppler shift*, f_d and *coherence time*, T_c are the parameters that describe the time varying nature of the spatial channel caused by the dynamic environmental changes including the mobile user motion [7]. Coherence time is the time duration over which the channel response is basically invariant. Moreover, the Doppler spread and coherence time are inversely proportional to each other. The Doppler shift is a function of the relative speed of the mobile user v_u and the angle θ between the

²A flat channel is a channel which passes all spectral components of the signal with approximately equal gain and linear phase.

direction of the user's motion and the direction of the signal arrival. It can be proven that;

$$f_d = \frac{v_u}{\lambda} \cdot \cos\theta. \quad (2.3)$$

According to the above mentioned factors, there are different classifications for the multipath fading in wireless channel. They are as follows.

1. Fading due to physical environment:

If a given physical channel is assumed to be static (i.e. Tx, Rx and the surrounding environment are fixed, even the leafs of the trees are fixed), then the wireless signal will undergo either flat fading or frequency selective fading, depending on the characteristic of the given physical channel and it will continue with that fading for good. These types of fading are briefly described below.

- Flat Fading: It occurs if the spatial channel has a constant gain and linear phase response over a bandwidth that is wider than the bandwidth of the transmitted signal, i.e.: $B_c > B_s$. This could be interpreted in time domain by saying that the received signal will undergo flat fading if the delay spread is much smaller than one symbol duration as if all components arrive almost at the same time.
- Frequency Selective Fading: In contrary to the Flat Fading, Frequency Selective fading happens if the spatial channel is spectrally flat over a bandwidth that is narrower than that of the transmitted signal i.e.: $B_c < B_s$. In this case the delay spread is going to be high enough to cause the intersymbol interference (ISI) which interpreted in the frequency domain, some frequency components in the received signal have greater gains than others.

2. Fading due to moving environment:

The physical wireless channel is in fact dynamic, changing from a given channel to another. In this case, the fading is going to be dynamic as well, alternating from flat fading to frequency selective fading and even to another different frequency selective fading. Such fading variation could be fast or slow depending on how rapid the environment changes. Below, fast and slow types of fading are briefly described.

- Fast Fading: A channel is fast fading channel when its impulse response varies quickly within one symbol duration. In other words, the coherence time of the channel is smaller than the symbol duration of the transmitted signal, i.e. $T_c < T_s$.
- Slow Fading: A slow fading channel has an impulse response that changes much slower than the transmitted signals. Accordingly, the channel may be viewed as static channel over one or more symbol durations, i.e. $T_c > T_s$.

Statistical Models for Multipath Effect

Among many different multipath models, a two well-known models will be presented here.

1. Rayleigh Fading:

When the channel consists of several weak paths, i.e.:

$$h(t) = \sum_{i=1}^{n(t)} a_i(t) \delta(t - \tau_i(t)), \quad (2.4)$$

where $n(t)$ is the number of paths at time t , $a_i(t)$ is the gain of path i at time t , and $\tau_i(t)$ is the time delay associated with path i at time t . Then it is common that the Rayleigh distribution is a potential model to describe

the statistical variation of the received envelope of a fading signal [6, 7]. The Rayleigh distribution probability density function (pdf) is:

$$f_R(r) = \begin{cases} \frac{r}{\beta^2} \cdot e^{-\frac{r^2}{2\beta^2}} & (0 \leq r \leq \infty) \\ 0 & (r < 0) \end{cases} \quad (2.5)$$

where β^2 is the time-average power of the received signal.

Since this research is concerning about inter-cell interference which is more sever on cell edge areas where all the desired signal components are weak, multipath model based on Rayleigh distribution is considered in this thesis.

2. Ricean Fading:

When there exists a strong nonfading component in addition to several weak multipath components, then the output of the detector is a sum of strong dc-component with random multipath components arriving at different times. In this case, the small scale fading envelope can be characterized using Ricean distribution [6, 7]. The probability density function (pdf) of the Ricean distribution is given by:

$$f_R(r) = \begin{cases} \frac{r}{\beta^2} \cdot e^{-\frac{(r^2+A^2)}{2\beta^2}} \cdot I_0\left(\frac{Ar}{\beta^2}\right) & (r \geq 0, A \geq 0) \\ 0 & (r < 0) \end{cases} \quad (2.6)$$

where A represents the dominant component's peak amplitude and $I_0(\bullet)$ is the modified Bessel function of the first kind, where

$$I_0(x) = \frac{1}{2\pi} \int_0^{2\pi} e^{x \cos \phi} d\phi \quad (2.7)$$

Although multipath fading effect is one of the most difficult impairments to tackle, it can be reduced significantly by considering the transmission scheme used in on-hand system. For example, in second generation (2G) TDMA system, equalization techniques were crucial players in defeating multipath fading. Moreover, Rake receiver in third generation (3G) CDMA systems is a brilliant means against multipath impairments whereas orthogonal frequency division multiplexing transmission scheme is a great solution for the multipath problem in fourth generation (4G) OFDM systems.

2.1.4 Interference Effect

Interference is a significant limiting factor in the performance of the wireless systems. Sources of interference are mainly depending on the type of the transmission scheme used in the system. Whereas the main interference in the CDMA systems is the intra-cell interference, the OFDM system's sources of interference are inter-cell interference and inter-carrier interference³ (ICI). Moreover, the sources of interference in TDMA systems are inter-cell interference as well as inter-symbol interference (ISI) which is due to the frequency selective environment associated with high symbol rate. In any system, the SINR can be expressed as follows:

$$\gamma = \frac{h_{i,i}p_i}{I_i + \sigma^2} \quad (2.8)$$

where $h_{i,i}$ and p_i are respectively the channel power of the desired signal and the transmitted power. I_i is overall interference experienced by user i whereas σ^2 is the power of the additive white Gaussian noise (AWGN). While path loss, shadowing and multipath are degrading the SINR through degrading the power of the desired channel $h_{i,i}$, interference is reducing the SINR through increasing the value of the denominator.

³More details to follow in the OFDM section (2.4)

While the interference is affecting the SINR in the same way as the noise does, the interference has more adverse impact on the SINR due to the higher power it possesses as well as its severe randomness nature. Whereas noise can be modeled by Gaussian distribution, interference is very hard to be analytically modeled since there are many random variables involved. However, There are only one case where the interference can be efficiently modeled that is when there are so many interferers, interference can be then regarded as Gaussian random variable owing to central limit theorem.

This thesis is going to focus on the inter-cell interference in OFDM systems. Accordingly, Let's assume the received signal is $y(t)$ such that;

$$y(t) = \sqrt{h_{i,i}(t)}s_i(t) + \sum_{j \neq i} \sqrt{h_{i,j}(t)}s_j(t) + n(t) \quad (2.9)$$

where the power of the transmitted signal $s_i(t)$ is p_i and the second term is the overall inter-cell interference whereas the third term is the additive white Gaussian noise (AWGN) which has a variance of σ^2 . Then, the SINR can be expressed as follows:

$$\gamma = \frac{h_{i,i}p_i}{\sum_{j \neq i} h_{j,i}p_j + \sigma^2} \quad (2.10)$$

In OFDM systems, if the interference is described by Gaussian distribution⁴, then the optimum strategy to deal with it is by adopting water filling power allocation policy. In water filling policy, the total power is distributed over the subcarriers in such way that the strongest subcarrier gets the highest level of power. In other words, the stronger the subcarrier is the more power it gets. However, if the interference is not a Gaussian, which is the most happening case, then there are no specific technique

⁴In this case, since the second and third terms of equation 2.9 are Gaussian, then their sum is going to be a Gaussian as well. So, the channel could be considered as noise-limited channel with higher noise power and hence the system could be considered as one cell system.

that guarantee the optimality. Chapter 3 is reviewing many of the proposed schemes to combat the effect of non-Gaussian interference.

2.2 Channel Adaptation

Due to the large fluctuations in a wireless channel, there is often a gain in adapting transmission to the channel variations, so-called link adaptation. Parameters that can be adaptively set are for instance the modulation constellation size and the code rate. Transmission techniques which do not have the capability to adapt with the fading conditions require a modulation and coding scheme that guarantee an acceptable performance at instants of poor channel. So, these systems are designed for worst-case conditions where the signal loss might reach up to 30 dB [6]. Designing for the worst-case conditions, leads to a very inefficient utilization of the channel. Therefore, Channel adaptation can increase throughput, decrease required transmitting power or reduce the bit error rate (BER) by exploiting the favorable channel conditions to send at higher rates or lower power and by reducing the data rate or increasing transmit power if the channel deteriorates. Figure (2.1) shows how the choice of modulation

Figure 2.1: Adaptive modulation assignment [1]

occurs. Assume, for example the required BER is 10^{-3} , then the transmitter should be in idle mode in case the SINR is less than 7 dB. However, if the SINR became higher than that and lower than 11 dB, the transmitter should transmit using BPSK mode. The transmitter should transmit with 4-QAM, if the SINR falls between 11 dB and 17 dB and so on and so forth.

Adaptive modulation systems require some channel state information at the transmitter. This could be acquired in time division duplex systems by assuming the channel from the transmitter to the receiver is approximately the same as the channel from the receiver to the transmitter. Alternatively, the channel knowledge can also be directly measured at the receiver, and fed back to the transmitter.

Although the adaptive modulation and coding scheme switches from one modulation level to another in a discrete manner with respect to SINR, the following spectral efficiency formula is used to analytically capture the effect of the link adaptation scheme in a continuous fashion with SINR [8]:

$$\eta = \log_2 \left(1 + \frac{-1.5 \gamma}{\ln(5 \text{ BER})} \right)$$

where η is in bps/Hz. Throughout this thesis, it is assumed that all wireless systems are equipped with link adaptation technique and equation (2.11) are used to reflect this assumption in the simulations.

2.3 Resource Reuse

In order for a network to have as high capacity as possible, it is desirable to reuse the available transmission resources as often and in as many cells as possible without causing too much interference in the system. The fact that a transmitted signal is

attenuated as it travels through the air is then used to the system's advantage by allowing two transmitters to transmit on the same resource if they are sufficiently far away from each others respective receivers. In a cellular network this translates to resource reuse in cells-basis. In this thesis, the objective is to allow for a universal frequency reuse that is all frequency resources are available to each base station. The resulted inevitable inter-cell interference can be controlled using the proposed schemes in this thesis.

2.4 Orthogonal Frequency-Division Multiplexing (OFDM)

OFDM is a multi-carrier transmission technique in which the high data rate bit stream is divided into many parallel low data rate streams [6]. These low data rate streams are then sent over multiple narrow-band subchannels. The frequency response on each subchannel can then be considered flat due to the fact that the coherence bandwidth of the spatial channel is much wider than each subchannel's bandwidth which greatly eliminates the inter-symbol interference (ISI).

In the limit, each subchannel is very narrow and if the total available power is distributed in an optimal way over the subchannels, the multi-carrier system will achieve optimum performance on the channel [6]. Moreover, The granularity nature of the subchannels makes the scheduling to be more efficient and accurate.

2.4.1 Orthogonality in OFDM

In contrast to frequency division multiplexing (FDM), whose subchannels are often not just non overlapping but also separated by guard bands to protect against power leakage and inaccuracies in frequency, subchannels in OFDM system are overlapping,

Figure 2.2: Multicarrier with overlapping subcarriers

yet at the same time cleverly orthogonal [6]. To prove Orthogonality in OFDM, let's assume that the set of subcarriers is;

$$\left\{ \frac{1}{\sqrt{T_s}} \cos(2\pi(f_0 + iB_{sc})t), \quad i = 0, 1, 2, \dots, N-1 \right\} \quad t \in [0, T_s]. \quad (2.12)$$

where T_s is one symbol duration, f_0 is the base carrier frequency, and B_{sc} is subcarrier spacing as shown in figure (2.2). Note that $T_s = \frac{1}{B_{sc}}$ and $f_0 + iB_{sc}$ is the frequency of subcarrier i .

Let's now test the orthogonality of the OFDM system by finding the correlation between any two arbitrary subcarriers i and j :

$$\begin{aligned} & \frac{1}{T_s} \int_0^{T_s} \cos(2\pi(f_0 + iB_{sc})t) \cdot \cos(2\pi(f_0 + jB_{sc})t) dt \\ &= \frac{1}{T_s} \int_0^{T_s} 0.5 \cos(2\pi(i-j)B_{sc}t) dt + \frac{1}{T_s} \int_0^{T_s} 0.5 \cos(2\pi(2f_0 + (i+j)B_{sc})t) dt \quad (2.13) \\ &\approx \frac{1}{T_s} \int_0^{T_s} 0.5 \cos(2\pi(i-j)B_{sc}t) dt = 0.5\delta(i-j) \end{aligned}$$

$$= \begin{cases} 1 & (i = j) \\ 0 & (i \neq j) \end{cases} \quad (2.14)$$

The approximation is due to the fact that the second term of (2.13) is approximately zero since $f_0 T_s \gg 0$. Based on (2.14), these subcarriers are orthogonal and hence, the modulated signals transmitted over each subcarrier can be easily separated out at the receiver. Furthermore, it can be shown that orthogonality cannot be maintained on $[0, T_s]$ with frequency separation other than B_{sc} .

2.4.2 Discrete Implementation of OFDM

In this part, the basic principles of discrete Fourier transform (DFT), which represent the soul of OFDM implementation, are reviewed. Then, the implementation of OFDM transceiver using (DFT) and inverse DFT, is illustrated.

Discrete Fourier Transform and its Inverse (DFT/IDFT)

For any discrete time sequence $x[n]$, $0 \leq n \leq N - 1$, the N-point DFT of $x[n]$ is defined as [9]

$$DFT\{x[n]\} = X[i] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x[n] e^{-j2\pi ni/N}, \quad 0 \leq i \leq N - 1. \quad (2.15)$$

DFT is simply the discrete-time equivalent to the continuous-time Fourier transform, because $X[i]$ contains the frequency contents of the discrete time sequence $x[n]$ which is associated with the original continuous-time signal $x(t)$.

The sequence $x[n]$ can be easily recovered from its DFT by using the IDFT:

$$x[n] = IDFT\{X[i]\} = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i] e^{j2\pi ni/N}, \quad 0 \leq n \leq N - 1. \quad (2.16)$$

The DFT and IDFT are typically implemented via hardware using the efficient fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) algorithms.

When a data stream $x[n]$ is passed through a discrete time channel $h[n]$, the output $y[n]$ is the discrete-time *linear convolution* of the data sequence $x[n]$ and channel impulse response $h[n]$:

$$y[n] = x[n] * h[n] = \sum_k h[k]x[n - k]. \quad (2.17)$$

On the other hand, the N-point *circular convolution* of $x[n]$ and $h[n]$ can be defined as:

$$y[n] = x[n] \otimes h[n] = \sum_k h[k]x[n - k]_N \quad (2.18)$$

where $x[n - k]_N$ is a periodic version of $x[n - k]$ with period N. From DFT definition, circular convolution in time domain leads to multiplication in frequency domain, i.e.

$$y[n] = x[n] \otimes h[n] \xleftrightarrow{DFT/IDFT} Y[i] = X[i]H[i], \quad 0 \leq i \leq N - 1 \quad (2.19)$$

where $H[i]$ is the N-point DFT of the sequence $h[n]$.

OFDM Implementation

A block diagram of N-subcarrier OFDM transceiver is shown in figure (2.3). After the input data is modulated by a QAM modulator whose output is a stream of complex symbols, a serial-to-parallel converter takes every N consecutive symbols $X[0], \dots, X[N - 1]$ and demultiplex them into N parallel outputs each is corresponding to one subcarrier. These N-parallel symbols, which represents the frequency components of the OFDM output $s(t)$, are passed through an inverse fast Fourier transform (IFFT) to convert them into time samples in order to generate $s(t)$. The output of IFFT is the OFDM symbol which consists of the sequence $x[n] = x[0], \dots, x[N - 1]$ of

Figure 2.3: Discrete implementation for OFDM transceiver

Figure 2.4: Adding the cyclic prefix

length N , where

$$x[n] = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i] e^{j2\pi ni/N}, \quad 0 \leq n \leq N-1. \quad (2.20)$$

After that, the parallel output of IFFT is converted into a serial sequence of N -time samples to form $x[n]$. The cyclic prefix is then added to the time sequence $x[n]$ to result in the modified time sequence $\tilde{x}[n] = \tilde{x}[-\xi], \tilde{x}[-\xi+1], \dots, \tilde{x}[N-1] = x[N-\xi], \dots, x[0], \dots, x[N-1]$ as shown in figure (2.4), assuming the channel $h[n]$ has ξ time samples. The reason for adding the cyclic prefix is to convert the linear convolution between the channel input $x[n]$ and the impulse response $h[n]$ into N -point circular convolution [6], i.e.

$$y[n] = \tilde{x}[n] * h[n] = x[n] \otimes h[n] \quad (2.21)$$

Circular convolution is favored over the linear convolution due to the fact that the former facilitates easier detection of $X[i]$ as long as the receiver possesses the knowledge of $Y[i]$ and $H[i]$, i.e.

$$Y[i] = DFT\{y[n] = x[n] \otimes h[n]\} = X[i]H[i], \quad 0 \leq i \leq N-1. \quad (2.22)$$

$$\implies X[i] = \frac{Y[i]}{H[i]}, \quad 0 \leq i \leq N-1. \quad (2.23)$$

The modified time sequence $\tilde{x}[n]$ is then passed through a digital-to-analog (D/A) converter to generate the baseband OFDM signal $\tilde{x}(t)$ which is then upconverted to frequency f_0 . The receiver on the other side undo on the received signal $r(t) = \tilde{x}(t) * h(t) + n(t)$ what has been done in the transmitter as it is shown in figure (2.3).

2.4.3 Scheduling in OFDM Systems

In a system of multiuser-OFDM, the system resources (power, bandwidth, time) are shared by several users. The role of radio resource management is to optimally distribute these resources among users according to the adopted policy. The underlying requirement is to develop a scheme for deciding which user to schedule first, which and how many subcarriers to allocate to it and how to determine the suitable power level for each subcarrier.

In this section, three typical allocation policies will be introduced.

Maximum Fairness (MF) policy

From its name it strongly cares about fairness. In MF schemes, sub-channels and the power are distributed between users such that minimum throughput for every user is maximized [10]. In other words, for all users $j = 1, 2, \dots, J$, the scheduling problem can be formulated as follow:

Maximize Th_{min}

subject to:

$$Th_j = \sum_{i=0}^{N-1} M(\gamma_{i,j}, BER_j) \cdot b_{i,j} \geq Th_{min}, \forall j = 1, \dots, J.$$

$$\text{and } \sum_{i=0}^{N-1} p_i \leq P_{total}$$

where Th_j is user j throughput, $M(\gamma_{i,j}, BER_j)$ is the appropriate modulation level which is a function of channel quality and the required quality of service. the solution of the above optimization problem is to find the binary matrix $[b_{i,j}]$ whose elements are:

$$b_{i,j} = \begin{cases} 1 & \text{if subchannel } i \text{ is assigned to user } j \\ 0 & \text{Otherwise} \end{cases}$$

In general, it is too difficult to find the optimum subchannel and power allocations from the above problem. However, this scheme can be realized through different suboptimal approaches. Static TDMA scheme (Round Robin) is one of them.

Maximum Sum Rate scheme (MSR)

The extreme apposite of the previous scheme is Maximum Sum Rate scheme (MSR) [10]. The objective here is to maximize the total (aggregate) throughput subject to total power constraint.

Consider a matrix H that describe the power of every sub-channel with respect to every user So the capacity for every user j is:

$$Th_j = \sum_{i=0}^{N-1} M(\gamma_{i,j}, BER_j) \cdot b_{i,j} = \sum_{i=0}^{N-1} M\left(\frac{h_{i,j}p_{i,j}}{\sigma^2}, BER_j\right) \cdot b_{i,j}$$

And the total capacity is:

$$Th_{Total} = \sum_{j=1}^J \sum_{i=0}^{N-1} M\left(\frac{h_{i,j}p_{i,j}}{\sigma^2}, BER_j\right) \cdot b_{i,j}.$$

Then, the objective is:

$$\begin{aligned} & \underset{\sum_{i=0}^{N-1} p_i \leq P_{total}}{\text{maximize}} \quad Th_{Total} \end{aligned} \quad (2.24)$$

The simplest way to Maximize Th_{Total} is by looking at H matrix and assigning subchannel i to the user j where,

$$h_{i,j} > h_{i,l}; \quad \forall l = 1, \dots, J, \text{ and } l \neq j,$$

then the power is distributed over the assigned subchannels using water-filling technique.

It is noteworthy that those who have excellent sub-channels (i.e. near to base

station) will be assigned all the resources while the other will be extremely underserved. Moreover, in this strategy, the instantaneous absolute value of channel power h is the only metric for deciding the assignment. MSR technique is suitable when the main goal is to send as much data as possible and the users can tolerate longer delay (latency).

Proportional Fairness Scheduling (PF)

In homogeneous application and fixed data rate, OFDM/TDMA (Round-Robin) is an appropriate scheme. However, in most cases, users are interested to send heterogeneous applications with different QoS requirements with a latency of less than 5 ms. In this case, more sophisticated scheduling techniques based on channel conditions and QoS constraints are crucial for higher system performance. Proportional Fairness scheme is a compromise scheme that is optimally taking care of both fairness and total capacity enhancement [11]. In PF, sub-channel i is assigned to the user j who has the maximum ratio of estimated data rate R to the current average throughput. In other words, if we assume $Th_{i,j}(t)$ is the average throughput achieved by user j on sub-channel i up to time slot t , and $R_{i,j}(t)$ is the instantaneous data rate that user j can achieve through channel i , then subchannel i will be assigned to user k such that:

$$k = \arg \max_{j=1,2,\dots,J} \frac{R_{i,j}(t)}{Th_{i,j}(t)}. \quad (2.25)$$

Unlike MSR whose decision is solely based on h , PF decides the assignment based on the relative value of R (or SNR). This metric provides comparable throughputs for users and long term high total throughput.

2.4.4 OFDM: Pros and Cons

The Advantages of OFDM transmission scheme over the single carrier scheme are as follows:

Robustness against multipath fading

Due to its very narrow spectral subchannels, OFDM symbol time is longer than that of single carrier transmission scheme. Such longer symbol time means that the multipath delay is corresponding to a smaller portion of the total OFDM symbol time and hence, OFDM can tolerate longer multipath delays. In other words, the longer the OFDM symbol, the better the tolerance against multipath fading. However, the symbol time T_s must be much smaller than the channel coherence time T_c to avoid fast fading due to Doppler shift.

Exploiting frequency diversity

OFDM gives access to the frequency domain for scheduling and adaptation since each subchannel can be independently scheduled and independently adapted to the radio conditions on each subchannel. For example, one subchannel can use 4QAM and a code rate of 1/4 while another subchannel can use 64QAM and a code rate of 1 depending on the fading condition of every subchannel.

Furthermore, Since channel impairments might affect some percentage of the subcarriers, Performance on these subcarriers will be severely degraded. However, by loading every one codeword on nonconsecutive subcarriers separated by more than coherence bandwidth, the affected bits can be recovered effectively through forward error coding (FEC) techniques due to the independence between the selected subcarriers.

Exploiting multiuser diversity

In an OFDM system, users can be multiplexed freely over the subchannels to give users their best-quality subchannels owing to multiuser diversity. The rationale behind multiuser diversity is the fact that the fading parameters of different locations (apart by more than wavelength) are independent and hence, same subchannel can be seen differently by different users.

Granularity and bandwidth Scalability

Due to granularity of the sub-channels, radio resource allocation can be differently allocated to the users based on their transmission requirements which are usually different. So each user is given almost the exact amount of spectrum (number of sub-channels) that meets its requirement without any additional provision. Thus the spectrum is utilized effectively in OFDM systems.

Furthermore, OFDM makes it easy to scale the bandwidth of a system without changing basic parameters. The subcarrier spacing B_{sc} can be kept the same and the bandwidth can be changed by adding or subtracting subcarriers. The same system can also operate in several different non-continuous spectrum allocations by only assigning power to subcarriers in these allocations.

Although OFDM has several strong advantages, it naturally has few drawbacks. The major OFDM shortcomings are:

Sensitivity to frequency and timing offset

Being overlapped, yet orthogonal is an advantage of OFDM transmission scheme. However, the price is that OFDM is so sensitive to frequency and time offset which might be caused by mismatched oscillators, Doppler shift or timing synchronization errors. For instance, if the accuracy of the frequency oscillator is 1 part per 10 million,

then the frequency offset is $f_\epsilon = (0.1 \cdot 10^{-6})f_0$. In case of $f_0 = 5 \text{ GHz}$ ⁵, then $f_\epsilon = 500 \text{ Hz}$ which is going to corrupt the orthogonality of the subchannels simply because the received samples of the FFT will contain interference from adjacent subchannels. Such interference is called inter carrier interference.

Large peak-to-average power ratio (PAR)

The peak-to-average power ratio (PAR) is an essential characteristic of any communication system. In a low PAR the average and peak values of the signal are close to each other which allows the transmit power amplifier to operate efficiently. However, in a high PAR, where the values of signal peak and signal average are relatively apart, the transmit power amplifier has a large backoff in order to ensure linear amplification. Moreover, a high PAR requires high resolution for the D/A and A/D converters since they need to operate with good precision over a large range. In addition to their higher cost, high-resolution D/A and A/D add more complexity burden as well as increase power consumption.

⁵5 GHz is the carrier frequency for 802.11a WLAN

Chapter 3

Inter-cell Interference in OFDM Networks: A Literature Review

This chapter is going to review the main contributions and landmark papers that have proposed significant solutions for combating ICI in OFDM systems. Most of inter-cell interference (ICI) schemes (practical or theoretical) fall either in a signal processing techniques category or interference coordination/avoidance category. Accordingly, this chapter will be divided into two sections: signal processing category solutions and interference coordination category solutions.

3.1 Signal Processing Category Solutions

In this category, receiver and/or transmitter are equipped and aided with extra or modified signal processing techniques. In the literature there are many proposed ideas that follow this tactic. The following are the main of them.

Interference Randomization

In the interference randomization(whitening), the *effect* of the interference is reduced by averaging it spectrally, which is done by spreading the signals over a distributed

set of non-consecutive subcarriers (chosen pseudo-randomly) in order to achieve frequency diversity [12], [13]. Since pseudorandom permutation of subcarriers is independently performed in each interfering cell, the coded bits within a given codeword all experience independent interference. Furthermore, because a limited number of the subcarriers -for each user- are going to be affected by interference, it is feasible for the decoder to correct the affected bits passed through interfered subcarriers. There are two means for implementing interference randomization; cell-specific scrambling and cell-specific interleaving. In the former method, the codeword is scrambled and distributed over the subcarriers using a pseudo-random PN that is unique for the cell of interest(as shown in figure (3.1a)). Alternatively, in the scheme of cell-specific interleaving, the signal transmitted in each cell is uniquely interleaved (as shown in figure (3.1b)).

Although randomization scheme can be easily implemented using scrambling or interleaving [12], it in fact does not reduce the level of interference in the cell, but it rather averages it. However, interleaving method can be combined with interference cancellation to enhance the performance of interference mitigation, but the price is more complexity as we will see below. Moreover, using interference randomization alone has advantages that its approach is suited to practical systems as it requires a low complexity resource management and no signalling overhead for cells coordination.

In [13], authors compared between interference randomization and interference coordination using a collision based model [14] that permits to analytically assess the bit-error-rate for both techniques. It has been found that interference coordination is effective for moderate system load, whereas interference randomization achieves a definite performance improvement in case of heavy loaded system due to the frequency diversity gain.

Figure 3.1: Randomization methods

Interference Cancellation

Interference cancellation is another signal processing technique that aims to suppress the interference from the received signal in a successive manner. Interference cancellation can be used against inter-cell interference as well as intra-cell interference (in case multiuser detection is employed within a cell) [15]. To define the interference cancellation, we borrow Andrews's definition in [16]: *interference cancellation should be interpreted to mean the class of techniques that demodulate and/or decode desired information, and then use this information along with channel estimates to cancel received interference from the received signal.* So, it is a kind of regenerating the interfering signals and subsequently subtracts them from the received signal. Consequently, in every cycle of this process the number of dimensions of the interference is reduced by one [5], [15]. In the literature, there are different methods of interference cancellation: Successive interference cancellation (SIC), Parallel interference cancellation (PIC), Iterative interference cancellation and spatial interference cancellation. Although interference cancellation technique is very effective in terms of performance, it adds more complexity in the system for the following reasons:

1. Inter-base station synchronization is required [17].
2. Increasing Overhead: UE needs to receive more information about the desired signal (e.g. Interleaving pattern ID) as well as more information about the interfering signals (e.g. modulation & coding scheme) [17].
3. To regenerate accurate interfering signal, it is crucial to have accurate estimation of channel, frequency offset, time delay and received power under different fading scenarios [15], [17].

Network-level Multiple-Input Multiple-Output (MIMO)

In this technique, the antenna on each base station (BS) is regarded as an element of a spatially distributed multiple input- multiple output(MIMO) array. This type of techniques may take different forms. For broadcast services, soft combining of signals transmitted from multiple base stations can give a significant performance benefit, converting the inter-cell interference into a diversity source. A central node¹ distributes the same signal to the base stations controlling the cells covering the desired broadcast area. Clearly, it is beneficial if broadcast transmissions in the cells use the same scrambling sequence and are time aligned within the cyclic prefix as the OFDM receiver in this case can exploit the benefits without additional processing [12].

For unicast transmission, under the condition that the base stations cooperation is enabled, then theoretically cooperative encoding among neighboring base stations can combat ICI. However, such joint encoding requires precise time and phase synchronization of the transmitted signals coming from different base stations, and it also requires accurate channel knowledge at all base stations. These strict requirements makes joint encoding practically impossible [5].

practically network MIMO can improve unicast transmission through exploiting the macro diversity which can be achieved via fast cell selection techniques. In such schemes, the UE provides measurements to the network and, based on this reports, the network transmits unicast data from one of the cells in the active set [12].

Maximum Likelihood Multiuser Detection

If all the interferers' channels information is instantaneously available, then maximal likelihood (ML) multiuser detection (MUD) is known to minimize the bit error rate (BER). However, having to attain the channels' information is not the only difficulty that makes ML practically impossible, but also the complexity that it adds to a

¹e.g. In LTE standard, it is called Radio Node Controller (RNC)

low-power mobile handset. In an $N \times N$ MIMO system which uses M-QAM, the complexity is in the order of M^{KN} , where K is the number of interferers [18]. Although there are some other suboptimal detectors such as sphere decoder, each one of them has its own drawback which makes implementation difficult.

Beamforming

beamforming usually refers to a class of signal processing techniques which are used for maximizing the signal energy sent to/from intended user, while minimizing the interference sent toward/from interfering users. It might be even used to support multiple users through what is known as spatial division multiple access (SDMA). Theoretically, beamforming is a very efficient and sophisticated technique, but its requirements are difficult to attain. A successful beamforming requires the complete interference statistics as well as the knowledge of the intended and interfering channels. However, to avoid such tough requirements, next chapter is proposing a scheme based on opportunistic beamforming and it requires only the intended user's SINR.

3.2 Interference Coordination Category Solutions

In this class of techniques, the planner is applying certain restrictions to the resource scheduling in a coordinated manner between cells in such a way to minimize the inter-cell interference. This process is also known as frequency reuse planning and the applied restrictions could be in frequency, time and/or power domain. Frequency reuse could be classified² as hard where the whole bandwidth is divided into a number of mutually exclusive sub-bands according to a selected reuse factor and lets neighboring cells transmit on different sub-bands. Furthermore, frequency reuse could be also soft frequency reuse type where the power on some of the sub-bands are reduced

²The following classification is not explicitly mentioned in the literature. It is, in fact, the conclusion of my extensive reading in this area.

rather than not utilized. Soft frequency reuse can be further divided into static, semi-static and dynamic depending on its ability of adaptation with the interference level and the traffic load in the system. While static reuse is predetermined fixed and can be only reconfigured every couple of days, semi-static reuse has the ability to move from one reuse factor to another in a basis of a fraction of a minute [17]. The advantage of semi-static reuse over static reuse is that the former gives the system opportunity to work with the whole spectrum in each cell (in instants of low traffic load). Dynamic frequency reuse is instantaneously changing with the interference level and traffic load with the objective to maintain optimal operation. In near to medium term, dynamic frequency reuse is inefficient since it causes a huge computation burden on the network and requires more signaling which in turn makes the scheduling process too complex. On the other hand, static and semi-static types are being now seriously considered in the standardization process [2, 3, 12, 19–22].

Among different interference coordination proposals, the most seriously considered in different standards³ are introduced below.

Hard Frequency Allocation

This type of allocation is considered the simplest frequency planning scheme in cellular network. Here the planner uses a reuse factor of 1 where the whole spectrum is used in every cell which could lead to high peak data rates. However, inter-cell interference is going to pass tolerable limits specially at cell edges. The classical solution is to divide the the available spectrum into 3 equal sub-bands, and allocate them to every 3 adjacent cells. This planning is called frequency reuse 3 and leads to low interference with a cost of large capacity loss due to the lower availability of radio resources in every cell.

³Such as 3GPP LTE standard

Soft Frequency Allocation: Static Allocation

A soft frequency reuse scheme is proposed in [19] and described in [23] where the whole band is divided into two subcarrier group; “major subcarrier group” and “minor subcarrier group” as shown in figure (3.2). Major subcarrier groups between neighbour cells should be orthogonal, therefore major subcarrier group can be used by all the UEs in a cell. Minor subcarrier group can be used only in the central area of every cell and cannot be used by cell edge users. So, this scheme is sometimes called full isolation assignment since the cell edge user is fully protected from adjacent cell’s interference. A user is allocated to each subcarrier group based on its power. The so called “Power Ratio” is the ratio between transmit power limitation of minor sub-carriers and major subcarriers. As power ratio is adjusted gradually from 0 to 1, the effective reuse factor changes from 3 to 1. When the high traffic happens at the cell edge, the power ratio should be set to a relatively small value to get a high cell edge bit rate (i.e. frequency reuse factor ≈ 3). On the contrary, when the traffic is mainly located at the inner part of the cell, a relatively large value for the power ratio is reasonable (i.e. frequency reuse factor ≈ 1).

A partial isolation, static frequency reuse scheme based on interference coordination approach is proposed in [12]. Only a part of the frequency is used for cell-edge users with full power and should be orthogonal between neighbor cells to mitigate most of the interference. Cell-center users may use the whole spectrum with restricted power to transmit/receive. So, owing to the long distance and relatively low transmit power the amount of ICI will be mild and tolerable although the same frequency is used. This scheme is illustrated in figure (3.3).

Another scheme proposed by Alcatel in [20], [21] divides the whole band into multiple sub-bands (e.g. 7) denoted as F_n . Then, each cell edge area is assigned a band that is assigned to the central area of the adjacent cell. In other words,

Figure 3.2: Full isolation scheme

Figure 3.3: Partial isolation scheme

Figure 3.4: Alcatel's proposal

each cell is assigned a sub-band which will be used by the users close to the cell but belonging to the neighbor cells. In figure (3.4), every cell is denoted by $\bar{n}$. If for example, terminal T_1 approaches cell $\bar{1}$ as depicted by the green arrow, it gets allocated frequency patterns from subset F_1 . With the proposed interference coordination all frequencies are unaffected in the inner circle. Restrictions by network planning and coordination only take place in the border regions where the availability of the frequencies is only slightly reduced (e.g. 6/7).

The requirement for this approach is that every terminal needs to report the strongest interfering signal back to its serving base station. This could be done using classical handover algorithms. However, the disadvantage of this scheme is the frequent spectral hand off.

The performance of different frequency allocation (hard & soft) schemes was studied and evaluated in [23]. Authors found that a partial isolation scheme which consists of using all the frequency band at each cell with a smart power allocation to mitigate

interference, achieves high cell throughput with an acceptable cell-edge rates. Accordingly, it has been concluded that partial isolation scheme could be considered as the best compromise between the different proposed frequency planning schemes for both up and down links.

Soft Frequency Allocation: Semi-Static Allocation

In the real systems, the traffic load varies between cell-center users and cell-edge users, so the static allocation schemes which are fixed will lead to system performance loss. Therefore, A semi-static coordination of reserved frequency sub-bands among cells is preferable in order to effectively address the varying throughput requirements and UE populations near the cell edge.

Figure (3.5) describes the frequency reuse scheme proposed in [2] where the entire frequency band is divided into N sub bands, then X sub bands are used for cell-edge users, and $N - 3X$ sub bands are used for cell-center users. The X sub bands used for cell-edge users in neighboring cells are orthogonal with a reuse factor equals 3, while the $N - 3X$ sub bands used for cell-center users are the same in all cells. The frequency utilization of cell-edge users will be changed by the traffic load, which means, if one more sub band is used for cell-edge users, the sub bands used for cell-center users will decrease by 3 sub bands. A user is allocated to each subcarrier group based on its geometry.

What distinguish [2]'s proposal from the above mentioned ones is that the frequency reuse factor in the outer cell can be adjusted by traffic load every fraction of a minute. However, the disadvantage of this scheme is that the spectrum utilization rate is not high, especially for the case of central area sub-band which reduces considerably.

Another proposal in [3] divides the whole band into multiple sub-bands. Then for every cell, each sub-band is assigned an allocation priority so that a sub-band

Figure 3.5: A semi-static allocation in [2]

with higher priority is allocated to users with higher transmit power (see figure 3.6). Resource allocation priority of the sub-bands should be decided in such a way that overlapping of high power transmission between neighbor cells is minimized. It is possible to assign an equal resource priority to more than one sub-band.

Figure 3.7(a) shows that when the traffic load in each cell is $1/3$ (i.e. $1/3$ of system resources are occupied), the inter-cell interference between 3 cells can be avoided ideally since the occupied sub-bands in adjacent cells are orthogonal. Figure 3.7(b) illustrates the resource allocation when traffic load in each cell is $2/3$. In this case, overlapping of resource allocation in frequency domain between 3 cells is inevitable. However, it does not happen that all the 3 cells use a same sub-band with same level of power. so, the worst interference case can be avoided.

In contrary to the mentioned scheme in [2] which takes into account the variation of traffic loads between the cell edge and cell center, [22] proposes a semi-static frequency reuse scheme which consider the fact that throughput requirements vary among adjacent cells. in this scheme, the size of the reserved frequency sub-bands

Figure 3.6: A semi-static allocation in [3]

Figure 3.7: Frequency allocations in different traffic load levels

depends on the traffic load near the cell edge (from both sides of the edge). If adjacent cells have similar total rate requirements near their edges, the reserved resource allocation may be equally divided to $1/3$ of the total. If a cell has smaller total rate requirements near its edge, then the adjacent cells can use more than $1/3$ of the frequency resources at their edge. In that manner, the frequency resources are efficiently utilized while avoiding excessive interference for users near the cell edge.

It has been indicated in [23] that schemes, which adapt the allocation of users to the load of each cell, may outperform the static schemes by achieving higher throughputs in case of heterogeneous traffic and mild signaling overhead.

3.2.1 Schemes based on Game theory

Game theory is a mathematical discipline which resolves a conflict in which two or more players are competing for common resources. Game theory approach has been extensively studied in CDMA-based networks to control the intra-cell interference. However, there are few works that considered game theory to control inter-cell interference in OFDM-based networks [24–27].

In [25–27], a decentralized scheduling are proposed for inter-cell interference control as alternatives for the centralized types which are too complex. In these mentioned papers, the competing competitors (players) are the schedulers in each base station or the co-channel users in adjacent cells. Moreover, while the games' objectives of these papers are different, these works considered the case where the action set available to the users is the frequencies or time resources only. On the other hand, in chapter 5, ICI is reduced by controlling the transmit power through a noncooperative game in which the transmit power is considered to be the action set available to the users.

In [24], the game components are as same as those in the our proposed scheme in chapter 5 except that [24] added one more dimension in the action set that is the rate

choice on each subchannel. However, in [24], authors considered only a simple case of 2 users each in different cell which are competing on 2 subchannels. Alternatively, chapter 5 proposed scheme considered multiple users in multiple cells.

3.3 Final Note

As far as inter-cell interference is concerned, there is almost a common consensus among researchers about the following points:

1. In future generation network which demands very high requirements, inter-cell interference is far beyond mitigating it by single technique. In fact, effective combination of existing techniques is very crucial to be considered [5], [15], [17].
2. Inter-base station cooperation could play very important role for a more efficient interference mitigation technique [5], [28]. In fact, LTE standard defines two indicators which are exchanged between base stations: *high interference indicator and overload indicator* [29].
3. Inter-cell interference mitigation technique could get benefit from the knowledge about user location within a cell [29]. Position information is not difficult to obtain as it was used for hand off management in second generations and it is also used in third generation networks for power control purpose as well as a part of value-added services (VAS) provided to the users.

Chapter 4

Location-Assisted Scheme Using Opportunistic Beamforming

As Opportunistic Beamforming (OB) induces more fluctuations in the channel, it can be used as an effective means for inter-cell interference management. This chapter presents a new scheme to decrease the effect of inter-cell interference by utilizing the information of users' locations along with the inter-base station cooperation in a system that employs opportunistic beamforming. The performance of the proposed scheme is analyzed and compared with different schemes. Simulation and analytical results are presented to show the effectiveness of the proposed scheme.

There are several motivations for choosing the OB approach. First, LTE-3GPP standard has indicated in [17] that beamforming antenna solutions at the base station represent a general technique that can be considered as a means for inter-cell-interference mitigation. Second, in recent work [15], OB has been considered as a possible means for inter-cell interference management. Moreover, Since OB was introduced in [30], it has been extensively studied for scheduling purposes within a cell (e.g., [31–33]). However, few works have been done in using OB for ICI management although it has been mentioned in [30] that OB is a potential solution for ICI. Furthermore, inter-cell coordination as well as users' location information are useful tools

for a more effective inter-cell interference management [5], [28], [29].

The rest of this chapter is organized as follows. In Section 4.1, I briefly discuss the opportunistic systems (opportunistic scheduling and opportunistic beamforming). In Section 4.2, the system model and associated assumptions are introduced. The proposed location-assisted ICI scheme is introduced in Section 4.3. System performance analysis is presented in Section 4.4. Simulation results are discussed in Section 4.5. Finally, Section 4.6 concludes this chapter.

4.1 Opportunistic Systems

Among different opportunistic wireless systems available in the literature, this chapter considers here an opportunistic system that consists of two main parts: opportunistic scheduling and opportunistic beamforming. The latter creates opportunities and the former exploits them. The following two subsections briefly explain each part.

4.1.1 Opportunistic Scheduling

Unlike traditional TDMA system that schedules the users in a predetermined fixed cycle (regardless of users' channel conditions), opportunistic scheduling selects the user whose channel quality is at its peak. The sum capacity of such strategy is far higher than that of non-fading channel whose SNR is constant and equals to the average SNR of the fading channel. The underlying principle behind that is multiuser diversity gain. Thus, by always scheduling the best user whose channel is at its peak, from the system perspective, system is always operating on the best SNR, which makes the overall spectral efficiency of the system significantly higher than that of non-fading systems that always operate on the same average SNR.

Waiting for the user's channel to reach its peak should not be too long. In fact, the time between two consecutive peaks in the channel of user k should be less than

latency time scale so that delay constraint would not be violated; otherwise the scheduler will be forced to schedule the user at lower gain to cope up with delay constraint. So, the faster and the larger the fluctuations of the channel, the higher the capacity. Now, what about if the channel naturally fades slowly (slow fading) and fluctuates around the average gain (almost constant)? Certainly the multiuser diversity gain is going to be too low. The solution for enhancing the gain is to induce artificial fast and large fluctuations into the channel. This could be done by opportunistic beamforming [30].

4.1.2 Opportunistic Beamforming

Beamforming is a signal processing technique that concentrates the signal energy towards the intended user. In general, an array of transmit antennas is employed at the base station as shown in figure 4.1. In coherent beamforming (not opportunistic), user k estimates the complex gain of spatial subchannel from each antenna n and feed it back to the base station. Then, base station will choose the weight in every antenna to be:

$$\alpha_n = \frac{|h_{nk}|^2}{\sum_{n=1}^N |h_{nk}|^2} ; n = 1, \dots, N. \quad (4.1)$$

$$\theta_n = -\arg(h_{nk}) ; n = 1, \dots, N. \quad (4.2)$$

This assignment of the power (i.e. α) and phase (i.e. θ) is called *beamforming configuration*, at which the peak value of the channel occurs and the signal energy is focused towards user k . Nevertheless, this requires accurate estimation of different spatial subchannels and feeding them back to the serving base station.

In opportunistic beamforming however, the system will choose the complex weight in every antenna randomly according certain distribution [30]. If there are many users in the system, then at any given time, there will be at least one user whose

Figure 4.1: Beamforming antenna array.

spatial subchannels' gains are almost at beamforming configuration. Such user can be identified by its feedback of overall SNR which must be the maximum among all users.

Another way to look at the situation is as follow. In time slot t , the same block of symbols $x(t)$ is transmitted from every antenna after it has been multiplied by different random gain and shifted by a random phase. In the air, all the output of the antennas are going to be added naturally to each other and the resultant signal will reach the user either constructively or destructively depending on the random complex weight in every antenna as well as the complex gain of every physical spatial subchannel. If the normalized complex gain of every spatial subchannel happens to be close to the conjugate of the weight employed in the corresponding antenna, then the overall channel gain is at its peak. It has been proved in [30] that opportunistic beamforming increases the rate and amplitude of the fluctuations seen by users which makes it perfect environment for opportunistic scheduling to exploit. In fact, opportunistic beamforming does not only increase the rate and amplitude of the peaks, but it also increases the rate of deeper fades which is called opportunistic nulling.

Figure 4.2: Three main cases, cell edge user could experience in an opportunistic multi-cell system.

These deep fades can be also exploited by neighboring cells to reduce the inter-cell interference impacts. The idea is to schedule the user when its desired signal at the peak AND interfering signal at its null (see figure 4.2 at time t_1). Figure (4.2) shows the desired signal of user k as well as the interference signal coming from neighboring cell (red colored cell). At time t_2 , user k is suffering from high interference while its desired signal is weak. As a result, opportunistic scheduling will avoid it for its low SINR. At time t_3 , however, the desired signal is very good, but the interference is unluckily high. This chapter is going to use the user location information along with the inter-cell collaboration to achieve contention resolution.

Before we proceed, it is important to clarify one point that could cause misunderstanding. Since the system opportunistically works, it cannot beam towards a certain predefined user by only selecting special pattern of the antennas' weights, simply because beamforming depends also on the spatial subchannels' responses h_{nk} which are unknown. The system in fact, throws the random weights and then identifies the

best user via the overall SINR feedback. This user could be anywhere inside the cell. Accordingly, if one base station knows that there is a certain area free of interference, then it cannot intentionally beams towards the users in that area by only using opportunistic beamforming.

4.2 System Model

The cell of interest (cell 0 in figure 4.3) is divided into 6 equal areas each with a random number of users Y_j such that $E[Y_j] = K/6; \forall j$ and $\sum_{j=1}^6 Y_j = K$, where K is the total number of users in the cell. Accordingly, users are assumed to be uniformly distributed within the cell, which means that any user could be in the cell edge¹ area with probability $p_{ce} = (D^2 - d_c^2)/D^2$, where D is the cell radius, and d_c is the radius of the central region of the cell (see figure 4.3, cell 6)). Moreover, it is assumed that any border user within one area is going to be affected severely by the interference coming at most from 2 neighboring cells, which are called “interfering neighbors”. For instance, user k in cell 0 at area 1 is susceptible for interference from cell 1 and 2. Since the worst case scenario of the inter-cell interference is considered, it is assumed that the beam radiation covers a complete 60 degree sector. In addition, due to uniformity distribution and dividing each cell into 6 equal areas, the probability for any user to belong to a certain area is $1/6$. it is also assumed that the system knows the users’ locations within the cell and the inter-base station coordination is facilitated.

Since OFDM transmission scheme is employed, the physical channel is assumed to be flat during one time slot duration (i.e., coherence time is equal to one time slot). Moreover, the noise is assumed to be an identically independent distributed (i.i.d.) Gaussian random process.

¹Cell edge area is the border area of the cell which is more closer to the neighboring cell. Cell edge area is usually modeled as the outer ring of the cell and it consists 10% to 20% of the cell area

Figure 4.3: A cellular network topology.

In The OB-OFDM system shown in figure (4.4), the number of inverse fast fourier transform (IFFT) equals to the number of antennas N , and the weights are applied just before the IFFT in a subchannel basis (i.e., every subchannel m has a set of N weights. The weight w_n^m is applied to the subchannel m on the IFFT n which corresponds to the antenna n). Furthermore, the weight sets are spectrally independent over the subchannels, hence the subchannels' beams are directed to different directions independently making the resources distributed fairly over the cell. So for simplicity, the algorithm below and the corresponding performance analysis are applied to one subchannel, but it can be applied straightforwardly to all remaining subchannels.

Figure 4.4: OFDM opportunistic beamforming with FFT implementation (for two antennas)

4.3 The Proposed Location-assisted ICI Control Scheme

The proposed location-assisted ICI control (LaICIC) scheme works as follows (also shown in figure 4.5):

1. Randomly choose the antennas' weights, and send pilot signals.
2. Each user equipment (e.g. user handset) measures its SINR and feeds it back to the base station.
3. A scheduler (e.g., proportional fair scheduler) selects the optimum user.

4. Is the optimum user at cell edge? (This information can be obtained using any positioning technique.)
 - (a) If No: Assign the subchannel to the optimum user.
 - (b) If Yes: Is the corresponding spectral subchannel from the interfering neighbors beamed towards the optimum user? (This information can be acquired via inter-cell collaboration.)
 - i. If No: Assign the subchannel to the optimum user.
 - ii. If Yes: Go to step (1). (Since the scheduler failed to schedule with the current antenna weights due to severe inter-cell interference in the area of the selected user, it has to change the antenna weights to find a free-of-interference user located in another area).
5. End.

In this scheme, the scheduler protects users from inter-cell interference by scheduling them only when they are at the center or when their interferer neighbors are not radiating towards them (i.e., when the interference is at null). It is worth mentioning that if the scheduler failed to assign a subchannel towards an area, it could however assign some other interference-free subchannels to the same area. This comes from the fact that every subchannel has its own independent weight set.

4.4 System Performance Analysis

Before we proceed with the performance analysis, it is important to note that in terms of inter-cell interference, the performance of 1-cell system is the optimum system performance because it has all resources available and it is ICI-free system. As a result, the performance of any inter-cell interference mitigation scheme used in a

Figure 4.5: Flow chart of LaICIC algorithm

multi-cell system should be evaluated by comparing it with the performance of 1-cell system.

In the LaICIC scheme, the first 3 steps are just similar to that in a 1-cell system. Step (4) however, makes the difference and it is the source of degradation from the performance level of 1-cell system.

With every failure of scheduling, there are two impacts. First, the total number of available users (opportunistic beamforming pool) is going to decrease by $E[Y_j] = K/6$ due to avoidance of the current area j which is suffer from ICI. Such reduction in the

number of users is going to degrade the performance of opportunistic beamforming and reduce the multiuser diversity gain [30]. Second, since the time is considered as a system resource, there is a portion of this resource going to be consumed in extra computation resulted due to rescheduling. Below is the mathematical analysis of these impacts.

4.4.1 Reduction in the Total Number of Users

According to the algorithm, the probability that scheduler will fail to assign the subchannel (i.e, it has to go to step 4.b.ii) is the probability that the optimum user is at cell edge AND at least one of the interfering neighbors is beaming towards it. The probability of this event is:

$$p_f = p_{ce} \cdot \left(\frac{1}{3}\right) = \frac{D^2 - d_c^2}{3D^2}. \quad (4.3)$$

Consequently, the probability of successful scheduling is $p_s = 1 - p_f$.

If we assume X is the number of failures until the subchannel is successfully scheduled, then X is a geometric random variable with the parameter p_s ; the probability of success. The statistical average of X is:

$$E[X] = \frac{1 - p_s}{p_s}. \quad (4.4)$$

Now, with every failure, scheduler has to exclude the current area users from the next trial since they are surely affected by inter-cell interference. Accordingly, with every failure OB pool loses in average $1/6$ of the total number of users K . Then, the number of the lost users² until the subchannel is assigned is:

²Lost users are those who will not be considered for scheduling in next trials. Accordingly there will be a lost in multiuser diversity gain.

$$L_u = X \cdot \left(\frac{K}{6}\right). \quad (4.5)$$

The average number of lost users is:

$$E[L_u] = E[X] \cdot \left(\frac{K}{6}\right). \quad (4.6)$$

Let's assume that the central area is 80% of the cell. Then for every 1000 users in the cell, the system is going to lose only 12 users on average, which means the performance of LaICIC is close to the performance of 1-cell system.

The average throughput of a multi-cell system can be written as a function of 1-cell system throughput, both with respect to the number of users in the cell:

$$Th_M(K) = Th_1(K - L_u) = Th_1\left(K - X \cdot \left(\frac{K}{6}\right)\right). \quad (4.7)$$

equation (4.7) is derived from the fact that step 4 in LaICIC scheme is going to reduce the performance of multi cell system form the level of 1-cell system performance due to the reduction in multiuser diversity gain. Consequently, multi cell system throughput can be as same as the throughput of 1-cell system that incurred the same amount of multiuser diversity loss. multiuser diversity loss can be reflected by a reduction in the number of users available in the cell (i.e. $-L_u$).

4.4.2 Time Consumption Due to Extra Computation

Assume there are a 1-cell system and a multi-cell system with LaICIC working independently. If T sec period has been assigned to both systems for transferring data, then the 1-cell system will use the whole T sec in data transferring operation. In the multi-cell system, however, out of T sec there will be a small portion C sec (consumed time) dedicated for extra computation due to rescheduling. Now, how much is this

cost (the reduction in throughput)?

Let's assume T is 100 time slots (or scheduling cycles) each with τ sec, then $T = 100\tau$. Moreover, assume each failure requires additional computation process of ε sec. So, the consumed time per each time slot (or scheduling cycle) is:
 $c = X \cdot \varepsilon$, where X is the number of failures in that time slot. Then, the average consumed time per a time slot is:

$$E[c] = E[X] \cdot \varepsilon. \quad (4.8)$$

Since we have 100 time slots, the total consumed time is:

$$C = 100 \cdot E[c] = 100 \cdot E[X] \cdot \varepsilon. \quad (4.9)$$

Now we can calculate the throughput of the multi-cell system in terms of the 1-cell system throughput:

$$Th_M = Th_1 \cdot \frac{[T - C]}{T}. \quad (4.10)$$

$$Th_M = Th_1 \cdot \frac{[100 \tau - 100 \varepsilon E[X]]}{100 \tau}. \quad (4.11)$$

$$Th_M = Th_1 \cdot \frac{[\tau - \varepsilon E[X]]}{\tau}. \quad (4.12)$$

In the worst case scenario, let us assume the computation time ε is as long as the complete time slot τ , then:

$$Th_M = (1 - \bar{X}) \cdot Th_1, \quad (4.13)$$

where,

$$\overline{X} = E[X] = \frac{1 - p_s}{p_s}. \quad (4.14)$$

If we assume that the central area is 80% of the cell and the remaining is considered for cell edge, then:

$$Th_M \approx 0.92 Th_1. \quad (4.15)$$

4.4.3 Combining Both Impacts

By combining both impacts in Subsections 4.4.1 and 4.4.2, the resultant throughput as a function of the number of users in the cell can be written as:

$$Th_M(K) = (1 - \overline{X})Th_1 \left(K - X \cdot \left(\frac{K}{6} \right) \right). \quad (4.16)$$

The average throughput can be found statistically as follows:

$$E[Th_M(K)] = E \left[(1 - \overline{X}) Th_1 \left(K - X \cdot \left(\frac{K}{6} \right) \right) \right]. \quad (4.17)$$

By Jensen's inequality,

$$E[Th_M(K)] \leq (1 - E[X]) Th_1 \left(K - E[X] \cdot \left(\frac{K}{6} \right) \right). \quad (4.18)$$

4.5 Simulation Results and Discussions

In this section, the performance of the proposed LaICIC scheme in opportunistic multi-cells systems is determined by system level simulations. The simulator consists of three opportunistic systems: a 1-cell system, a multi-cell system without the

Table 4.1: Simulation parameters

Parameters	Value
System Frequency	2 GHz
System Bandwidth	10 MHz
Subcarrier Bandwidth	15 KHz
Cell Radius	0.5 Km
No. of antenna at BS	2
User Speed	Pedestrian
Total NBe Power	43.0 dBm
Noise Power Spectral Density	-174 dBm/Hz
Path loss Model	$128.1 + 35.2 \log(d)$; d in Km.
Shadow Fading Deviation	8 dB
Small Scale Fading	Rayleigh fading.
Scheduler	Proportional fair Scheduler
Target BER	10^{-6}
Length of Time Slot	1 ms
Number of Time Slots	1000
Number of Replication	10
Link	DownLink
Residual interference	5.9693×10^{-21} W

LaICIC scheme and a multi-cell system with the LaICIC scheme. Simulation parameters are shown in Table 4.1. it is assumed that the transmit power has been distributed equally over all subcarriers.

In addition, since there is little amount of interference coming from other cells which are either non-interfering neighbors (non-closest cells) or from second and third tiers, a residual interference power has been added to the multi-cell systems as a correction factor.

Simulation program has been developed using Matlab software. The simulation

runs 10 independent replications. In each replication, channel realizations $h(t)$ of 1000 time slots and over 180 users are generated using:

$$h(t) = \sum_{n=1}^N \sqrt{\alpha_n(t)} \cdot e^{j\theta_n(t)} \cdot h_{nk}(t) \quad (4.19)$$

where $\alpha_n(t)$ is the amplitude of the antenna weight whose distribution is as mentioned in [30], $\theta_n(t)$ is the phase of the antenna weight distributed which has uniform distribution (i.e. $U(0, 2\pi)$), and $h_{nk}(t)$ is Rayleigh distributed physical subchannel from antenna n to user k . Then, at for every user within the cell of interest, its SINR is calculated under three different scenarios: one cell system scenario (i.e. there is no interference), multi-cell system without interference control and multi-cell system aided with LaCIC scheme. After that, proportional fair (PF) scheduling algorithm [11] is run to find the optimum user in each scenario. In case that the optimum user in the LaCIC-aided system is in cell edge or one of the interfering neighbors is beamforming towards it, number of users is reduce by 1/6 and a counter of time consumption counter is triggered. After successful scheduling, throughputs for the optimum users in different system are calculated using equation (2.11). Finally, average aggregate throughput is found by averaging the throughput over frequency, time and replications.

Figure (4.6) shows the simulation results in terms of the average throughput of different opportunistic systems with respect to the number of users per cell. All curves are increasing with the number of users because of multiuser diversity gain, which is further enhanced by opportunistic beamforming. Obviously, the best throughput is for the one-cell system, simply because it does not suffer from any inter-cell interference. It is also noticeable that with a low number of users in the system, the performances of all systems are close to each other. This is due to the fact that the amount of inter-cell interference is low as there are only a few active users in every

Figure 4.6: Average throughput vs. the number of users per cell in different systems.

cell.

Compared to the system without the ICI mitigation scheme, the LaICIC scheme has improved the throughput of the system by more than 20% (when the number of users exceeds 20 users per cell). This improvement comes as a result of the ability of the LaICIC scheme to avoid the interference areas. The theoretical throughput of the multi-cell system has been sketched using the right part of the inequality (4.18). As a result, the simulated throughput appeared in the graph is less than the theoretical one.

The CDF graphs of the throughput for the fully loaded three different systems are shown in figure (4.7). We can see that the throughput CDF of the multi-cell system with the LaICIC scheme is about to fit the CDF of the 1-cell system throughput while the CDF of the multi-cell system without ICI mitigation scheme is falling far behind them. This means that the LaICIC-aided system does not only have a very good improvement compared to the multi-cell system without ICI mitigation scheme,

but also it is approaching the performance of the 1-cell system. Moreover, since the scheduler is proportional fair, it is obvious that the performance of cell-edge users in the LaICIC-aided system is going to be much better than that of cell edge users in the multi-cell system without the ICI mitigation scheme as the throughput of the LaICIC system is likely to be always better than that of the multi-cell system without the ICI mitigation scheme.

Figure 4.7: Empirical CDF of different systems' throughput when the number of users is 180/cell.

4.6 Conclusion

To meet the increasing demand for various wireless mobile services, wireless spectrum efficiency is becoming increasingly important. In wireless networks, users experience location-dependent and time-varying interference conditions. In an opportunistic system, where fading instants increase, location information can be employed to avoid the

inter-cell interference. This chapter presented a scheme which utilizes user location information along with inter-cell collaboration in a system that employs opportunistic beamforming to decrease the effect of ICI. Analytical and Simulation results were presented to show the effectiveness of the proposed scheme.

It is quite clear that the proposed scheme is done at the base station (by opportunistic scheduler and beamforming) while the UE is considered to be oblivious. Accordingly, since the possibility to perform inter-cell interference cancellation at the UE is considered irrespective of the interference mitigation scheme adopted at the base station [17], there is a good chance for this proposed scheme to be combined with the interference cancellation techniques at UE. This idea will be considered for a future work.

Chapter 5

Game Theory Approach for Inter-Cell Interference Control

In this chapter, a transmit power adaptation method using game theory approach is developed in such a way to reduce the inter-cell interference in the whole network. While satisfying every user's minimum requirements, the main objective is to control the inter-cell interference and enhance the total data rate of multiuser-multicell orthogonal frequency division multiplexing (OFDM) system. In general, the gaming problem is formulated by allowing that a subchannel could be shared by multiple neighboring cells (i.e. universal frequency reuse). The data rate enhancement is derived via two steps: assigning the subchannel to the optimum user assuming the system has the ability to do so, and finding the optimum transmit power for each co-channel user using the proposed scheme in this chapter.

Adopting a non cooperative game theory approach has several motivation. First, the resource allocation based on global optimization is inherently complicated meaning that it does not only need a global knowledge of the users' varying information, but also it is computationally hard to find an optimum solution. So, it looks reasonable to delegate part of the allocation process to a selfishly smart users using a non cooperative game with a network-oriented rules. Second, the trend of the future

networks is to get rid of central controllers and migrate to a more distributed systems which could be highly supported by game theory approaches. Such decentralized strategy aided with game-based power control could allow for dynamic soft frequency reuse which surly leads to a plug and play operation and universal frequency reuse¹. Third, game theory approaches does not concern about user-rate maximization, but rather it tries to maximize the rate of the whole network while satisfying the minimum requirement of every user. Accordingly, game theory approaches try to make the level of service evenly equal over all users wherever they are and hence it is implicitly fair.

This chapter is organized as follow. Section 5.1 will provide a necessary and brief background about game theory. System model and assumptions are displayed in section 5.2. Detailed descriptions of the noncooperative game are presented in section 5.3. Section 5.4 discusses the simulation results and then it is followed by the conclusion in section 5.5.

5.1 Game Theory: An Overview²

Game theory is a mathematical discipline that aim to model, describe and analyze a competitive situation in which two or more decision makers have to take specific actions that include mutual conflict. Although the most tremendous research effort has been exerted to model the games on the economic feild as the premier application area for game theory³, game theory has been recently applied in networking and wireless communication, mostly to solve routing, and resource allocation problems in a competitive environment. For instance, the decision makers (i.e. players) in wireless communications are rational network entities who control their communication parameters to cope with the scarcity in the radio resources that imposes a conflict

¹This could be done as long as the entities within one cell can decide their transmit power based on network-oriented rules.

²Most of this section is taken from [34].

³most of the concrete and mature models are inspired by economic field.

of interests. So, they attempt to resolve such kind of conflicts by adopting certain actions such as transmitting later, changing their transmission channel or adjusting their transmission power.

Definition 5.1. *A game is described by a set of rational players, the actions associated with the players and the utilities (or payoffs)⁴ for the players: $\mathcal{G} = (\mathcal{K}, \{\mathcal{A}_k\}, u_k)$.*

- $\mathcal{K} = \{1, 2, \dots, K\}$ is the set of rational players.
- $\mathcal{A}_k = \{a_{k1}, a_{k2}, \dots, a_{kv_k}\}$ is the set of actions⁵ available to player k , where v_k is the number of available actions for that player.
 $\mathcal{AP} = \mathcal{A}_1 \times \mathcal{A}_2 \times \dots \times \mathcal{A}_K = \{(a_1, a_2, \dots, a_K)\}$ is the set of the actions profiles, that is all the possible combinations of the players' actions, where $a_k \in \mathcal{A}_k$.
- $u_k : \mathcal{A}_1 \times \mathcal{A}_2 \times \dots \times \mathcal{A}_K \rightarrow \mathbb{R}$ is the utility function for each player k . It maps an actions profile to a numerical real number. If $a_{k1}, a_{k2} \in \mathcal{A}_k$, player k prefer a_{k1} over a_{k2} if and only if $u_k(a_{k1}) \geq u_k(a_{k2})$.

Note that player's utility values only convey ordinal information. In other words, if $u_k(a) > u_k(b)$, that means player k prefers action a over action b . accordingly, utility function could take negative values [34].

In a noncooperative game, each player seeks to choose its action which maximize its own utility, mathematically:

$$\underset{a_k \in \mathcal{A}_k}{\text{maximize}} \quad u_k, \quad \forall k = 1, \dots, K. \quad (5.1)$$

At this point, it is important to introduce the concept of Nash equilibrium (NE).

⁴in communication literature, the term "utility" is widely used whereas in economic and game theory literature the term "payoff" is mostly used.

⁵Actions and strategies terms may be used interchangeably

Definition 5.2. A NE is an actions profile $(a_1^*, a_2^*, \dots, a_K^*)$, such that no player can unilaterally improve its own utility, i.e.

$$u_k(a_k^*, a_{-k}^*) \geq u_k(a_k, a_{-k}^*) \quad \forall a_k \in \mathcal{A}_k \text{ and } k = 1, \dots, K, \quad (5.2)$$

where $a_{-k}^* = (a_1^*, \dots, a_{k-1}^*, a_{k+1}^*, \dots, a_K^*)$.

At NE no player has any incentive to change its strategy. Accordingly, NE is a stable outcome of the game $\mathcal{G}$.

One efficient way to obtain a Nash equilibrium is to use the best responses of the players. Consider a player k , For any given actions of the players other than k (i.e. a_{-k}), the best response B_k of player k is the action $a_k \in \mathcal{A}_k$ that maximizes its utility, i.e.

$$B_k(a_{-k}) = \{a_k \in \mathcal{A}_k : u_k(a_k, a_{-k}) \geq u_k(a'_k, a_{-k}) \quad \forall a'_k \in \mathcal{A}_k\} \quad (5.3)$$

As a result, the Nash equilibrium can be found by identifying the best response (i.e. optimal action) of each player given other players' actions. After considering all possible combinations of players' actions, the Nash equilibrium is identified as the set of best responses of all players. consequently, the game solution (i.e. the equilibrium of the game) is the action profile adopted by the players such that none of the players wants to deviate from it. Formally, at a Nash equilibrium $(a_1^*, a_2^*, \dots, a_K^*)$,

$$a_k^* \in B_k(a_{-k}^*), \quad \forall k \in \mathcal{K}. \quad (5.4)$$

To illustrate what has been discussed so far, consider the well-known Prisoners' Dilemma in which two suspects of a crime are arrested. They are taken into separate rooms and each of them has been given the choices (actions) with the corresponding consequences (utilities) (see figure 5.1). If they both confess, they will stay at jail

		Suspect 2	
		Confess	Refuse
Suspect 1	Confess	$(-6, -6)^*$	$(0, -10)^*$
	Refuse	$(-10, 0)^*$	$(-2, -2)^*$

$^*(x, x) = (\text{suspect 1 utility}, \text{suspect 2 utility})$

Figure 5.1: Prisoners' dilemma game.

for 6 months. On the other hand, If both of them refuse to confess, they will stay at jail for two months. However, if only one of them confess, he will be released immediately while the other suspect will stay at jail for 10 years. Now, since they are in separated room and hence they cannot cooperate, the best way for both of them is to act selfishly trying to minimize the charges (i.e. maximizing the utility). From figure 5.1, if the first suspect confesses or refuses to confess, the best action for the second suspect to maximize his utility is to confess. Moreover, if the second suspect confesses or refuses to confess, the best action for the first suspect is to confess. As a result, the profile action (confess, confess) is the only equilibrium point for prisoners' dilemma game.

In brief, there are two important characteristics in game theory: individualism and interdependence. Individualism influences the rationality and self interest while interdependence determines the actions of the players in response to those of other players (i.e. a player's utility does not only depend on his action, but it also depends on the other players' actions).

User equipments (UEs), who are in an OFDM wireless network located in adjacent cells and operating on the same subchannel, are in fact affecting each other through

Figure 5.2: System layout.

inter-cell interference. Such users' interaction can be modeled as a game whose players are those UEs which are competing for network resources (i.e. bandwidth and energy). Obviously, any action taken by a user affects the performance of other users in the network. Accordingly, game theory is the natural method for studying such interaction.

5.2 System Description

In a cellular network (figure 5.2), all the bandwidth is available to every base station (i.e. Fractional Frequency Reuse: FFR=1). It is assumed that every user is aware of its channel h_k strength as well as the amount of cochannel interference I_k . The base stations are asynchronous in terms of scheduling. In other words, if a base station j is in a scheduling process for a certain subchannel, the other base stations could be in operation mode so that the amount of interference coming to j^{th} cell is almost constant rather than being dynamic which makes the power adaptation based on game theory more difficult. Each cell consists of user equipments and their assigned base station. The total number of perfectly orthogonal OFDM subchannels

is M . Moreover, the total number of users within one cell is K and the total number of co-channel users (i.e. the users in adjacent cells who are operating in the same subchannel) is J . Since, OFDM is the system's transmission scheme, the channel is considered flat during resource block duration (e.g. Block duration in LTE is 7 OFDM symbol duration). Considering the uplink, the signal to interference plus noise ratio (SINR) on the m^{th} subchannel of the k^{th} user's signal at the base station, can be expressed as:

$$\gamma_k^m = \frac{p_k^m h_{k,k}^m}{\sum_{j \neq k} p_j^m h_{j,k}^m + \sigma_k^m} = \frac{p_k^m h_{k,k}^m}{I_k^m + \sigma_k^m} \quad (5.5)$$

where p_k^m and p_j^m are the transmit power on the m^{th} subchannel, from user k and the interfering user at cell ' j ', respectively. $h_{k,k}^m$ and $h_{j,k}^m$ are the desired signal channel and the interferer channel, respectively. σ_k^m is the thermal noise power at base station of interest k and on m^{th} subchannel. I_k^m is the total interference experienced by base station of interest k on subchannel m .

5.3 Noncooperative Game

Let $\mathcal{G} = (\mathcal{J}, \{\mathcal{P}_j\}, \{u_j\})$ represents a game where:

- $\mathcal{J} = \{1, 2, \dots, k, \dots, J\}$ is the set of user equipments in adjacent cells who are using the same subchannel.
- $\mathcal{P}_j = \{p_j : p_j \in [0, p_{max}]\}$ is a Continuous set of transmit power which represents the space of user's actions. $p_{max} > 0$, is the maximum allowable transmit power per subchannel, it could equal $\frac{p_{total}}{M}$. The selected action (transmit power) has to be smart enough to maximize the user's utility.
- u_j : is the j^{th} user's utility.

According to the discussions in the previous section, the choice of the utility function has a great impact on the nature of the game and on the users's behaviors. Thus,

the following subsection is dedicated to introduce and analyze the proposed utility function.

5.3.1 Utility Function

We have already defined the utility function in the perspective of game theory. In the context of wireless communication, however, utility function can be defined as follow:

Definition 5.3. *Utility function is a mathematical expression that quantifies the level of satisfaction a user gets by using the system resources.*

For any game, there are many utility functions that could describe the set of the desired rules of that game. In fact, The function that places the elements of the actions set $\mathcal{P}$ in the desired order is a candidate for a utility function. In the following, the game preference relations that are specific in our interference mitigation problem are identified and then the utility function that represents this structure is introduced and described.

The factors that have an effect on the quality of multimedia services include delay and clarity. The main causes of delay is the low data rate and the frequent retransmission which are basically because of low level of SINR. Moreover, weak SINR increases the bit error rate (BER) which degrade the level of clarity, specially in voice services. Obviously, the physical channel conditions play a crucial role in affecting the received SINR, service quality and hence the level of user's satisfaction. Weak signal and interference in wireless channel are the underlying sources of service degradation. One way to deal with such situation is by fixing an application-based BER, while enhancing the throughput, which should be basically variable and adaptive.

When maximizing the spectral efficiency is the main objective, it is preferable to define the user's utility as a concave increasing function of the user's SINR [35–38]. To this end, the first function comes into mind is the logarithmic Shannon capacity

Figure 5.3: Utility function: a) with respect to SINR while power is fixed, and b) with respect to power while SINR is fixed

function or a function proportional to it. However, for a fixed interference I and fixed desired channel power $h_{j,j}$, the best way for a user to maximize such utility function in a non-cooperative game is transmitting with the highest possible power. Such behavior will increase the level of interference in the network and hence reduce the system's spectral efficiency rather than improving it. As a result, such a function is not a complete utility function. To complete it, a pricing term (or cost) should be incorporated to it so that it prevents the users from always transmitting at full power. Thus, If SINR is fixed, the utility function should be a decreasing function with respect to the transmit power.

Accordingly, for subchannel m , the following user's utility function is devised for the on-hand game-based power control:

$$u_j(p_j, \gamma_j) = \ln\left(1 + \frac{\gamma_j^m}{\beta_j}\right) - \alpha_j p_j^{2^m}, \quad p_j, \gamma_j \geq 0 \quad (5.6)$$

where β_j is an application-dependent positive factor that takes into account the required BER and also it represents a mathematical approximation factor for adaptive transmission, $\beta = \frac{-\ln(5BER)}{1.5}$ [?, ?, ?]. If the required BER for all users are equal,

then there is no need for β since it become a common factor among all users. α_j is a user's location-dependent pricing factor which makes the price for radiating power dependent on the user's location. If the user is at cell edge, it should be allowed to transmit relatively higher power to compensate its channel weakness and overcome the higher interference, but this reasonable strategy is going to cost such a user to incur a higher loss in its utility value. To be fair, it should be assigned a relatively low value of α_j . However, for the central user, since it has the privilege of strong channel and weak interference, it should be firmly restricted from radiating too much power to protect the whole system from unwanted higher interference. To restrict such a user, its α_j should be a relatively high value. As a result, the price (second term in the utility function) is not uniformly equal over the users, in fact as the users go further from the base station, as the price of every watt they radiate goes down. In general, the value of α_j should be proportional with channel power $h_{j,j}$ and inverse proportional with the amount of interference I_j , i.e.:

$$\alpha_j \propto h_{j,j} \quad \text{and} \quad \alpha_j \propto \frac{1}{I_j} \quad (5.7)$$

Note that since γ_j is a function of p_j and $\mathbf{p}_{-j}$ ($\mathbf{p}_{-j} = \{p_j, \dots, p_{j-1}, p_{j+1}, \dots, p_J\}$), then utility function can be also written in terms of p_j and $\mathbf{p}_{-j}$, i.e. $u_j(p_j, \mathbf{p}_{-j})$. This form of utility function could be also used anywhere in this chapter.

According to the designed utility function in (5.6), it is important to note the following properties, assuming the game is played over the subchannel m :

1. For a fixed transmit power p_j ,

- (a) $\frac{\partial u_j(p_j, \gamma_j)}{\partial \gamma_j} = \frac{1}{\beta_j + \gamma_j^m} > 0$, i.e. utility is an increasing function of SINR.
- (b) $\frac{\partial^2 u_j(p_j, \gamma_j)}{\partial \gamma_j^2} = \frac{-1}{(\beta_j + \gamma_j^m)^2} < 0$, i.e. the rate of the increasing utility is decreasing with respect to SINR. In other words, as SINR gets higher, the utility

function gets slower (see figure 5.3(a)).

2. For a fixed SINR γ_j ,

- (a) $\frac{\partial u_j(p_j, \gamma_j)}{\partial p_j} = -2\alpha_j p_j^m < 0$, i.e. utility is a decreasing function of the transmit power.
- (b) $\frac{\partial^2 u_j(p_j, \gamma_j)}{\partial p_j^2} = -2\alpha_j < 0$, i.e. the rate of the decreasing utility is increasing with respect to the transmit power. In other words, the utility function decline faster, as the user increases its transmit power (see figure 5.3(b)).

3. If $h_{j,j}$ and I_j are fixed, then $u_j(p_j, \mathbf{p}_{-j})$ is a concave function of transmit power p_j . To prove this property, let us assume that $\ln(1 + \frac{p_j^m h_{j,j}^m}{\beta_j(I_j^m + \sigma_j^m)}) = \Psi_j(p_j, \mathbf{p}_{-j})$ and $-\alpha_j p_j^2 = \Omega_j(p_j)$. Now, since $\Psi_j(p_j, \mathbf{p}_{-j})$ and $\Omega_j(p_j)$ are concave functions of p_j , then their sum $u_j(p_j, \mathbf{p}_{-j}) = \Psi_j(p_j, \mathbf{p}_{-j}) + \Omega_j(p_j)$ must be also a concave function of p_j [39].

properties 1.b and 2.b are due to the fact that utility function is a concave function of SINR and transmit power, respectively. Why concavity?

Before we answer this question, it is important to introduce the concept of *marginal utility*. Marginal utility is defined as the additional satisfaction, or additional amount of utility, gained from each extra unit of consumption (i.e. marginal utility = derivative of the utility w.r.t. consumption argument).

There are two ways for a user to increase its utility; first, by improving its SINR through transmitting more power. Second way is by reducing the cost(price) which is done by transmitting less power (i.e. getting more utility by being friendly with the network).

$$u_j(p_j, \gamma_j) = \underbrace{\ln(1 + \frac{\gamma_j}{\beta_j})}_{\text{improving utility through SINR}} + \underbrace{-\alpha_j p_j^2}_{\text{improving utility through cost reduction}} \quad (5.8)$$

Figure 5.4: SINR utility and its price in low and high power regimes

For our utility function defined in (5.6), the marginal utility of SINR is $\psi_j = \Psi'_j(p_j, \gamma_j^m) = \frac{\partial u_j(p_j, \gamma_j)}{\partial \gamma_j} = \frac{1}{\beta_j + \gamma_j^m}$, while the marginal utility of holding the power is $\omega_j = \Omega'_j(p_j) = \frac{\partial u_j(p_j, \gamma_j)}{\partial p_j} = -2\alpha_j p_j^m$. From property 1.b, the marginal utility of SINR decreases as SINR increases. Moreover, property 2.b tells us the marginal utility of holding power decreases as we hold more power (see figure 5.4). However, if more power is radiated, the price is going to increase significantly.

In this case, since the user is looking to maximize its utility, the concavity property is going to encourage him to stop radiating more power when it reaches the maximum utility. Interestingly, After reaching the maximum utility, the utility is going to decrease if the user increases its power simply because the marginal utility of SINR is going to diminish while the additional price is going to increase dramatically causing the utility function to deteriorate as it is depicted in figure 5.5. In other words, while increasing the power, the user will reach a point where marginal utility of SINR is less than marginal utility through cost reduction, forcing the user to stop pumping more power.

Figure 5.5: Utility function w.r.t power, when desired channel h and interference I are fixed.

In brief, the proposed utility function makes sure that the level of service each user gets worths the price it pays leading to a stable state⁶.

5.3.2 Game Equilibrium

With the system model described in previous section, it is preferred to find the optimal transmit power for each user j in the adjacent cells who are using subchannel m . the p_j should be most satisfying for user j as well as minimizing for interference in the network. This could be found through the following formulated optimization problem:

$$\underset{p_j \in \mathcal{P}_j}{\text{maximize}} \quad u_j(p_j, \mathbf{p}_{-j}), \quad (5.9)$$

Property (3) indicates that the utility function $u_j(p_j, \mathbf{p}_{-j})$ is a concave function

⁶Exactly like a stable economy where there is neither inflation nor deflation.

of the user's transmit power p_j . Then there exists an equilibrium as follow:

$$u_j(p_j, \mathbf{p}_{-j}) = \ln(1 + \frac{\gamma_j}{\beta_j}) - \alpha_j p_j^2, \quad \text{where } \gamma_j = \frac{p_j^m h_{j,j}^m}{I_j^m + \sigma_j^m}. \quad (5.10)$$

To find the power that maximizes the utility, take the derivative for both sides with respect to the transmit power p_j , then equalize it to zero.

$$\frac{\partial u_j}{\partial p_j} = \frac{1}{\beta_j + \gamma_j} \cdot \frac{h_{j,j}}{I_j + \sigma^2} - 2\alpha_j p_j = 0, \quad \text{for } j = 1, 2, \dots, J. \quad (5.11)$$

equivalently;

$$\frac{\partial u_j}{\partial p_j} = \frac{h_{j,j}}{\beta_j(\sum_{i \neq j} p_i h_{i,j} + \sigma^2) + h_{j,j} p_j} - 2\alpha_j p_j = 0, \quad (5.12)$$

where $i \in \mathcal{J}$, is an interferer for user j .

Since there are J users, then there are J equations with J unknown variables (i.e. p_j ; $j = 1, 2, \dots, J$). However, To solve this system, all parameters (i.e. $h_{j,j}, \beta_j, h_{i,j}, \alpha_j$ for all j) of the above system are required to be sent to a central entity for computation which could cause a huge burden on the network. Instead a distributed algorithm has been suggested in the next subsection.

5.3.3 Distributed Power Control

Let us rearrange equation (5.12):

$$\frac{h_{j,j}}{\beta_j(\sum_{i \neq j} p_i h_{i,j} + \sigma^2) + h_{j,j} p_j} = 2\alpha_j p_j \quad (5.13)$$

.

Now, for $j = 1, 2, \dots, k, \dots, J$, obviously the left hand side (LHS) of equation (5.13) is a monotonically decreasing function with respect to the transmit power p_j while the right hand side (RHS) is a monotonically increasing function of p_j . Therefore,

there is a unique intersection which is the equilibrium.

Moreover, Equation (5.11) can be rewritten as:

$$\frac{1}{\beta_j + \gamma_j} \cdot \frac{h_{j,j}}{I_j + \sigma^2} = 2\alpha_j p_j. \quad (5.14)$$

By assuming $\frac{h_{j,j}}{I_j + \sigma^2} = cf_j(\mathbf{p}_{-j})$, which is a known constant factor due to the assumed knowledge of $h_{j,j}$ and I_j , equation (5.14) can be written in terms of marginal utilities as follows:

$$\psi_j \cdot cf_j = -\omega_j. \quad (5.15)$$

It can be inferred from equation (5.15) that the maximum utility happens when the marginal price (or the negative of marginal utility of cost reduction) equals the marginal utility of SINR times a constant factor. This suggests that in general, when the marginal utility of price reduction is less than the product of marginal utility of SINR and cf_j , then increasing the power is a good option. On the other hand, if the marginal utility times cf_j is less than marginal price, user j should decrease its radiated power. As a result, the following algorithm is proposed in [38] for such game-based power control:

1. Set the following variables: initial transmit power vector $\mathbf{p}^0$, initial positive step size δ_j^0 for all $j \in \mathcal{J}$, number of iteration $t = 0$ and the accuracy parameter ϵ .
2. for every $j \in \mathcal{J}$, iterate: $p_j^{t+1} = p_j^t + \delta_j^t \cdot [cf_j^t \cdot \omega_j^t + \psi_j^t]$.
 - if the sign of $[cf_j^{t+1} \cdot \omega_j^{t+1} + \psi_j^{t+1}]$ is same as the sign of $[cf_j^t \cdot \omega_j^t + \psi_j^t]$, then double the step size of user j , i.e. $\delta_j^{t+1} = 2\delta_j^t$, otherwise divide it by 2. This feature is for accelerating the convergence.
3. if $|p_j^{t+1} - p_j^t| > \epsilon$, increment t and go to step 2. Otherwise stop.

Figure 5.6: Performance results w.r.t time: a) average total throughput, b) cell edge user throughput

It is important to note that this algorithm requires and assumes the system to have a radio allocation strategy within the cell for allocating each subchannel to the optimum user based on the normalized channel power $hn_{j,j}^7$ and I_j . Then, that user will be eligible to play the game for power allocation purpose.

5.4 Simulation Results

In this section, the effectiveness of game-based power control for interference management is shown through computer simulation. Two networks having different power transmitting schemes have been simulated. While the first network is equipped with the game-based power control, the other one is just transmitting with equal constant power; $p_{max} = \frac{p_{total}}{M}$. In addition to the system model and the associated assumptions mentioned in subsection 5.2, the simulation parameters are displayed in table 5.1.

Simulation program has been developed using Matlab software. The simulation

⁷ $hn_{j,j} = \frac{h_{j,j}}{d_{j,j}}$, to make the users as if they are at the same distance from the base station. This is done for fairness purpose.

Table 5.1: Simulation parameters

Parameters	Value
System Frequency	2 GHz
System Bandwidth	5 MHz
Subcarrier Bandwidth	15 KHz
Cell Radius	0.5 Km
Antenna Configuration	single input single output (SISO)
User Speed	Pedestrian
Power per subchannel	8.3 dBm
Noise Power Spectral Density	-174 dBm/Hz
Path loss Model	$128.1 + 35.2 \log(d)$; d in Km.
Shadow Fading Deviation	8 dB
Small Scale Fading	Rayleigh fading.
Scheduler	Opportunistic fair Scheduler
Target BER	10^{-6}
Number of Time Slots	500
Number of Replication	10
Link	UpLink

runs 10 independent replications. In each replication, the program starts off by creating generating randomly distributed users within cells. Then, large and small scales fading of the desired signals as well as the interference are generated in a form of channels realizations of 500 time slots. After that, the amount of interference on each subchannel at the base station of interest is calculated in the case where there is no interference control followed by calculating SINR. To find out the amount of interference on each subchannel at the base station of interest in the game-based system, a game should be first played to find out the transmit power for every user. The algorithm mentioned in the previous section is used to find the transmit power for every user within the cell of interest. Then, the optimum user among those users is selected based on the maximum utility function assuming these users are within the same distance from the base station (i.e. using their normalized h). Once the transmit power is decided, interference and hence SINR can be calculated easily. In both systems (with and without game-based scheme) SINR can be mapped into throughput using equation (2.11). On each subchannel, average throughput is taken over time and replications. Finally, the aggregate throughput (in bit/bit/Hz) is found by adding the average throughputs over frequency and dividing the result by the total bandwidth.

Figure (5.6) shows the performance results which have been observed for a user density of 25 user per a cell. As it is depicted, the proposed game-based power control scheme copes with the inter-cell interference and hence enhances the aggregate throughput as well as the cell edge user throughput. While both systems exploits multiuser diversity as well as employing adaptive modulation and coding technique, the gain in the proposed scheme is solely due to interference reduction of about 20 dB, as it is shown in figure (5.7).

Due to multiuser diversity, as the number of users increases in the network, the aggregate throughputs of both systems increase as well (figure 5.8). However, it is

Figure 5.7: Interference power experienced by BS of interest

obvious that the proposed scheme always outperforms the traditional constant power scheme. Furthermore, it is also noticeable that as the load increases as the gap between the two curves increases too which proves the robustness of the proposed game-based scheme.

Unlike the aggregate throughput, the cell edge user throughput in both systems decreases with the increase in the number of users as it is displayed in figure (5.9). This is due to the fact that the available radio resources are fixed resources which means each user's share of radio resources is going to decrease as the number of active users increases. Nevertheless, the border user in the system which is aided with the game-based power control scheme is enjoying on average 300 kbps higher data rate than the traditional system border user.

Furthermore, in the traditional constant power system, as the available power per one subchannel increases, the interference on that subchannel is going to increase as well which leads to an almost constant throughput with respect to the available power per subchannel as it is shown in figure (5.10). However, for a system aided with

Figure 5.8: Average aggregate throughput with respect to the number of users per a cell

Figure 5.9: Cell edge user throughput with respect to the number of users

Figure 5.10: Performance results w.r.t maximum power per one subchannel: a) average total throughput, b) cell edge user throughput

game-based power control scheme, while it benefits from any increase in the available power per subchannel, the game-based power control scheme is effectively working to reduce the resulting interference leading to an overall improvement. Accordingly, as the system adopts a higher number of subchannelization as the performance of the proposed scheme is going to decrease simply because the available power per one subchannel is going to decrease owing fixed available total power (see figure (5.11)).

5.5 Conclusions

A novel viable interference reduction scheme using game theory approach is presented in this chapter. The action of Each co-channel user located in adjacent cell is choosing the transmit power level, seeking to maximize its own utility while satisfying its QoS requirement. The utility function considered here makes sure that the level of service gotten by a user exactly worths the price it pays. Such strategy is absolutely leading to a very justified interference on the air which is on minimal levels. Based on simulation results, the game-based power control scheme outperforms the reference traditional

Figure 5.11: Performance results w.r.t number of subchannels: a) average total throughput, b) cell edge user throughput

constant-power scheme not only in terms of the higher aggregate throughput, but also in achieving significant enhancement for the throughput and fairness⁸ of cell edge user. It is noteworthy that both systems are exploiting similar multiuser diversity as well as employing similar adaptive transmission scheme. Therefore, the observed performance gain is the game-based power control scheme is definitely because of the achieved interference reduction.

This proposed scheme is based an economic model which study the power control for cellular system in such a way to minimize the interference in the network. According to this model, it might be worthy in future to consider controlling the number of users who are allowed to share the same subchannel (i.e. J). That is because J is a part of SINR equation and excluding the most interfere player could help reduce more interference power and provide even more enhancement to the total throughput.

⁸due to the implicit fairness feature of the game theory approach

Chapter 6

Conclusions and Future Work

Due to the orthogonality between spectral subchannels in OFDM system, intra-cell interference could be totally eliminated. Accordingly, the the main interference in OFDM system will be the inter-cell interference (ICI) which may significantly reduce the system performance and result in low level of quality of service. So, this thesis is concerning about finding solution for this issue, and accordingly it has proposed two different schemes. This chapter includes two parts. In the first part, we present an overview of the main conclusions drawn from the study of Inter-Cell Interference and schemes proposed in this thesis. The second part describes possible future contributions in ICI management and how this work can be continued.

6.1 Conclusions

This thesis was concerning about the inter-cell interference management in OFDM-based cellular systems seeking highest possible spectral efficiency to cope with the increasing demand for high data rate services. After introducing the required theory background and the related ICI works, two ICI management schemes have been proposed. The first scheme, which is introduced in chapter 4 is based on opportunistic beamforming. Since the users are experiencing location-dependent and time-varying

interference condition, this scheme exploits the knowledge of users' location along with the BSs' collaboration to avoid inter-cell interference. The advantages of this scheme are as follow: first, all radio resources can be available at every cell with full power (i.e. frequency reuse factor is 1). Second, the required information from users is only the overall SINR. Finally, it does not require inter-cell synchronization. Simulation and analytical results are presented to show the effectiveness of the proposed scheme. The improvement is a %20 increase in the throughput over the same system without the proposed scheme.

In the second proposed scheme, which is presented in chapter 5, game theory principles have been applied to the problem of inter-cell interference. The interferers located in adjacent cell and competing over a certain subchannel are considered the players of the game. A utility function has been designed to capture the rules of the game including minimal interference levels in the air. Simulation results showed the effectiveness of the proposed scheme comparing to the reference traditional constant-power scheme while both of them are exploiting multiuser diversity as well as link adaptation technique. It has been shown that the performance of the proposed scheme is superior in terms of both aggregate throughput as well as cell edge user throughput.

There are some differences between the two proposed schemes. The first scheme requires multiple antennas at the transmitter (i.e. base station) for beamforming purpose and hence it is more convenient for downlink only. On the other hand, single input single output (SISO) antenna configuration is sufficient for the second scheme and hence it could be suitable for downlink as well as uplink. Moreover, unlike the first scheme which needs to get the information of users' location, second scheme requires only the user's distance from base station. In addition, user equipment in the first scheme is considered oblivious and the whole interference avoidance task is done at the base station. However, the second scheme is working in a distributed fashion in which the user equipment is delegated to do the power allocation in such

a way to reduce the interference in the whole network.

6.2 Possible Future Contribution

In the opportunistic beamforming-based scheme, the proposed scheme is obviously done at the base station (by opportunistic scheduler and beamforming) while the UE is considered to be oblivious. Accordingly, since the possibility to perform inter-cell interference cancellation at the UE is considered irrespective of the interference mitigation scheme adopted at the base station [17], there is a good chance for this proposed scheme to be combined with the interference cancellation techniques at UE.

Moreover, combining the space diversity at the receiver with the proposed opportunistic beamforming-based scheme is another opportunity. If there are multiple antennas at the receiver (i.e. user hand set), it might be considered for diversity purposes to improve the SINR even more. So, the setup is that the multiple antennas at the transmitter are used for opportunistic beamforming purpose while the antennas at the receiver are exploited for diversity enhancement.

According to The second proposed scheme which is based on economic model, it might be worthy for a future work to examine controlling the number of users who are allowed to share the same subchannel (i.e. J). That is because J is a part of SINR equation and excluding the most interfere player might help reduce more interference power and provide even more enhancement to the total throughput.

In [23], authors found that a partial isolation scheme, which consists of using all the frequency band at each cell with a smart power allocation to mitigate interference, achieves higher cell throughput with an acceptable cell-edge rates comparing to the other coordination-based schemes. Since game theory-based power allocation scheme has been shown to be effective, it is worthy to examine the opportunity of combining the partial isolation coordination scheme with power allocation based on game theory.

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Appendix A

Matlab Code of the First Scheme Simulation

Here is the Matlab code for the simulation in chapter 4.

```
clear all

K=[2 4 8 16 64 128 150 180]; % Number of users

M=2; % # number of antennas

D=0.5;

std=8;

Pnd=3.9811e-021; % noise power density in watts/Hz.

Pn=Pnd * 15 * 10e3;

P=0.0333;

dB_P=10*log10(P);

Pri=5.9693e-021; % residual interference coming from other
nieghboring base station and far away base stations

B2=(Pn * 0.22124 * 1013.74)/2 * (P);

B=sqrt(B2);

us=10;

BER=10e-6;
```

```

subc=600;
for Rep=1:10
clear snr1;
clear snrM;
clear snrn;
h=ch_gainP(K(8),M,B,us,subc);
for i=1:8
if i==1
for k=1:K(i)
d(k)=sqrt(rand() * D^2); % distance of user k from base station
pathloss(k)= 128.1+35.2 * log10(d(k));
y(k)=std* randn(); %log-normal shadowing
end
else
for k=K(i-1)+1:K(i)
d(k)= sqrt(rand() * D^2);
pathloss(k)= 128.1+35.2 * log10(d(k));
y(k)=std* randn();
end
end
d(1)=0.45;
et=zeros(us,subc); % additional computational time.
clear r1 rL rM;
T1=ones(1,K(i));
T=ones(K(i),subc);
TM=ones(1,K(i));
TT=ones(K(i),subc);

```



```

LaT=ones(1,K(i));
LT=ones(K(i),subc);
for t=1:us
count1=0;
countM=0;
countL=0;
for c=1:subc
if i==1
for k=1:K(i) %this loop for calculating SNR
dB_snr1= dB_P-pathloss(k)+y(k)+h(k,t,c)-10*log10(Pn);
dB_snrn= dB_P-pathloss(k)+y(k)+h(k,t,c)-10*log10(Pn+Pri);
snr1(k,t,c)=10(dB_snr1/10); (snr for one cell system)
snrn(k,t,c)=10(dB_snrn/10);
%below we consider these users are in multicell system:
hex=rand();
if hex <= 1/36 %( two cells are beaming towards user k)
% now simulating the effects of two interfering beams on the snr
of the intended user.
% first geometry calculation:
b=2*D- d(k);
theta1 = (pi/3)*rand();
theta2 = (pi/3)-theta1;
a1=2*d(k)*sin(theta1/2);
a2=2*d(k)*sin(theta2/2);
cc1=b2 + a12 - 2 * a1 * b * cos((pi + theta1)/2);
cc2=b2 + a22 - 2 * a2 * b * cos((pi + theta2)/2);

```

```

    d_ibs1= sqrt(cc1); % distance of user k from interfering base
station(ibs) # 1

    d_ibs2= sqrt(cc2); % distance of user k from interfering base
station(ibs) # 2

    pathloss_ibs1 =10-(137.3+35.2*log10(d_ibs1))/10;
    pathloss_ibs2 =10-(137.3+35.2*log10(d_ibs2))/10;

    fading_ibs1=Interfer(K(i),M); %shadwing and small scale fadings of
first interfereing beam

    fading_ibs2=Interfer(K(i),M); %shadwing and small scale fadings of
second interfereing beam

    interfer_P1= P*pathloss_ibs1*fading_ibs1; % interference power from first bases
    interfer_P2= P*pathloss_ibs2*fading_ibs2; % interference power from second base
    dB_snrM= dB_P-pathloss(k)+y(k)+h(k,t,c)- (10*log10(Pn+interfer_P1+interfer_P2+P
    snrM(k,t,c)=10(dB_snrM/10);

    elseif hex<=1/3 % (only one cell is beaming towards user k)

    % now simulating the the only one cell beam

    % first geometry calculation:

    b=2*D- d(k);

    theta = (pi/3)*rand();

    a=2*d(k)*sin(theta/2);

    cc=b2 + a2 - 2 * a * b * cos((pi + theta)/2);

    d_ibs= sqrt(cc); % distance of user k from interfering base
station(ibs)

    pathloss_ibs =10-(137.3+35.2*log10(d_ibs))/10;

    fading_ibs=Interfer(K(i),M); % shadwing and small scale fadings

    interfer_P= P * pathloss_ibs * fading_ibs;

    dB_snrM= dB_P-pathloss(k)+y(k)+h(k,t,c)- (10*log10(Pn+interfer_P+Pri));

```

```

snrM(k,t,c)=10(dB_snrM/10);
else % ( no cell is beaming towards user k)
dB_snrM= dB_P-pathloss(k)+y(k)+h(k,t,c)- (10*log10(Pn+Pri));
snrM(k,t,c)=10(dB_snrM/10);
end %if end for the SNR calcualtin of Multiuser system
end % END of for loop:  for k=1:K(i)
else % in case i not = 1.
for k=K(i-1)+1:K(i) %(this loop for calculating SNR)
dB_snr1= dB_P-pathloss(k)+y(k)+h(k,t,c)-10*log10(Pn);
dB_snrn= dB_P-pathloss(k)+y(k)+h(k,t,c)-10*log10(Pn+Pri);
snr1(k,t,c)=10(dB_snr1/10);%(snr for one cell system)
snrn(k,t,c)=10(dB_snrn/10);
%below we consider if these users are in multicell system:
hex=rand();
if hex <= 1/36 %( two cells are beaming towards user k)
% now simulating the effects of two interfereing beams on the snr
of the intended user.
% first geometry calculation:
b=2*D- d(k);
theta1 = (pi/3)*rand();
theta2 = (pi/3)-theta1;
a1=2*d(k)*sin(theta1/2);
a2=2*d(k)*sin(theta2/2);
cc1=b2 + a12 - 2 * a1 * b * cos((pi + theta1)/2);
cc2=b2 + a22 - 2 * a2 * b * cos((pi + theta2)/2);
d_libs1= sqrt(cc1); % distance of user k from interfering base
station(ibs) # 1

```

```

    d_ibs2= sqrt(cc2); % distance of user k from interfering base
station(ibs) # 2
    pathloss_ibs1 =10-(137.3+35.2*log10(d_ibs1))/10;
    pathloss_ibs2 =10-(137.3+35.2*log10(d_ibs2))/10;
    fading_ibs1=Interfer(K(i),M); %shadwing and small scale fadings of
first interfereing beam
    fading_ibs2=Interfer(K(i),M); %shadwing and small scale fadings of
second interfereing beam
    interfer_P1= P * pathloss_ibs1 * fading_ibs1; %
interference power from first basestation
    interfer_P2= P * pathloss_ibs2 * fading_ibs2; %
interference power from second basestation
    dB_snrM= dB_P-pathloss(k)+y(k)+h(k,t,c)- (10*log10(Pn+interfer_P1+interfer_P2+P
snrM(k,t,c)=10(dB_snrM/10);
    elseif hex <= 1/3 % (only one cell is beaming towards user k)
% now simulating the case of only one cell beam
% first geometry calculation:
    b=2*D- d(k);
    theta = (pi/3)*rand();
    a=2*d(k)*sin(theta/2);
    cc=b2 + a2 - 2 * a * b * cos((pi + theta)/2);
    d_ibs= sqrt(cc); % distance of user k from interfering base
station(ibs)...
    pathloss_ibs =10-(137.3+35.2*log10(d_ibs))/10;
    fading_ibs=Interfer(K(i),M); % shadwing and small scale fadings
    interfer_P= P * pathloss_ibs * fading_ibs;
    dB_snrM= dB_P-pathloss(k)+y(k)+h(k,t,c)- (10*log10(Pn+interfer_P+Pri));

```

```

snrM(k,t,c)=10(dB_snrM/10);
else % ( no cell is beaming towards user k)
dB_snrM= dB_P-pathloss(k)+y(k)+h(k,t,c)- (10*log10(Pn+Pri));
snrM(k,t,c)=10(dB_snrM/10);
end %if end for the SNR calcualtin of Multiuser system
end % End of for loop:  for k=K(i-1)+1:K(i)
end % End of if condition:  if i==1.  %
ocell= Prop_fair(snr1(:,t,c),K(i),T1);
C1(t,c)=ocell(1,1);
b_user1=ocell(1,2);
T(:,c)=ocell(:,3);
if b_user1==1
r1(t,c)=C1(t,c);
count1=count1+1;
end
Lacell=Prop_fair(snrn(:,t,c),K(i),LaT);
LaC(t,c)=Lacell(1,1);
b_user=Lacell(1,2);
LT(:,c)=Lacell(:,3);
if (d(b_user)< 0.44)|| (hex > 1/3)
if b_user==1
rL(t,c)=LaC(t,c);
countL=countL+1;
end
else
hex2=hex;
nu=ceil(K(i)-K(i)/6)-1;

```

```

while (d(b_user)>= 0.44)&(hex2 <= 1/3)
et(t,c)= et(t,c) + 1e-3/4;
h2=ch_gainP_1c(nu,M,B,1);
clear nT;
clear nsnr
for j=1:nu %(this loop for calculating SNR)
dB_snr_af= dB_P-pathloss(j)+y(j)+h2(j)-10*log10(Pn+Pri);
nsnr(j)=10(dB_snr_af/10);%(snr for one cell system)
nT(j)=LaT(j);
end
nLacell= Prop_fair(nsnr',nu,nT);
LaC(t,c)=nLacell(1,1);
b_user=nLacell(1,2);
hex2=rand();
nu=ceil(nu-K(i)/6)-1;
if nu<=0
nu=1;
end
end
if b_user==1
rL(t,c)=LaC(t,c);
countL=countL+1;
end
end
Mcell= Prop_fair(snrM(:,t,c),K(i),TM);
CM(t,c)=Mcell(1,1);
b_userM=Mcell(1,2);

```

```

TT(:,c)=Mcell(:,3);
if b_userM==1
rM(t,c)=CM(t,c);
countM=countM+1;
end
end % this end is for : for c=1:subc
for k=1:K(i)
T1(k)=mean(T(k,:));
TM(k)=mean(TT(k,:));
LaT(k)=mean(LT(k,:));
end
end % END of Loop: for t=1:us
CL1(i,Rep)=mean(mean(C1));
CLM(i,Rep)=mean(mean(CM));
ALaC(i,Rep)=mean(mean(LaC))*(us * 1e-3-sum(eet))/(us * 1e-3);
if (i==8)
cdfplot(mean(C1'))
hold on
cdfplot(mean(CM'))
cdfplot(mean(LaC'))
hold off
pause
end
end
end
CL1R=mean(CL1');
CLMR=mean(CLM');

```

```
ALaCR=mean(ALaC');  
plot(K,CL1R)  
hold on  
plot(K,ALaCR,'k')  
plot(K,CLMR,'r')  
hold off
```


Appendix B

Matlab Code of the Second Scheme Simulation

Here is the Matlab code for the simulation in chapter 5.

```
clear all

ID=1000;

BS=[0 0; ID*cos(pi/6) -ID*sin(pi/6); ID*cos(pi/6) ID*sin(pi/6); 0
ID; -ID*cos(pi/6) ID*sin(pi/6); -ID*cos(pi/6) -ID*sin(pi/6); 0 -ID];

N=7; %number of BS. maximum is 7 cells

K=25; %number of users per a cell.

M=200; %number of spectral of dm subchannel

T=500; % number of time slots

ps=0.1; %intial power.

SER=1e-6;

cf=0.92e-14; % correction factor for the interference that come
from 2nd 3rd tiers.

q=-(log(5*SER))/1.5;

e=0.005; % the required accuracy of the game.

std=8;
```

```

%Starting the Code

for b=1:N
    B(b,:)=BS(b,:);
end

for Rep=1:10
    userloc=cellular(ID,K,N,B);
    for i=1:N
        d(:,i)=sqrt((userloc(:,1,1)-B(i,1)).2 + (userloc(:,2,1) - B(i,2)).2);
    end
    d(1,1)=470;
    pathloss= 128.1+35.2*log10(d/1000);
    for t=1:T % t here for time slot.
        shad=(10(std*randn(1,N,K)/10));
        R=zeros(1,K);
        Rg=zeros(1,K);
        Rge=zeros(1,K);
        for m=1:M % for every spectral subchannel
            Intrf=floor(1+K*rand(1,N-1));
            G =L.F(K,N,B,pathloss,shad,userloc,Intrf);
            for k=1:K
                clear p I
                delta=0.03*ones(1,N);
                H=G(:, :, k);
                h=diag(H); %column vector
                h=h'; %row vector
                n_h(k)=10(pathloss(k,1)/10) * h(1); %n_h is a normalized h
                Hd=H-H.*eye(N);
            end
        end
    end
end

```

```

i=1; % i here is for iteration #.
p(i,:)=ps*ones(1,N); % intial power for each user.
for n=1:N
Hd(n,1)=1/2 *Hd(n,1); % correction factor for interference power
end
pn= 5.5e-17; % noise power
I(i,:)=2*p(i,:)*Hd+pn; % row vector
Int(k)=I(i,1);
snr(k,:)= (p(i,:).*h)./(I(i,:)+cf);
snr_0(k)= snr(k,1);
snr_Ou(k)=(p(i,1).*n_h(k))./(I(i,1)+cf);
% Gaming Algorithm
den=ps*(ps* h +I(i,:));
L=10*h./den;
X(i,:)= h./I(i,:).*(-3*L.*p(i,:).^2) + I(i,:)./(I(i,:) + h. * p(i,:
));% row vector
l=1;
while (l)
p(i+1,:)=p(i,:)+delta.*X(i,:);
for j=1:N % j here is for interfering users at different BS
if p(i+1,j)<0
p(i+1,j)=0;
elseif p(i+1,j)>ps
p(i+1,j)=0;
end
end
end
I(i+1,:)=2*p(i+1,:)*Hd+pn;

```

```

X(i+1,:)=h./I(i+1,:).*(-3*L.*p(i+1,:).^2)+I(i+1,:)/(I(i+1,:)+h.*
p(i+1,:));
for j=1:N
if X(i,j)*X(i+1,j)>0
delta(j)=2*delta(j);
else
delta(j)=delta(j)/2;
end
end
if abs(p(i+1,:)-p(i,:))>e
i=i+1;
else
l=0; % to end the while loop and stop the algorithm
end
end % To end while loop.
snrg(k,:)=(p(i+1,:).*h)./I(i+1,:);
snrg_0(k)=snrg(k,1);
Tg_0u(k)=log2(1+(p(i+1,1).*n_h(k))./pn) - L(1)*p(i+1,1)^2;
Intg(k)=I(i+1,1);
Tt(k)=mean(log2(1+snr(k,:)));% average th. for interfering users
without game.

Ttg(k)=mean(log2(1+snrg(k,:)));% average th. for interfereing
users with game.

end % To end K for loop

%scheduling within the cell of interest
maxu_0=max(log2(1+snr_0u)); % th. in the cell of interest without game.
maxug_0=max(Tg_0u);% th. in the cell of interst with game.

```

```

indx = find((log2(1+snr_0u))==maxu_0);
indxg= find((Tg_0u)==maxug_0);
T_0(t,m)=log2(1+snr_0(indx)/q); % th. in the cell of interest without game.
Tg_0(t,m)=log2(1+snrg_0(indxg)/q); % th. in the cell of interest with game.
Ti(t,m)=Tt(indx);
Tig(t,m)=Ttg(indxg);
% User's rate if indx==1
R(indx)= R(indx)+ 15 * T_0(t,m);
end
if indxg(1)==1
Rg(1)= Rg(1)+ 15 * Tg_0(t,m);
end
I0(t,m)=Int(indx);
Ig0(t,m)=Intg(indxg(1)); %End scheduling within the cell of interest
end % To end M for loop
Th(Rep,t)=mean(Ti(t,:));
Thg(Rep,t)=mean(Tig(t,:));
Th_0(Rep,t)=mean(T_0(t,:));
Thg_0(Rep,t)=mean(Tg_0(t,:));
Ce_R(Rep,t)=R(1);
Ce_Rg(Rep,t)=Rg(1);
int(Rep,t)=mean(I0(t,:));
intg(Rep,t)=mean(Ig0(t,:));
end % To end T for loop
end % to end Rep for loop
t=1:T;
plot(t,mean(Th),'r')

```

```
hold on
plot(t,mean(Thg),'b')
hold off

pause

plot(t,mean(Th_0),'r')
hold on
plot(t,mean(Thg_0),'b')
hold off

pause

plot(t,mean(Ce_R),'r')
hold on
plot(t,mean(Ce_Rg),'b')
hold off

pause

plot(t,10*log10(mean(int)),'r')
hold on
plot(t,10*log10(mean(intg)),'b')
hold off
```