Inter-Cell Interference Mitigation in LTE-Advanced Heterogeneous Mobile Networks

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List of Abbreviations

3GPP	3rd Generation Partnership Project
AAA	Authorisation, Authentication, and Accounting
ABS	Almost Blank Subframes
CA	Carrier Aggregation
CC	Component Carrier
CCH	Control Channel
CDMA	Code Division Multiple Access
CE	Cell Expanded
CoMP	Coordinated Multipoint
CRE	Cell Range Expansion
CRS	Common Reference Signal
CS	Circuit-Switched
CSG	Closed Subscriber Group
CSI	Channel State Information
CSO	Cell-Specific Offset
DCS	Dynamic Cell Selection
DL	Downlink
DPS	Dynamic Point Selection
DSL	Digital Subscriber Line
DwPTS	Downlink Pilot Timeslot
eNB	enhanced Node B
EPC	Evolved Packet Core
EPS	Evolved Packet System

FDD	Frequency Division Duplex
FD-ICIC	Frequency-Domain ICIC
FDMA	Frequency Division Multiple Access
FeICIC	Further enhanced ICIC
FFR	Fractional Frequency Reuse
GP	Guard Period
GPRS	General Packet Radio Services
GSM	Global System for Mobile communications
HARQ	Hybrid Automatic Repeat Request
HetNets	Heterogeneous Networks
HO	Handover
HOF	Handover Failure
HPNs	High Power Nodes
HSG	Hybrid Subscriber Group
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
ICI	Inter-cell Interference
ICIC	Inter-Cell Interference Coordination
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
IP	Internet Protocol
ITU	International Telecommunication Union
JP	Joint Processing
JT	Joint Transmission

LA	Link Adaptation
LP-ABS	Low-Power ABS
LPCs	Low Power Cells
LTE	Long Term Evolution
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIMO	Multi-Input Multi-Output
MME	Mobility Management Entity
MRs	Measurement Reports
NAS	Non-Access Stratum
NCL	Neighbouring Cell List
NGMN	Next Generation Mobile Networks
OAM	Operation and Maintenance
OFDM	Orthogonal Frequency Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSG	Open Subscriber Group
PCC	Primary Component Carrier
PCI	Physical Cell Identity
PCRF	Policy and Charging Rules Function
PDCP	Packet Data Convergence Protocol
PD-ICIC	Power-Domain ICIC
PDN	Packet Data Network
PRB	Physical Resource Block
PS	Packet-switched

QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RA	Resource Allocation
RAT	Radio Access Technology
RE	Resource Element
RLC	Radio Link Control
RNC	Radio Network Controller
RPS	Reduced Power Subframes
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resources Management
RSRP	Reference Signal Received Power
RSS	Received Signal Strength
SCC	Secondary Component Carrier
SGSN	GPRS Support Node
SINR	Signal-to Interference plus Noise Ratio
TDD	Time Division Duplex
TD-ICIC	Time Domain-ICIC
TDMA	Time Division Multiple Access
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UpPTS	Uplink Pilot Timeslot
UTRAN	UMTS Terrestrial Radio Access Network

Abstract

Heterogeneous Networks are one of the most effective solutions for enhancing the network performance of mobile systems, by deploying small cells within the coverage of the ordinary Macro cells. The goals of deploying such networks are to offload data from the possibly congested Macro cells towards the small cells and to achieve enhancements for outdoor/ indoor coverage in a cost-effective way. Moreover, heterogeneous networks aim to maximise the system capacity and to provide lower interference by reducing the distance between the transmitter and the receiver.

However, inter-cell interference is a major technical challenge in heterogeneous networks, which mainly affects system performance and may cause a significant degradation in network throughput (especially for the edge users) in co-channel deployment. So, to overcome the aforementioned problem, both researchers and telecommunication operators are required to develop effective approaches that adapt different mobile system scenarios.

The research study presented in this thesis provides a novel interference mitigation scheme, based on power control and time-domain inter-cell interference coordination to improve cell and users' throughputs. In addition, powerful scheduling algorithms have been developed and optimised to adapt the proposed scheme for both macro and small cells. It is responsible for the optimum resource allocation to minimise the inter-cell interference to the minimum ranges.

The focus of this work is for downlink inter-cell interference in Long Term Evolution (LTE-Advanced) mobile networks, as an example of OFDMA (orthogonal frequency division multiple access)-based networks. More attention is paid to the Pico cell as an important cell type in heterogeneous deployment, due to the direct backhauling with the macro cell to coordinate the resource allocation among cells tightly and efficiently.

The intensive simulations and results analyses show that the proposed scheme demonstrates better performance with less complexity in terms of user and cell throughputs, and spectral efficiency, as compared with the previously employed scheme

Chapter One: Thesis Introduction

Over the last decades, wireless communications have grown rapidly, and the number of mobile users and their demands have increased exponentially. Accordingly, network planning and optimisation of the current networks became a vital matter for both researchers and mobile operators. The early mobile systems were thrived to satisfy the customers' needs of voice services. Since that time, frequency planning for these systems and site acquisition were one of the most concerns by the Radio Frequency (RF) engineers. Therefore, industries and mobile operators invested significant efforts in frequency planning and the efficient radio spectrum utilisation. Also, more attention has been paid to the impact of electronic interference, which has a direct impact on mobile network performance. With the increasing demands for mobile data (as shown in Figure 1-1) and the rapid spread of the smart applications on the current mobile devices, the limited spectrum became one of the main constraints in the mobile networks development and supporting higher data rates more challenging.

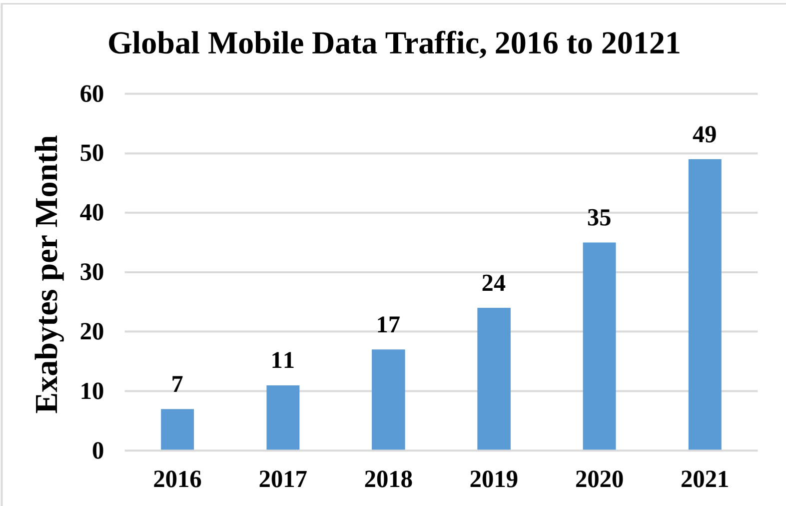


Figure 1-1: Predicted Data demands per month over the next years [1]

As a result, it was essential to move from spectrum efficiency towards the network efficiency. One of the effective methods in this field is the network densification, where the same allocated spectrum can be reused in smaller regions to achieve higher spectrum utilisation. However, inter-cell interference management turns into a more challenging issue, especially in mobile networks with heterogeneous deployment (HetNets).

1.1 Research Problem

Despite the significant benefits of deploying LTE-Advanced Heterogeneous Networks (HetNets) to increase the network capacity or to extend the coverage in a cost-effective way, Inter-cell interference (ICI) is one of the largest challenges in such networks when utilising co-channel deployment. ICI in such deployments has a negative impact on both user and cell throughputs of all cells in the network. Moreover, traffic balance is directly affected by such interference. Figure 1-2 illustrates the problem of ICI in LTE-A HetNets, where the conventional Macro cell is overlaid by Low-Power Cells (LPCs) to increase the network capacity and to offload more mobile users from the potential congested Macro cell towards these LPCs.

The conventional cell selection in LTE-A is based on the maximum Reference Signal Received Power (RSRP) by the User Equipment (UE) from the surrounding cells. However, due to the transmit power disparity in cells of different classes in the HetNets, most UEs tends to select the Macro cell as their serving cell as a result of high transmit power, leaving the Pico cell underutilised. In the same time, theses Macro UEs in the vicinity of the Pico cells can cause a severe Up Link (UL) interference problem towards the overlaid Pico cells.

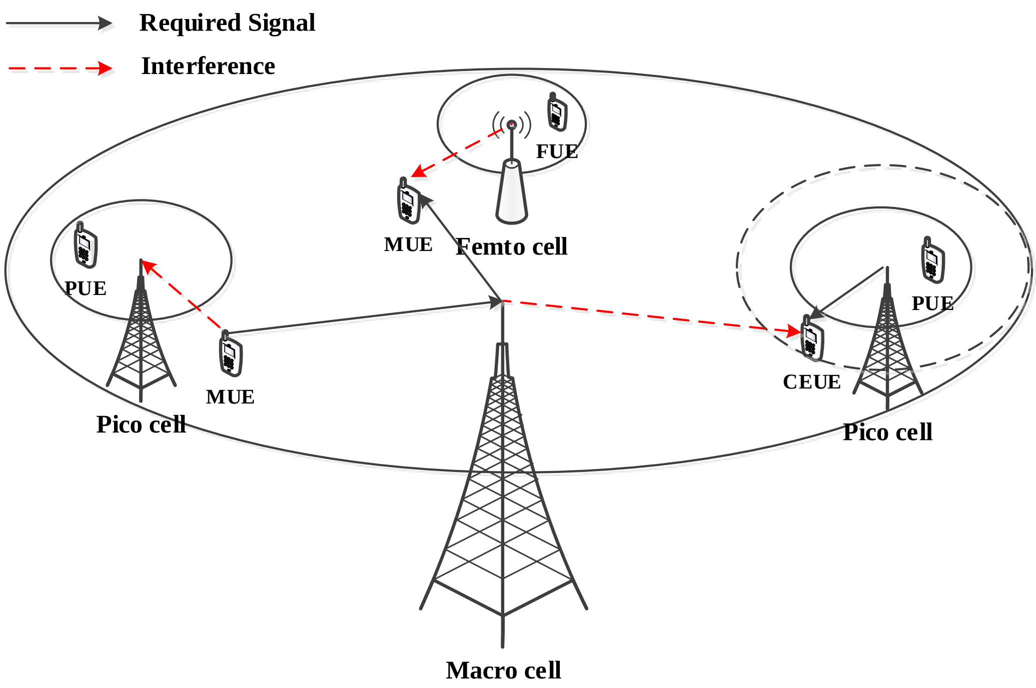


Figure 1-2: ICI problem in LTE-A HetNets

Cell Range Expansion (CRE) concept was suggested to solve the problem of UL interference and to achieve load balance in such types of LTE-A networks. It can be achieved by adding a positive Cell-Specific Offset (CSO) to the RSRP of Pico cells to increase their coverage area and offload more users toward these cells. However, the UEs in Cell Expanded (CE) region suffer from weak SINR and Downlink (DL) interference coming from the Macro cell as a result of biased RSRP and the high transmit power of the Macro cell.

Time-Domain Inter-Cell Interference Coordination (TD-ICIC) schemes were proposed by 3GPP in LTE release 10 onward, to mitigate the severe interference results from the co-channel deployment of LTE-A HetNets. These schemes aim to limit Macro cell transmit power activity in a certain amount of subframes (or resource blocks) to be usable by Pico UEs suffering from high DL interference.

1.2 Research Motivation

The radio frequency spectrum is a finite and a scarce resource, which should be optimally utilised when it is being allocated for a certain mobile system. Moreover, the high cost of spectrum allocation is one of the significant challenges for mobile operators.

The ever growing demands for mobile data and the spread of smart devices entails overriding the spectrum efficiency limitations by moving towards the network efficiency. The latter technique mainly utilises network densification to achieve higher performance in mobile networks by deploying small cells for more spectrum reuse and the lower distance between the transmitter and the receiver which results in less path loss. HetNets are one of the essential steps to achieve network densification, by overlaying the traditional Macro cells with LPCs to improve network capacity while keeping the backwards compatibility for old mobile users. However, ICI mitigation is a vital issue for co-channel LTE-A HetNets, which significantly affects the capacity of the network. Most TD-ICIC schemes have a permanent trade-off between the interference mitigation and the available radio resources for some cells, which has a negative impact on the overall network performance.

1.3 Aim and Objectives

This research project aims to improve the performance of LTE-A HetNets (in terms of user and cell throughputs) by mitigating the downlink ICI while achieving a balance between the performance of cell-edge users of the Pico cell and that of the Macro cell UEs. This aim can be fulfilled by developing an efficient TD-ICIC scheme with powerful user priority scheduling algorithms for both Macro and Pico cells, to ensure the optimum resource sharing among all cells in the network. In this way, the performance of the Macro cell will be optimised while keeping the performance of Pico cells intact, which in turn results in a higher network performance.

The principal objectives of this thesis can be summarised as follows:

- Study the impact of the interference on the network capacity of LTE-A networks and explore the current inter-cell interference coordination schemes in LTE-A HetNets.
- Survey the up to date ICIC schemes based on the literature, and investigate the effects of the Almost Blank Subframes (ABS) and the Reduced-Power Subframes (RPS) schemes on both radio resources accessibility and the user protection.
- Design a joint configuration utilising both ABS and RPS in the same scheme, to achieve a balance between the performance of cell-edge users of the LPC and that of the Macro cell UEs.
- Develop powerful user priority scheduling algorithms for both Macro and Pico cells, to provide higher scheduling priorities for all vulnerable users (victim users) in the LTE-A HetNets.
- Design a system model and implement the proposed scheme using DL system-level simulation, taking into consideration all the required modelling calculations and other simulation assumptions.
- Test and evaluate the proposed scheme and the user priority scheduling algorithms according to predefined performance metrics.
- Assess the performance of the final version of this scheme with other TD-ICIC schemes (ABS and RPS) to test the improvement in network performance against the other schemes.

1.4 Thesis Contribution

This thesis investigates the interference mitigation in LTE-A HetNets and contributes to mitigating the inter-cell interference in Macro cell- Pico cell scenarios. Such mitigation provides increased downlink network performance in terms of user and cell throughputs, which results in total network improvements.

In this thesis, TD-ICIC scheme has been chosen for further improvements as a result of its higher spectral utilisation by sharing the whole available bandwidth between the Macro cell and the LPCs, and the capability of employing higher CRE values which in some cases are necessary to achieve proper load balance in the HetNets. A joint configuration utilising both ABS and RPS in the same scheme has been proposed to achieve a balance between the performance of cell-edge users of the LPC and that of the Macro cell UEs. In this way, the performance of the Macro cell has been optimised while keeping the performance of Pico cells intact, which in turn results in a higher network performance.

1.5 Research Methodology

This research project adopts a research methodology that mainly relies on evaluation and improvement of the proposed scheme using Vienna Simulator. This downlink system-level simulator, which is built on MATLAB, has been modified to support the proposed solution. Feedback from the supervisor and the examiners at meetings, assessments was also working as a guideline during the long journey of the PhD research.

The following research methodology has been adopted in the research program, where the main steps are illustrated in Figure 1-3:

- ***Literature review on Heterogeneous deployment of LTE-Advanced (HetNets)***

  It was the first step of the research program since started the PhD research. After the intensive discussions with the supervisor about the recent mobile technologies and their limitations, we have chosen the heterogeneous deployment of LTE-Advanced as promising systems to satisfy the demands of the next generations of mobile networks. The supervisor created a roadmap for the research and gave correct guides to choose a critical problem and a novel idea to solve it. Wide literature review on LTE-Advanced and its heterogeneous deployment have been made, to identify the recently employed technologies and their limitations. In the same time, up-to date researches have been investigated.

- ***Identifying the Inter-Cell Interference (ICI) in LTE-A HetNet as a research problem***

  Based on the studied literature, ICI has been identified as a research problem, and the negative impact of ICI on network capacity and the spectrum utilisation have been taken into consideration.

  In this stage of the investigation, the problem of inter-cell interference in LTE-A heterogeneous deployment has been recognised as a major issue which severely affects the performance of the network and limits the benefits of deploying the low-power cells within the coverage of the conventional macro cells.

- ***Studying and analysing the problem, finding the recent solutions***

  To find a novel solution to the research problem, an extensive study was necessary on the state-of art solutions, analysing their advantages and their limitations. From the literature, several ICIC schemes were found to solve the problem of interference in co-channel HetNet, where two of them are working jointly with CRE to provide inter-cell interference coordination while balancing the load among all cells.

- ***Proposing a Joint scheme for Inter-Cell Interference Coordination (ICIC)***

  Several solutions have been suggested by 3GPP and developed by researchers to mitigate ICI in LTE-A HetNet. However, most of these solutions still have limitations due to the trade-off in performance between the macro cells and the low-power cells.

As a result, a joint scheme of using both Almost Blank Subframes (ABS) and Reduced Power Subframes (RPS) has been proposed achieve better results. Developing powerful scheduling algorithms in both macro cell and low-power cell is essential to achieve the aim of this interference mitigation scheme.

- ***Implementing the proposed scheme using system-level simulation***

  The implementation of the proposed solution includes system modelling and extensive simulations to get the implementation results. All the system assumptions and the mathematical equations required for the system model has been determined, taking into account the interference from the overlaid macro cell and the neighbour macro cells into account. Unlike some researches in the literature [2], [3], the interference coming from the adjacent low-power cell has also been taken into considerations.

- ***Results analysis, evaluation and comparison with the existing solutions***

  Simulation results are significant to analyse the performance of the system under this proposed solution, and taking the necessary measurements which are vital to evaluate the performance of the system. Subsequently, validation is essential to examine the applicability of the proposed scheme in practical life. Moreover, comparing these results with other schemes of the literature is crucial to evaluate the improvement against the existing ICI schemes.

- ***Writing up the PhD thesis***

  It is the final step of our research project after finalising and validating our scheme. It includes writing up all the required theories from the background to the standards then presenting the proposed scheme's results with all analyses and discussions. Moreover, all conclusions and the expected future work are submitted to the end of this thesis.

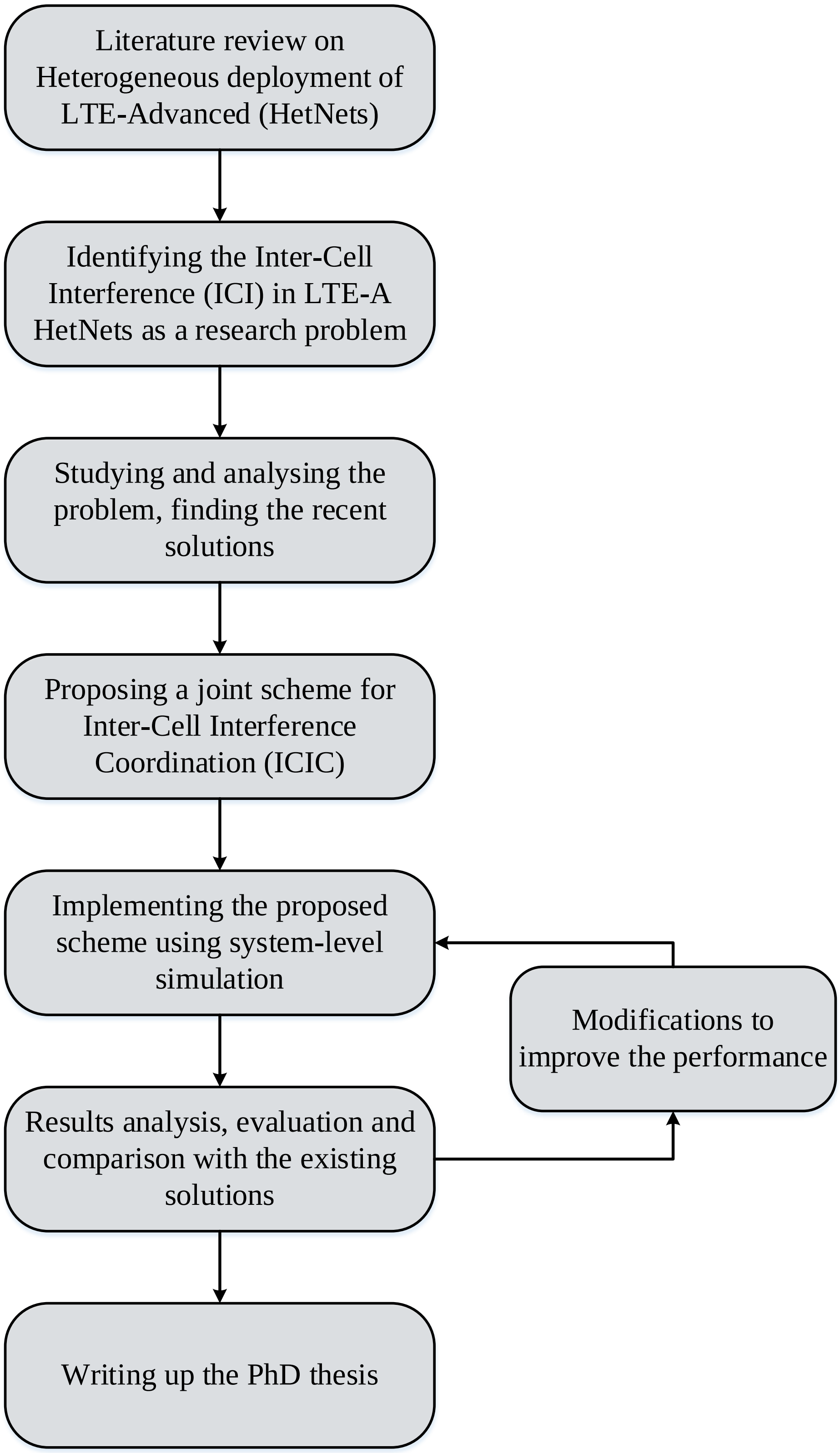


Figure 1-3: Research Methodology

1.6 Thesis Structure

This thesis is organised into six chapters. The ***current chapter*** represents a brief introduction to the PhD research project, which includes the definition of the research problem and the motivation of choosing to tackle such a problem. In addition, the aim and objectives of this research have been outlined. Moreover, the methodology followed in this research has been charted, and all its steps are explained.

Chapter two gives a general overview of the LTE-Advanced network as an example of OFDMA mobile systems. It describes the network architecture and its related elements in both homogeneous and heterogeneous deployments. Furthermore, the radio frame structure and the physical resource block have been explained thoroughly as basic elements in resource allocation.

As a research problem, inter-cell interference (ICI) has been discussed in ***chapter three***, reviewing the spectrum assignments in LTE-A and the main frequency reuse techniques used in homogeneous deployment. The second part of this chapter attempted to classify the ICI mitigation based on the studied literature, describing various mitigation schemes and concentrating on the time-domain inter-cell interference coordination scheme as a result of its higher spectral utilisation and the capability of employing higher CRE values which in some cases are necessary to achieve the proper load balance in the HetNets. This scheme has been chosen for further improvements in this thesis. Therefore, some related works in the literature have been studied and further investigated to give a big picture for the proposed solution in the next chapter.

Chapter four introduces the proposed joint scheme for inter-cell interference mitigation in LTE-Advanced HetNets. Moreover, the scheme design and the required scheduling algorithms for optimum scheme utilisation have been discussed thoroughly for both macro and Pico cells. The next section of this chapter depicts the system model and all simulation assumptions adopted in the system-level simulation. Furthermore, all the necessary equations for network modelling has been specified according to the standards.

All simulation results of the proposed scheme and their findings are shown in ***chapter five***. These results are based on the performance metrics defined in the previous chapter. They also include the evaluation of the scheduling algorithms and validating the proposed scheme by comparing it with other works in the literature to highlight the percentage of network improvements according to the aforementioned metrics. The last section of this chapter depicts a deep discussion of all simulation results, coming up with a clear picture for the next chapter.

Finally, the summary of thesis contribution and the outcomes of the research proposal have been outlined in ***chapter six***. Furthermore, this chapter determines the limitations of this research and creates recommendations for the future work.

Chapter Two: Background

2.1 Introduction

Since the first version of mobile communications and the concept of cells in 1947 by Bell Labs of USA, the requirements for mobile services and associated applications have grown rapidly to meet the ever-growing demands for more capacity, efficient radio spectrum use, and higher mobility support.

Packet data using mobile systems started commercially in the mid 1990's, where General Packet Radio Services (GPRS) was introduced in the Global System for Mobile communications (GSM) [4] and in other technologies like PDC standard in Japan. Since that time, the demands for mobile data has continued to rise exponentially, especially following the advancements in mobile terminal technologies. As a result, both researchers and commercial operators have an interest in conducting studies to develop the modern mobile networks to conform to the state-of art mobile data services, taking into account the potential constraints and future demands. So far, Long Term Evolution (LTE) mobile network in all of its releases is considered the most promising system as a part of OFDM technology and can satisfy the ongoing requirements for more advanced mobile data services. The subsequent sections in this chapter are going to outline a comprehensive background on the LTE-Advanced mobile network and its architecture as far as is required for this thesis.

2.2 Long Term Evolution-Advanced (LTE-A)

The ongoing growth of traffic and the future applications required by mobile users has led the 3rd Generation Partnership Project (3GPP) to develop a new Radio-Access Technology (RAT). Such new RAT is necessary to support the increasing demands for high-speed applications and advanced multimedia services to all mobile users with higher data rates, low latency, high mobility, and greater spectral efficiency (about 2-3 times that in HSPA) [5].

The performance of such (packet optimised systems) has been optimised by employing enhanced air-interface protocols, and presenting a Multi-Input Multi-Output antenna system (MIMO), which provides a better quality of received signals and reduces the co-channel interference, and presents Inter-Cell Interference (ICI) aware techniques.

LTE-A can fulfil Link Adaptation, where the Modulation and Coding Scheme (MCS) can be changed sensibly per user or frame, according to the channel conditions. In addition, signal to Interference plus Noise Ratio (SINR) and Hybrid Automatic Repeat ReQuest (HARQ) function can be utilised by the adaptation algorithm to maximise the throughput in the time-varying channel.

Unlike the previous mobile systems, two-dimensional resource scheduling (in frequency and time) can be employed in LTE, which enables multi-users' transmissions in one time slot.

LTE-Advanced comes to meet the requirements of the 4th Generation by ITU IMT-Advanced. It provides more enhanced services in the case of mobility and seamless handover, keeping the interoperability with traditional GSM and CDMA systems. LTE-Advanced also utilises a layered OFDMA to enhance the whole system performance and increase the spectrum efficiency.

Moreover, the new technique of Carrier Aggregation (CA) is also used with the layered OFDMA to combine the Component Carriers (CC's) on the physical layer to provide backwards compatibility with the LTE Release 8 users together with the LTE-A users.

2.2.1 LTE-A Requirements

3GPP has set the requirements for the new LTE system to adapt the modern demands of the Radio Access Technology (RAT). The most significant requirements are outlined as follows [6]:

- Scalable architecture with simplified implementation
- Seamless mobility, ensuring the Quality of Service (QoS) for higher speeds
- Reduced delays in both transmission and connection procedures
- Increased user data rates, taking into consideration the cell-edge throughputs
- Enhanced Inter-Cell Interference (ICI) mitigation schemes
- Reduced cost per bit, with a guaranteed spectral efficiency
- Flexible and efficient spectrum usage in all allocated bands
- Optimal power consumption, especially for UEs

Furthermore, Next Generation Mobile Networks (NGMN) alliance of network operators [7] serves as an additional guide for development and assessment for LTE design. Network operators' requirements support the development of the LTE next phase according to IMT-Advanced requirements of 3GPP.

2.2.2 Multiple Access

Multiple access refers to the way of accessing the available radio resources by the users of the same mobile network. The most basic types of multiple access methods are the Frequency Division Multiple Access (FDMA) and the Time Division Multiple Access (TDMA), which performs the multiple access of mobile users in frequency and time domains respectively. However, the recent trend of multiple access technique concentrates on Orthogonal Frequency Division Multiple Access (OFDMA), which offers mutual benefits of both FDMA and TDMA for optimum spectrum utilisation in the next generation of mobile networks [8].

OFDMA is based on OFDM concept [9], which divides the available spectrum into multiple orthogonal (overlapped) subcarriers (as shown in Figure 2-1) using Discrete Fourier Transform (DFT) and Fast Fourier Transform (FFT), to be used widely in highly frequency-time variant wireless radio channels [8].

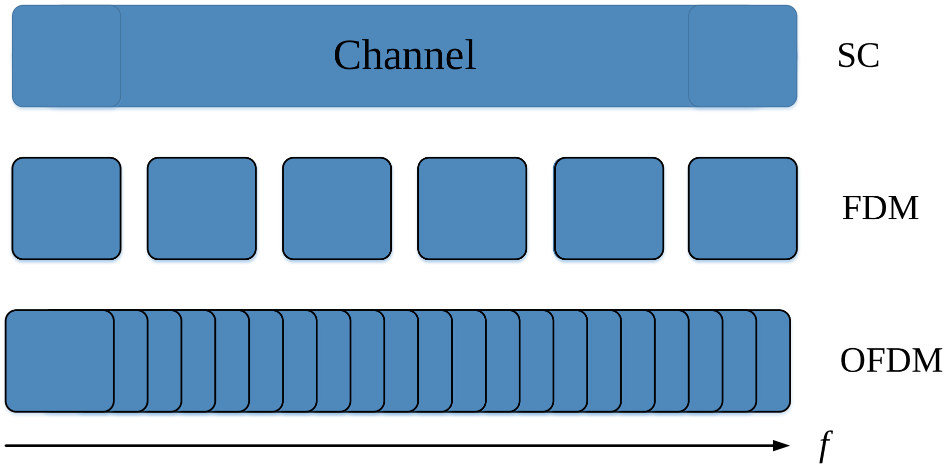


Figure 2-1: A graphical illustration of OFDM scheme

One of the most OFDM distinct features is the flexible and independent operation of the available spectrum (i.e. offering different channel bandwidths with low complexity at receiver side). Therefore, OFDMA has become the basic multiple access technique for LTE-A and the next generations [10].

2.2.3 LTE-A Architecture

LTE-A architecture is designed to introduce a packet-switched (PS) network, which supports all kinds of services including a voice in an easy way, with a minimum latency (as RNC is not included in the data path), seamless mobility and better Quality of Service (QoS).

Therefore, all the services that were traditionally Circuit Switched (CS) are now handled by IP Multimedia Subsystem (IMS) network in LTE.

The LTE architecture, which is called Evolved Packet System (EPS), comprises two parts: the radio part (E-UTRAN), and the network part (EPC) [11], [12].

3GPP designed the Evolved Packet Core (EPC) as a new packet core to support the E-UTRAN (shown in Figure 2-2) with a minimum number of network elements, and allow the connections to other networks easily and in a more functional manner. Moreover, an additional layer of security was already added to LTE-A system, Non-Access Stratum (NAS), to improve the system security between 3GPP and non-3GPP networks; it is also responsible for data ciphering.

Other control entities are included in EPC, such as Home Subscriber Server (HSS), and Authorization, Authentication, and Accounting (AAA) server, where HSS is responsible for all the subscribers' information, while the AAA is responsible for user activity tracking, and managing QoS, charging policies through Policy and Charging Rules Function (PCRF).

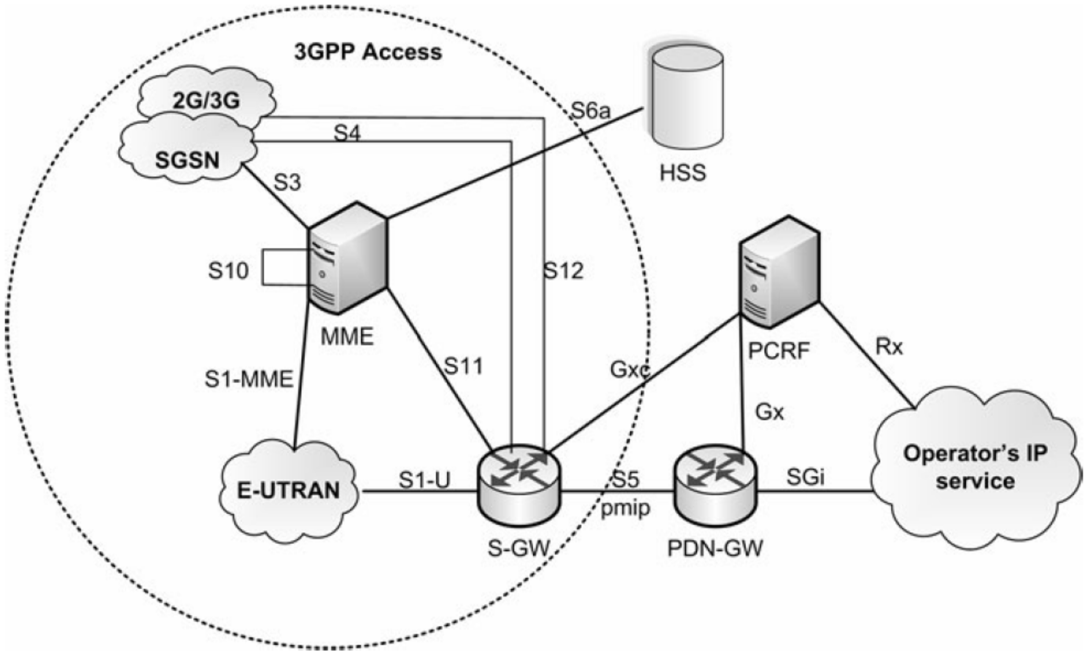


Figure 2-2: LTE-A Reference Model [13]

2.2.4 Network Elements

The distinct architecture of LTE-A introduces new control-plane elements to the EPC:

- **Mobility Management Entity (MME)**

A new control-plane Mobility Management Entity (MME) is responsible for new protocol implementation in LTE-A. MME communicates with the HSS for retrieving subscriber information, and with the serving gateway to establish and release the EPS bearers. It communicates with eNB over the S1 interface and supports mobility between 3GPP access networks via an S3 interface with the Serving GPRS Support Node (SGSN) [14].

- **Serving Gateway (S-GW)**

The main function of the S-GW is packet routing in the LTE-A network and packet buffering when paging a UE. It also acts as a local mobility anchor in case of inter-eNB Handover (HO). Furthermore, it communicates with the PCRF entity for charging control and lawful interception.

- **Packet Data Network Gateway (PDN-GW)**

PDN-GW is considered the default router to connect the UE of the network to an external Packet Data Network (PDN) such as internet and IMS. It is responsible for UE IP allocation as an LTE-A user can have several IP addresses with different PDNs. It also performs QoS enforcement of the IP (Internet Protocol) packet flow to the UE [15].

- **Evolved Node-B (eNB)**

The traditional base station in LTE-A is known as Evolved Node-B (eNB). Unlike the conventional Node-B, its function includes the protocol implementation, which is implemented by RNC. An eNB can perform admission control and Radio Resources Management (RRM). Also, it is responsible for providing scheduling, traffic load balance, and interference management [11], [12].

In light of this, the protocols and functions (PDCP, RLC, and RRC functions) were terminated in RNC, but now they are terminated at eNB itself, which reduces the latency and eliminates the role of the traditional existence of RNC [6].

- **S1 and X2 Interfaces**

The various elements in LTE-A network are interconnected to communicate and share the network information among them. Different mediums can be used to achieve such connections, while they result in different latency and throughput capabilities, as illustrated in Table 2-1 [16].

Table 2-1: Latency and Throughput of commonly used Backhaul mediums

Backhaul Technology	Latency (one way, ms)	Throughput (Mbps)
Fibre	2-30	50-10000
Cable	25-35	10-100
DSL	15-60	10-100
Wireless	5-35	10-100, maybe up to Gbps range

The basic interfaces in LTE-Advanced are X2 and S1; eNBs (such as Macro/ Pico cells) are interconnected through X2 interface. X2 interface is a point-to-point logical interface [17], which can help to exchange the interference and handover-related information and perform the interference coordination between the neighbouring cells. On the other hand, eNBs are connected through S1 to MME. S1 interface supports a many-to-many relationship between MME and eNBs [18].

2.2.5 Cell selection

Generally, two types of cell selection procedures are adopted in LTE-A [19]: initial cell selection and stored information cell selection.

The initial cell selection in LTE-A is done by the UE based on the highest received power from the neighbouring cells [20]. This method is known as Maximum RSRP (Max- RSRP), so the cell with highest RSRP towards the UE will be selected as a serving cell:

$$\boldsymbol{Serving\ cell} = \mathbf{arg}\max_{\boldsymbol{i}\in\boldsymbol{I}}(\boldsymbol{RSRP_i}) \qquad \textbf{(2-1)}$$

Where *i* represents the serving cell, and *I* is the set of all cells in the network.

On the other hand, the stored information cell selection requires stored information of the carrier frequency and cell parameters from the previously received measurements of the detected cells. In this thesis, the initial cell selection of UE idle-mode has been used for all simulation scenarios.

2.2.6 Operational Division Duplex

Both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes are considered in LTE-A for uplink-downlink duplexing schemes. FDD suggests different frequencies for both Uplink and Downlink transmission, which should be sufficiently separated whereas TDD implies different and non-overlapping time slots for both transmissions. Therefore, FDD requires a paired spectrum, while TDD can operate in an unpaired spectrum.

FDMA systems mainly use FDD because TDD mechanism is inappropriate in the case of real time voice or multimedia communication, as it requires very tight synchronisation procedures, which may not be viable in some scenarios [21].

2.2.7 LTE-A Frame Structure

As mentioned earlier in the previous subsection, LTE-A supports either FDD or TDD modes, and two types of frame structure are standardised by 3GPP TS 36.211 [22]:

- **Frame structure type 1:** where the radio frame is divided into ten equally-sized subframes of 1 millisecond time span, each subframe is composed of two time slots (0.5 ms). Therefore, one radio frame (10 ms) contains 20 time slots. Each radio frame has 307200 T_s (the basic time unit), which is 30.72 MHz, so one T_s equals 1/(15000×2048) seconds. Figure 2-3 illustrates the radio frame structure type 1, as it will be the standard frame structure used in this thesis.

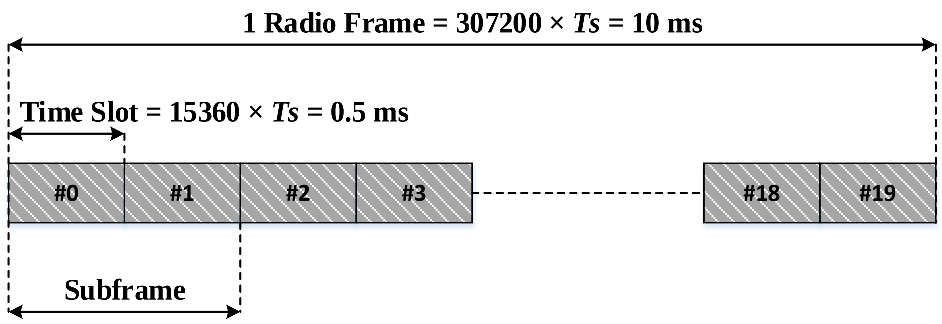


Figure 2-3: Radio Frame Structure (type1)

- **Frame structure type 2:** in this type, the radio frame is divided into two equal half frames, where each half is divided into five equal subframes of 1-millisecond size. Two types of subframes are defined in this frame, as shown in Figure 2-4: special and non-special subframes. The special subframes are subdivided into Downlink Pilot Timeslot (DwPTS), Guard Period (GP), and Uplink Pilot Timeslot (UpPTS), which exist in both halves of the radio subframe.

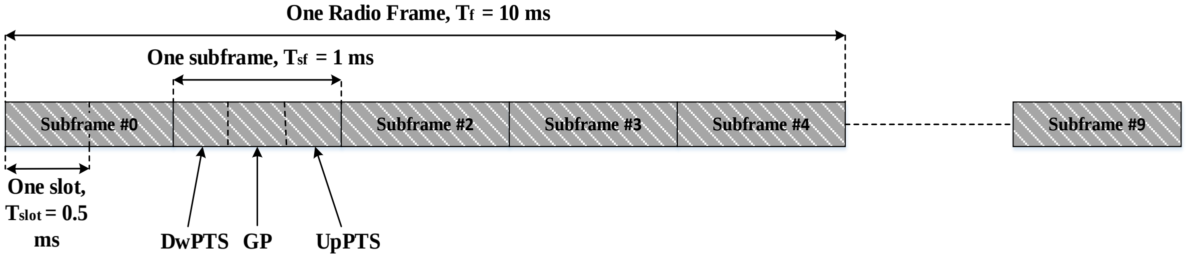


Figure 2-4: Radio Frame Structure (type 2)

- **LTE-A Physical Resource Block (PRB)**

Generally speaking, LTE-A systems simplify the resource allocation by grouping Resource Elements (REs), which are considered the smallest unit of the frame and contain a single complex value of data from a physical channel or signal, into a larger group known as Resource Blocks (RBs) [23]. An RB is defined as the smallest unit that can be allocated to a user by an eNB's scheduler of the eNB. It represents a time-frequency grid of REs (as shown in Figure 2-5), where each PRB spans 180 kHz and consists of 12 consecutive subcarriers (15 KHz width each) in frequency-domain and 7 OFDM symbols in time domain. However, in the case of using an extended prefix, the number of OFDM symbols will be six rather than 7.

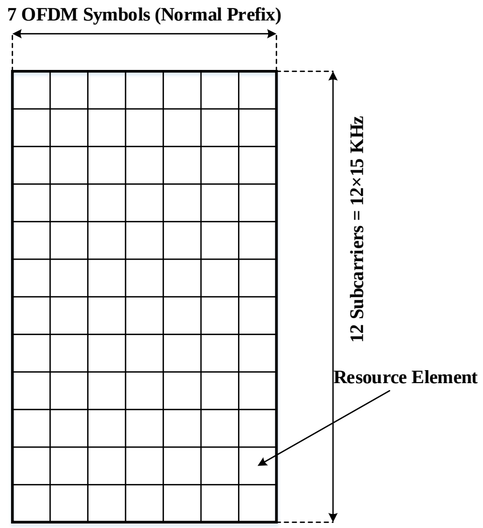


Figure 2-5: Physical Resource Block (PRB)

Thus, a variable number of RBs will be usable for allocation based on the total available bandwidth of transmission channel.

2.3 Heterogeneous Deployment of LTE-A

HetNet is one of the most efficient solutions for achieving optimum spectrum and network efficiencies [24]. In some research studies, HetNets have referred to the deployment of different radio access techniques within the same coverage area (Inter-RAT implementation), while in this thesis the term “HetNet” indicates the heterogeneous deployment of LTE-Advanced system where the regular High Power Cells (Macro cells) are overlaid by Low Power Cells (e.g. Pico cells), forming a multi-tier network (as shown in Figure 2-6). Such implementation is used to enhance network capacity and/ or network coverage in different deployment scenarios. Furthermore, such types of network can improve both average and cell-edge users throughputs [25].

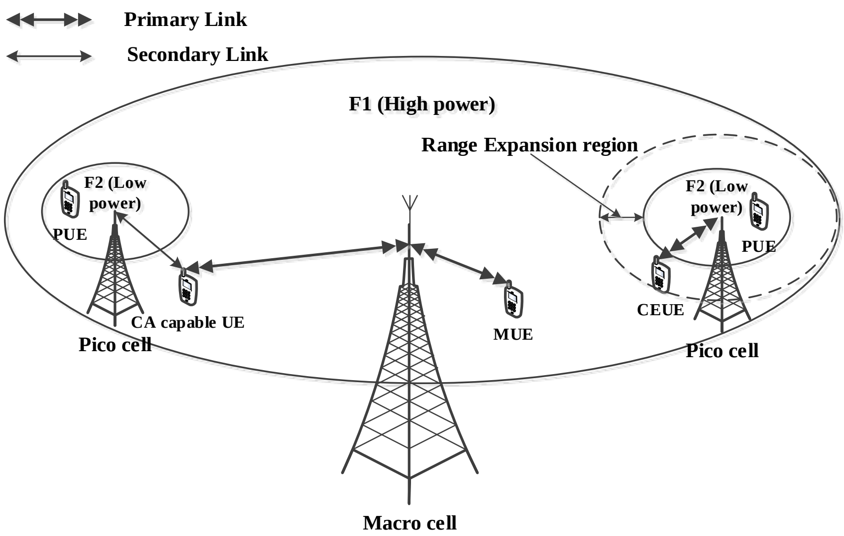


Figure 2-6: Heterogeneous deployment in LTE-Advanced network

These low-power cells include Micro cells, Pico cells, Femto cells, and Remote Radio Heads (RRHs), where the classification of cells is mainly based on transmit power, coverage area, physical size, and backhaul and radio propagation characteristics [26], [27]. Seven types of cells are classified, where cell radius of type A and type B represent a Macro cell and Micro cell respectively, according to ITU-R, as shown in Table 2-2.

Table 2-2: Cell Classification according to ITU-R [28]

Type	A	B	C	D	E	F	G
Cell Radius (m)	289	115	92	69	46	23	11
Tx power (dBm)	46	30	28	26	22	16	10
Antenna height (m)	60	26	24	22	20	18	16

Type C cell size=80% of type B; likewise, types D, E, F, and G cell sizes are 60%, 40%, 20%, 10% respectively compared to type B [28].

2.3.1 Advantages of Heterogeneous Networks

The goals of deploying HetNets are to offload data from the possibly congested Macro cells toward the LPCs, to achieve enhancements for outdoor/ indoor coverage, more spectrum reuse, and to increase the network throughput for cell-edge users. Moreover, it provides better link quality and low power consumption by reducing the path between the transmitter and the receiver. Small cells enhancement has significant importance in 3GPP TR 36.932 and TR 36.842 [29].

The new physical layer design of LTE introduces a flexible resource partitioning among cells of different power classes, to achieve the optimum resource utilisation.

However, interference is a critical issue that affects the operation of HetNets, so advanced techniques for interference management should be carefully chosen. In LTE Release 8, ICIC technique is used to mitigate the downlink interference between cells [30]. Consequently, ICIC techniques were enhanced efficiently in the next successive releases mainly to support co-channel deployment in heterogeneous networks.

Regardless of the high interference possibility due to unplanned deployment, offering a Closed Subscriber Group (CSG), open or even hybrid by deploying low-power cells (e.g.

Femto cells) to cover the gaps between cells and to provide better coverage for a certain number of indoor users is one of the applied solutions [31].

Since there is no X_2 interface defined between Macro/ Femto cells to enable interference coordination techniques, interference management for co-channel deployment can be done through Operation and Maintenance (OAM) and power control techniques (in Release 10) to minimise the link failure due to interference.

Studies on Release 12 and onward focus on network densification to meet the increasing demands for high-speed applications without affecting the scarce spectrum. In turn, such deployments require the development of the number of radio and protocols solutions to achieve that gain [27].

2.3.2 Carrier Frequency Allocation

Due to some regulatory limitations and heavy usage of the recent spectrum, most heterogeneous deployments focus on same-frequency operations (intra-frequency) wherein Macro/ low-power cell layers share the same carrier frequency(s).

3GPP has identified Release 12 requirements in TR 36.932, where different scenarios for heterogeneous deployment are suggested:

I. Macro/ low-power cells share the same carrier frequencies (Intra-frequency) [32], [33].
II. Macro/ low-power cells use different carrier frequencies (Inter-frequency).
III. Deployment of only low-power cells sharing one or more carrier frequencies.

Thus, using different carrier frequencies for both layers (Macro/ low-power cells) has less complexity as it does not require a centralised architecture or tight coordination between layers. However, such enhancement comes with the price of multiple carriers' usage, and Inter-frequency handover, which consumes more time and terminal battery life [34], [35].

On the other hand, Intra-frequency deployment is spectrum efficient since it can provide better resources partitioning [32] but it is more challenging to mitigate the cross-tier interference and mobility management between cells using the same carrier frequencies (especially in CE region) [36]. These two challenges require a robust UE solution to overcome such interference in heterogeneous deployment.

The availability of higher frequency bands (e.g. 3.5 GHz) can support better spectrum usage by using separate spectrums for each layer, which leads to minimised interference between the two network layers. Frequency-separated deployments can be used to exploit both duplex schemes (FDD/TDD) to achieve better performance [37]. Dynamic TDD is possibly beneficial in local area coverage, where the network can dynamically choose between UL and DL according to the instantaneous needs [38].

2.3.3 HetNet Components

HetNets follow the same architecture of any LTE-A network (as described in section LTE-A Architecture). However, several types of cells with different characteristics could be deployed in such networks, forming a multi-tier network:

- ***Macro cells***: refer to the conventional eNBs, which are installed by operators to provide open access to all users subscribed to the network. This type of cell has a high transmit power of up to 46 dBm and covers a wide area of a few kilometres. It is utilised to serve thousands of users with a minimum guaranteed data rate and tolerable delay.
- ***Pico cells***: they are fully-fledged eNBs with low transmit power (23-30 dBm), deployed by operators to improve network capacity/ coverage for either indoor or

outdoor environment [39]. They provide open access for all users of the network when Macro cell capabilities are insufficient for dense areas.

- ***Femto cells***: this term describes the low-power cells (up to 23 dBm) used to provide unplanned deployment by users for indoor environments (e.g. office, mall, etc.). This type of cell features some access restrictions for certain users, as they are deployed by the customers, and they utilise other types of backhauling (e.g. DSL) to reach the mobile network.
- ***Relay nodes***: refer to the access points used to route the data from Macro cells to the users to extend the coverage in new areas. They use wireless backhaul to connect the Macro cells and have limited capabilities as compared with other low-power cells.

2.3.4 Technical Challenges in HetNets

As a result of different power characteristics of cells (e.g. transmit power, power control settings) [40], HetNet has several challenges, which have significant impacts on the potential achieved performance of this type of deployment. Based on the literature, the most major challenges can be outlined as follows:

- Imbalanced coverage between UL/ DL: transmit power disparity between the Macro cell and low-power cell is one of the biggest problems in HetNets [40], where the best DL cell and the best UL cell for a certain UE may be different, as a result of different output power for each cell. Moreover, each cell may have a different UL power control setting. Due to a larger transmit power of Macro cell, handover boundaries are shifted closer to the low-power cell, which can lead to severe UL interference as a result of Macro user impact on low-power cell [30].

- More frequent handover due to smaller footprints of low-power cells, which leads to more signalling overhead. Signalling overhead could be minimised by using an RRC inactivity timer, where RRC connection is released by the base station when there is no data activity, which leads to less handover signalling overhead. Furthermore, it can be reduced when releasing inactive UEs during the handover process. A shorter RRC inactivity timer leads to less handover signalling overhead compared to connection setup overhead [41].
- Interference from Macro cell to low-power cells which causes underutilisation in low-power cells (which is the most effective challenge for many deployments) [42].
- Cell selection (especially for UE in CE region).
- UL interference due to shifted handover boundaries toward the low-power cells.
- Mobility robustness: due to the more frequent handover, heterogeneous deployment leads to more handover failure (HOF), which has a negative impact on the Quality of Service.
- Backhauling limitations between the Macro cell and low-power cell (e.g. there is no direct interface between the Macro cell and Femto cell).

2.3.5 Interference Scenarios in HetNets

Despite the significant benefits of deploying HetNets to increase the network capacity or to extend the coverage in a cost-effective way, the inter-cell interference is the largest challenge in such networks when using co-channel deployment. Figure 2-7 describes the possible inter-cell interference in an LTE-A network with cells of different classes.

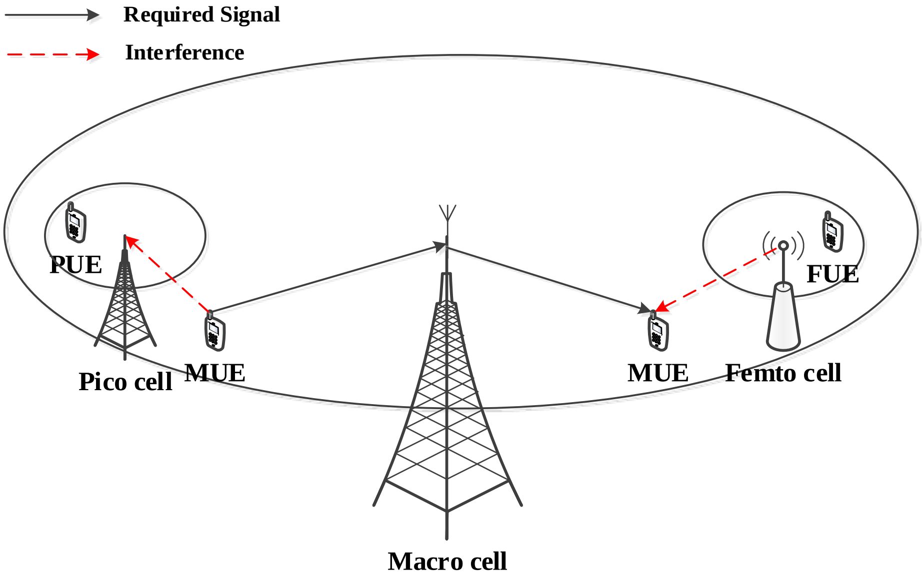


Figure 2-7: Interference Scenarios in HetNets

Uplink (UL) interference: Normally, the Macro UE (MUE) receives high transmit power from the serving Macro cell, and at the same time it transmits with high power in UL as well. For Macro/ Pico cells co-channel deployment, both cells share the same radio resources, so the Pico cell close to that Macro cell receives high UL interference from all MUEs located in its proximity [43]. In some cases, there is a UL interference coming from MUEs to the Femto cells, but it is mostly negligible due to the restricted access nature of these Femto cells.

Downlink (DL) interference: The main DL interference in HetNets is caused by Femto cells of CSG access because they still have high transmit power on MUEs in their neighbourhood while they reject those UEs from accessing their resources. There is another possible DL interference coming from Pico cells towards the MUEs in their vicinity [25], which needs to be considered in the proposed scheme in this thesis.

Furthermore, the severity of the inter-cell interference in HetNets depends on the deployment environments, such as coverage-limited (in the case of rural regions) and interference limited when deploying the network in urban or dense urban areas.

2.3.6 Transmission Mode (CSG, OSG, HSG)

Several access modes are identified in LTE-A HetNets to regulate the UEs access to the network:

- ***Closed Subscriber Group (CSG)***: It is the most restricted access mode, which is mainly defined for the Femto cells. In this mode, only predefined UEs have the exclusive permission to connect the Femto cell [44].
- ***Open Subscriber Group (OSG)***: Where all UEs in the network has the right to connect the open access cells.
- ***Hybrid Subscriber Group (HSG)***: In this mode, the highest priority access is for the predefined UEs; subsequently, the rest of the UEs can access that cell according to the available resources [45], [46].

2.3.7 Cell Range Expansion (CRE)

Conventionally, cell selection in LTE systems is done by a UE based on Maximum RSRP (Max. RSRP) among several surrounding cells [47]. As a result of different power characteristics in heterogeneous networks, this results in less offloaded users from Macro to the low-power cell, which leads to load imbalance in HetNets.

CRE is one of the recent solutions to solve the problem of UL interference. In this concept, the low-power cell RSRP is positively biased by a CSO, as shown in Figure 2-8 to increase their DL coverage [2], and to overcome the situation of fewer users offloaded from Macro cell towards the low-power cell [44], [45].

The bias value refers to a threshold that triggers handover between two cells. A positive bias means that UE will be handed over to the low-power cell when the difference in signal strength from the Macro cell and low-power cell drops below a bias value.

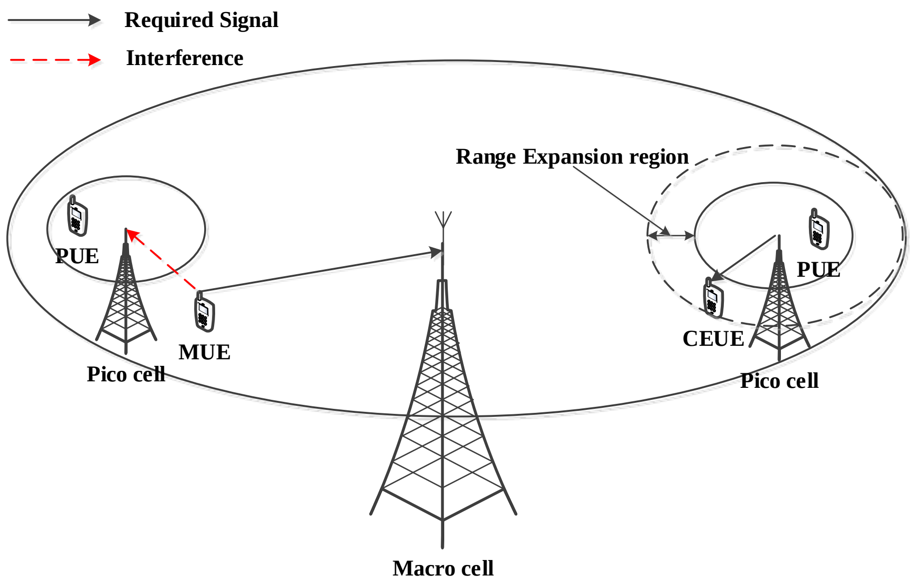


Figure 2-8: Cell Range Expansion

Maximum gain can be achieved by adjusting handover boundaries between the Macro cell and low-power cells.

Neighbouring Cell List (NCL) is periodically broadcast by the serving cell to facilitate users in monitoring air interface; this list includes neighbouring cells and their pilot signals. UE performs channel measurements and reports the results to its serving cell periodically [3], [50], which in turn decides whether to start HO procedures via exchanging HO-related command message [51] with the target cell. If the serving cell receives a measurement report (MR) from a UE about Pico cell, it will add a bias to the Downlink Received Signal Strength (DL RSS) pilot signal coming from that Pico cell (Pico RSRP). DL RSSs are usually averaged and filtered by UEs in both frequency and time domains to cope with signal fluctuation caused by channel fading [52].

It has been shown in [42] that, using optimal biasing achieves 35-40% better gain, compared to heterogeneous networks without biasing. A bias value (0~20 dB) [53] indicates the threshold to trigger handover between two cells [54]. A positive bias value is applied to the low-power cell where UE is handed over to the low-power cell when the difference in signal strength between Macro/ low-power cell in CE region drops less than this bias value. "CRE may be useful for the Macro cell to reduce the number of handovers" [35]. Employing a positive bias is necessary to improve load balance in HetNet [48].

However, fixed bias value could not adapt the change in user distribution over time, so it is important to dynamically adjust the RE region according to the system performance feedback, to achieve the optimum load balancing and better cell-edge user throughput while maintaining the overall cell performance.

2.4 Summary

This chapter gives a background to LTE-Advanced as an example of OFDM networks, describing the main features and requirements of such networks. LTE-Advanced architecture, network elements, and the frequency planning have been explained in relation to the purpose of this thesis. Both operation duplex division schemes (FDD, TDD) have been summarised, giving the features of FDD to provide a more realistic implementation in the case of real-time voice and multimedia services over the TDD scheme. Their significance in Resource Allocation (RA), especially in co-channel deployment, radio frame and the physical resource block structures, has been discussed thoroughly.

The second part of this chapter describes the heterogeneous deployment of LTE-Advanced, spotting the main features and the technical challenges of such deployment. Inter-cell interference has been highlighted as the main problem in HetNets, by describing the possible interference scenarios and the other literature on this issue. Finally, CRE concept has been outlined due to its impact on the proposed scheme for inter-cell interference mitigation of LTE-Advanced HetNets.

Chapter Three: Interference Management in LTE-Advanced

3.1 Introduction

Two main types of interference management have been highlighted in most mobile systems: Interference cancellation [55] and interference mitigation [56]. The first type of interference management is implemented on the received signals by subtracting the interfering signals to allow only the required signals from being decoded successfully. Despite the fact of achieving high capacity, the implementation of interference cancellation in mobile systems may result in high process complexity to estimate the interfering signals [57]. As a result, interference mitigation has gained more attention to prevent the interference before its occurrence. This mitigation can always be achieved by frequency planning, power control, and antenna planning. Mobile networks operators have several spectrum bands, which should be carefully utilised to achieve higher capacity while maintaining the lowest levels of interference.

3.2 Spectrum Assignment

The coverage area of any mobile network is required to serve high volumes of users at the same time. This issue leads to significant limitations in base station capabilities and the requirements for more carrier frequencies to adapt to such scenarios, which is impractical due to technical constraints and the expensive cost of the radio spectrum. Therefore, the cellular concept [58], [59] has been introduced to expand the coverage area of the network and to increase the number of accessible channels. In this concept, several base stations are utilised to cover the entire coverage using frequency reuse schemes to increase the network capacity while avoiding the unnecessary interference resulting from the frequency reuse. Each set of base stations (cluster) should be allocated a certain number of radio channels, where any adjacent base stations must utilise a different set of channels to avoid any excessive interference, especially in cell-edges. In this way, the same set of radio channels can be reused several times in other clusters safely. Several frequency reuse schemes have been adopted, as shown in Figure 3-1:

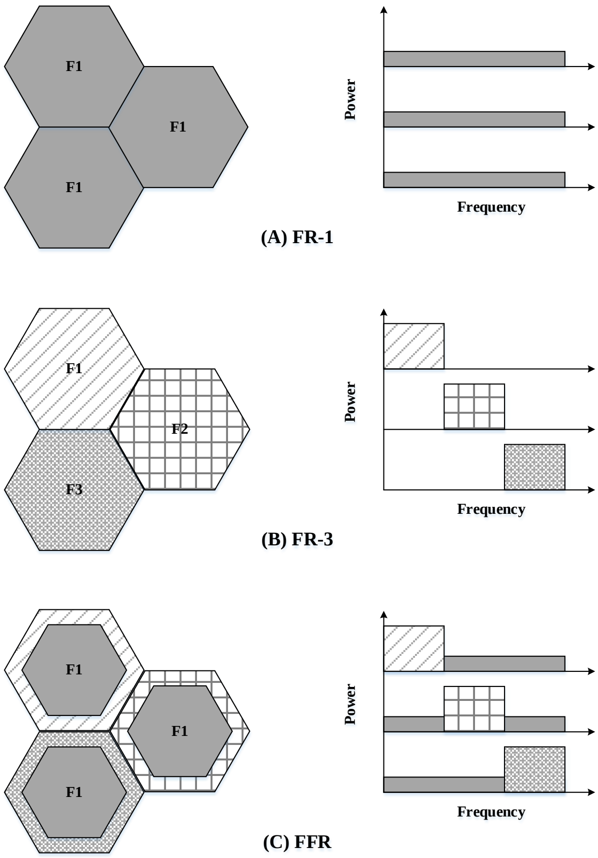


Figure 3-1: Frequency Reuse Schemes

3.2.1 Frequency Reuse

The simplest type of frequency reuse scheme is reuse factor-1, where the available bandwidth can be freely reused in each cell of the network without any restrictions. Despite the high potential throughput, the inter-cell interference in such a scheme is more critical, especially for cell-edge users [18]. In return, the reuse factor-3 results in better inter-cell interference mitigation with the price of less available capacity for each cell. In this scheme, the total bandwidth is divided into three orthogonal (non-overlapped) sub-bands to be allocated for adjacent cells safely. However, poor throughput may be achieved as one-third of the available bandwidth will be accessible by each cell [60].

3.2.2 Fractional Frequency Reuse (FFR)

As a trade-off between throughput and interference in the schemes mentioned above, Fractional Frequency Reuse (FFR) has been introduced to make a compromised solution [61], [62].

Inherently, UEs in cell-centres experience high signal quality and they are more protected against the interference resulting from neighbouring cells. On the other hand, cell-edge UEs are prone to higher interference and receive a degraded signal due to their far location to their serving cell. As a result, the cell-centre of every cell in the network employs frequency reuse factor-1 with lower transmit power, while the cell-edges operate frequency reuse factor-3 with full transmit power [60], [31]. In addition, other types of frequency reuse schemes are employed in Homogeneous networks, but they are beyond the scope of this thesis.

3.3 Inter-Cell Interference Mitigation in Heterogeneous Deployment

As a promising implementation, HetNets face several challenges that affect the performance of such networks (e.g. load balance, Inter-cell Interference, cell selection, mobility robustness, etc.), so many solutions have been introduced through the successive releases of LTE to overcome the aforementioned challenges.

Several spectrum assignments have been adopted in heterogeneous networks for efficient spectrum utilisation. One of these assignments is the fully-dedicated spectrum, where a different set of spectrum bands are assigned for the Macro cells and low-power cell. In this approach, the cross-tier interference is totally avoided. However, the limited spectrum share for each tier results in low spectrum efficiency which has a negative impact on the network performance. Therefore, shared spectrum (co-channel deployment) can offer higher spectrum utilisation but with the cost of high interference possibilities that necessitate a well-planned inter-cell interference coordination in such implementations. The next subsections will discuss some of the most efficient techniques to mitigate the ICI problem based on literature.

3.3.1 Power-Domain Inter-Cell Interference Coordination (PD-ICIC)

UEs measure the DL Received Signal Strength (RSS) of the pilot signals continuously of the surround cells to choose the serving cell. Noting that, the pilot signal is usually transmitted at a fixed power and it implies the Physical Cell Identities (PCIs). Moreover, the NCL, which contains the list of neighbour cells and the pilot signals are broadcast by the serving cell periodically. Thus, UE performs the channel measurements and report them back to its serving cell, which is significant for making a handover decision. In this scheme [2], a cooperative algorithm is required to make a decision for the maximum power that every Macro cell can apply on each RB used by cell-edge UEs to provide the necessary SINR for these UEs. UE calculates the maximum tolerable ICI, target SINR, and the noise power, to measure the maximum power and the RB index that can be used by the neighbour cell. In this way, Macro cells should allocate RB powers according to the power constraints derived from previous steps to mitigate the potential interference toward the cell-edge UEs of the neighbour cells. Such scheme requires a scheduling priority as there is independent power allocation for the available RBs. One of the main challenges in this scheme is how to maintain the required throughput of all attached UEs when using different power allocation on some RBs [63].

3.3.2 Coordinated Multipoint (CoMP)

It is a technique developed by 3GPP for LTE-Advanced (Release 11 and onward) to send and receive data to/ from several points to ensure the optimum performance regarding cell-edge and system throughputs [64]. The primary difference between the standard MIMO and CoMP is that the transmitters in the latter are not physically co-located.

The idea behind this technique is to enable dynamic coordination of transmission and reception over several base stations, to turn the Inter-Cell Interference into a useful signal, especially at cell borders where the problem of ICI increases [65]–[67]. Several types of CoMP have been introduced, which are defined for the downlink as follows:

- ***Joint Transmission (JT)***: This is a type of spatial multiplexing when more than one point cooperate so that UE data is transmitted simultaneously from several points.
- ***Dynamic Point Selection (DPS)***: In this case, all points share the UE data, while only one point is chosen to transmit this data according to the coordination of all surrounding points.

Other types of coordinated scheduling and beamforming are also defined where UE data is only available and transmitted from a single point, but all points coordinate their scheduling decisions and resource allocation inside the cooperating set.

Although CoMP has no specific support in LTE-A (Release 10) of 3GPP standards, some schemes can be implemented in this release, and simple upgrade is needed when the standardisation will be agreed in future releases [27]. Furthermore, a tight coordination between adjacent cells and a backhaul with a minimum latency are essential to implement this scheme.

3.3.3 Frequency Domain-based Inter-Cell Interference Coordination (FD-ICIC)

According to 3GPP standards in [68], CA is considered a prominent method of performing frequency-domain ICIC. Interference in DL control channels can be mitigated by partitioning the component carriers (CCs) in the cell layers into two different sets: Primary Component Carrier (PCC) for data and control, while the Secondary Component Carrier (SCC) is mainly for data (or also for control if power control applied) [35]. Figure 3-2 illustrates such a CA-based ICIC scheme. Carrier aggregation is used by both Macro cell and low-power cell layers where both layers enable data communication over f_1 and f_2. The Macro cell includes the control information only on f_1 while low-power cell includes the control information only on f_2.

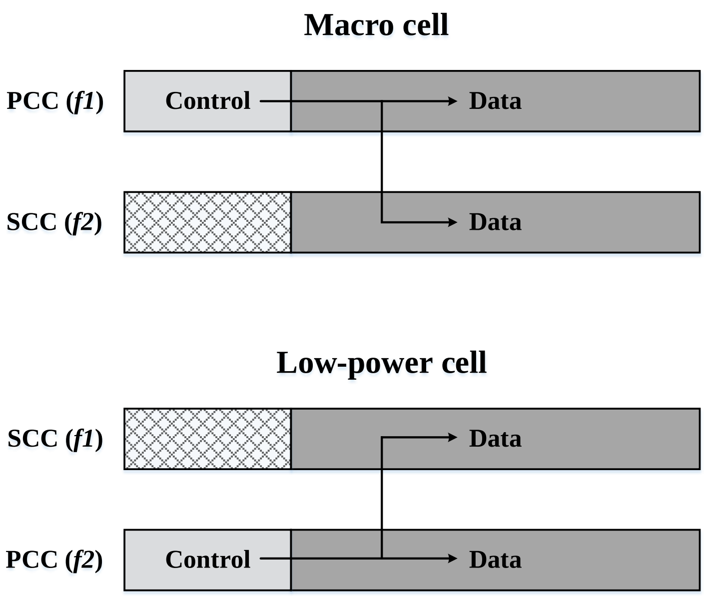


Figure 3-2: Frame configuration for CA-based ICIC scheme

By using this simple mechanism, the control signalling for the different layers is separated. In such a case, the Macro cell adopts the carrier f_1 as the PCC while applying power control schemes on carrier f_2 to minimise interference on low-power tier. Similarly, low-power cell utilises f_2 as the primary carrier and applies power control schemes on f_1.

Most researchers focus on Control Channel (CCH) interference [69], while few papers concentrate on both data and control signalling interference where the interference is mitigated by reducing the transmit power of some CCs of the macro cell which leads to less network capacity [70]. The above scheme, however, has the constraint that the different layers need to be time synchronised.

3.3.4 Time Domain-based Inter-Cell Interference Coordination (TD-ICIC)

The time domain-based ICIC schemes basically rely on reducing the transmission activity on certain subframes by each of the cell layers to minimise interference to the victim layers [71], [72]. These subframes are indicated as Almost Blank Subframes (ABS).

This solution is suggested by 3GPP LTE-A (Release 10) to solve the problem of low DL signal quality in cell expanded region and to reduce the PDCCH outage which causes link failure. Moreover, it can overcome the case of larger cell expanded region that causes more interference in DL [73]–[75].

Figure 3-3 illustrates this solution, where the Macro cell will be muted or transmit data with a minimum power through some “protected” subframes (ABS), to avoid the high cross-tier interference by enabling CE region UEs from using these protected sub-frames achieving better spectrum efficiency. Noting that in these ABSs, only common reference signals (critical control channels, broadcast, paging information) are transmitted by the Macro cell to maintain the mobility robustness in HetNets [76]. Noting that such scheme requires that both networks layers (macro/ low-power cell layers) should exchange ABS subframe information to achieve the required performance [69].

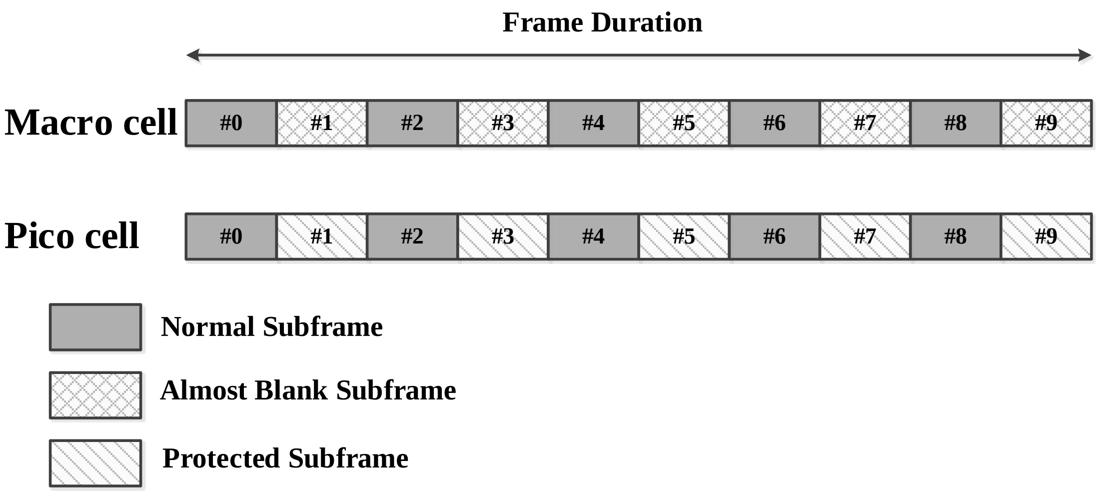


Figure 3-3: Example of (ABS) for range expansion in heterogeneous network

According to [77], ABS technique can improve both cell-edge and cell throughputs as a result of using these protected subframes by some Pico users as well, where Macro cell keeps silent through these subframes.

The simulation results of [76] show that both average and the cell-edge throughputs of the low-power cells (e.g. Pico cell) can be dramatically enhanced when employing ABS technique as a result of reducing DL interference for Pico users when Pico cell uses protected sub-frames for data transmission.

In HetNets scenario with CRE and ABS interference coordination, it is noted that data rates of offloaded user highly depend on the amount of ABSs rather than the bias value (especially from a user perspective), as a result of limited scheduling opportunities of offloaded users within ABSs.

Even though employing CRE, UE may suffer from significant interference from Macro cell using the same carrier frequency (intra-frequency).

3.4 Related Work in ICIC

3GPP has suggested TD-ICIC as a time-domain multiplexing technique for cross-tier interference mitigation in LTE Release 10 HetNets [54], which is called Almost Blank Subframes (ABS). In this technique, the aggressive node should refrain from transmitting data on a certain amount of spectrum (subframes or resource blocks) to be protected for the cell-edge users of the victim node that shares the same frequency band(s). In this way, only cell-specific reference signals (CRSs) [78], [79] and other synchronisation and paging signals will be transmitted through these subframes to keep the backwards compatibility with older versions of LTE UEs. Moreover, CRSs are used for radio resources management and channel estimation, so they are necessary to still being transmitted during these subframes. A scheduler has been proposed in [80] which effectively coordinates the inter-cell interference for vulnerable users of LTE-A HetNets with a minimum efforts of coordination using dynamic FFR. In this work, a decentralised resource allocation algorithm is embedded in the framework of LTE to avoid the interference on the cell edge users while maximising the sum throughput of the cell. The proposed scheduler exploits X2 interface to inform the neighbour cells with the reserved resources for its vulnerable users. Therefore, the results show substantial gain as compared to the standard schedulers.

The author of [81] proposes an ABS setting for DL interference management based on base station placement statistics, where UE can estimate the distance from BS by performing RSRP measurement. The results of simulation show a moderate performance gain for victim users in Macro/ Femto scenario, while it is substantial in Macro/ Pico scenario. They also show that in Macro/ Pico scenario using ABS with association bias improves the performance of the system considerably, so the fraction of victim users in outage decreases from over 95% to 30% or less, depending on the scheduling algorithm.

A large CRE for a given Pico cell requires larger ABS duty cycle (ratio of ABS to non-ABS subframes) to provide the desired QoS to PUEs in expanded region with the price of degraded MUE performance. Macro cell ABS duty cycle calculation with a load balance algorithm is proposed in [82] to offer a largest possible number of ABS to Pico cells while controlling MUE performance to achieve better spatial reuse. The load balance algorithm can be summarised when each Pico cell estimates the worst PUEs on their associated SINR on both ABS and non-ABS subframes. Based on achievable rate got from SINR, Pico cell decides to schedule those users with worst SINR on the suitable subframe. A dynamic cell selection framework is suggested in [83] for eICIC with two cell association algorithms: one for pure load balance and opportunistic approach for varying cell conditions. Besides this algorithm, an autonomous fast distributed muting algorithm suitable for irregular network deployment is developed for efficient eICIC. These two algorithms show higher capacity gains depending on the deployment environment.

Dynamic configuration of ABS ratio has got a significant interest to adapt the variation in network load. The effect of dynamic ABS according to a certain criterion is studied in [84], [85], [86].

A framework was proposed by [87] for network dependant eICIC taking into account the ABS ratio, UE association, and the CRE value jointly for optimal dynamic eICIC configuration. This framework uses two algorithms: first algorithm is developed to find the optimal ABS percentage and biasing value with static UEs scenario. After that, the second algorithm specifies the appropriate ABS pattern for these protected subframes. This framework was evaluated using Monte Carlo-based techniques to estimate the UE locations according to UEs densities and SINR distributions. The only drawback of this proposal is the high computation complexity during the joint computation, which could not adapt the prompt channel estimation in the network. As a result of this computation complexity, it takes 5-15 minutes to update the eICIC parameters, which increases the configuration outage especially in the case of significant load changes over the network.

Moreover, [88] proposes a dynamic ABS scheme based on Genetic algorithm for the optimum ABS ratio and location to mitigate the inter-cell interference efficiently for video streaming traffic in Macro/ Pico deployment with shared bandwidth. This scheme proves an improved user throughput and less outage probability when the ABS percentage has been suggested to be 10%, 50%, and 70% for 9, 12, and 15 dB bising, respectively. The simulation results show lower Macro throughput in low biasing values (e.g. 9dB) as a result of higher users connected to the Macro cell. Moreover, the ABS ratio has been proved to be set jointly with the biasing value to provide sufficient resources for all users in the network. However, this scheme has been applied for video streaming only and the ABS configuration was not fully dynamic. The conclusion shows that such configuration outperforms the static allocation only in higher CSO (for the full-buffer case) thanks to the higher load in CE region, while the static configuration is sufficient in lower CSO values since there are no many users in CE region in the latter case.

As mentioned earlier that cell association in LTE is essentially based on RSRP, so it is a critical issue to choose the appropriate CRE values in heterogeneous deployment to maintain a sufficient SINR for the users in that region.

CRE bias should be carefully selected to ensure the maximum benefits of such solution; small bias leads to fewer users to be offloaded towards the small cell [89], whereas the large bias can cause weak SINR for some users inside CE region which affects the CCHs decoding [90]. Several studies give an interest to the range of CSO values in HetNets; It was founded in [91] that optimal CSO value is closer to 6 dB than 12 dB. A cell selection scheme (based on Average SINR with different CSO values) and variable ABS densities are investigated in [36] to improve the spectrum efficiency-in time domain- and overall performance of both Macro/ Pico cells. However, the optimisation of CRE bias is seldom investigated by most researchers [92].

From the literature, it can be concluded that dynamic configuration for CRE bias value based on user distribution can optimally adapt user distribution within LTE-A HetNet to achieve better cell-splitting gain with the price of computation and mobility complexity. It is proposed in [93] a method for Pico-specific upper bound CRE bias estimation algorithm, to ensure the SINR requirements for Pico-UEs. It focuses on the method of CRE bias setting for Pico cell according to the power of ABS in HetNet.

TD-ICIC with CRE is a vital factor in cell planning. However, most works in [94]–[96] about cell planning was not considering it. The parameter values for CRE and TD-ICIC depends on the volume and distribution of data traffic. The author of [97] suggests a cell planning model for the downlink in HetNet with CRE and TD-ICIC, to find the minimum number of Pico cells under the constraint of covering all user data traffic. This planning is conducted for traffic distributions by a greedy algorithm, taking into account CRE values with ABS ratios and transmit power as well. It is concluded from the simulation results that ABS ratio and resources needed for LPCs is proportional with CRE region.

Almost Blank Subframe can effectively enhance the performance of the cell-edge users of the victim node with the cost of aggressor node's performance degradation since the aggressive node will not use these subframes.

RPS or Low-power Subframes (LP-ABS) is the most recent scheme proposed by 3GPP for Further enhanced ICIC (FeICIC) in LTE Release 11, to avoid such degradation [98], [99].

Instead of totally blanking some subframes, LP-ABS can be used by the aggressive node with reduced transmit power for better resources efficiency, giving priority to cell-centre UEs of the aggressor node to be scheduled on these subframes [99]. The transmit power of LP-ABS should be decreased (at least) as much as the CRE bias (or HO offset) compared to one of the normal subframes [100] or even adopt much lower power, such as 30 dBm as mentioned in [101] to guarantee the Macro cell edge user performance. Obviously, the optimum power level is variable which is dependent on the ABS ratio, CRE value and channel model, and so forth. For simplification, the 30dBm transmission power is always assumed for reduced-power ABS regardless of actual CRE bias value even if this is not the optimum value.

However, for the stable network operation purpose, the PCFICH, PDCCH and PDSCH, which are employed to transfer system information, are not suitable to transmit with low power. The purpose is to ensure the coverage of all the served UE[102].

A detailed analysis of RPS performance is given in [103]; based on their simulation results, RPS could provide relatively more steady performance gain in the cell average and cell edge throughput compared to ABS configuration. RPS configuration could boost both cell average and cell edge throughputs. A new user association method under RPS scheme has been proposed in [104] to investigate the network performance using stochastic geometry framework. Furthermore, the formula for an optimal biasing value has been analytically derived to maximise the overall rate coverage of the network. The analytical results show the RPS scheme proves better performance in static range expansion biasing provided that optimum resource sharing is achieved.

Further research studies focus on the optimum power consumption as an important factor in mobile networks. [105] proposed a centralised algorithm for joint user association and power minimisation in DL transmission of two-tier LTE-A network. This algorithm is derived using Lagrange dual composition method to study the load coupling and the protected subframe ratio impact on the SINR of the network. Likewise, [106] studies the optimisation of FeICIC and analyses the Energy Efficiency (EE) and SE in a two-tier LTE-A network using stochastic geometry. The simulation results under the stochastic geometry show a slight improvement (0.55 bit/s/Hz/W) with a CRE biasing of 12 dB as a best result. However, there was a trade-off between SE and EE in higher Pico cell density. In addition, [107] designs a power saving framework to modify the ABS pattern dynamically in a short term (i.e. few milliseconds), and to keep the traffic estimation at reduced power cost with less latency. It shows less power consumptions as compared to other employed frameworks, especially at low loads. On the other hand, the network service is degraded proportionally for all cells in the case of over loading. This degradation is a result of varying the transmit power of the RPS dynamically which leads to unnecessary interference fluctuation.

More advanced research on the impact of the small cell interference to the Macro cell has been tackled in [108], where an RPS scheme is introduced for both Macro and Femto cells to mitigate the interference on the Macro-edge users, in addition to protecting the Femto users from the high transmit power of the Macro cell. The analytical framework was derived and verified using Monte Carlo simulation, where the SINR of both edge and average user's throughputs are enhanced under the proposed framework. Therefore, the numerical results show up to 20% enhancements in Macro edge coverage gain when employing RPS in Femto cell.

3.5 Summary

This chapter discusses the ICI management in LTE-Advanced network as an example of OFDMA systems. It describes the spectrum assignment in homogeneous deployment (Macro cell-Macro cell) and the primary techniques for frequency reuse implemented to mitigate the potential ICI downlink transmission. After that, the challenging ICI in heterogeneous deployment has been discussed thoroughly, highlighting the main effective ICI mitigation schemes based on the literature. These schemes are classified into coordinated multi-point (CoMP), power-domain, frequency-domain, and time-domain ICI mitigation approach. In the light of this, the latter scheme got more importance in the literature as a result of its higher spectral efficiency, and it has been chosen for further improvements in this thesis. Finally, some related works in time-domain ICI coordination have been investigated to give a big picture for the proposed solution in the next chapter.

Chapter Four: The Proposed Scheme for Inter-Cell Interference in HetNet

4.1 Introduction

This chapter introduces the design of the proposed TD-ICIC scheme, to improve the DL performance of the LTE-A HetNets in the case of Macro cell- Pico cell scenario. In this scheme, both ABS and RPS are utilised in the same configuration to achieve a balance between the performance of cell-edge users of the Low-Power Cell (LPC) and that of the Macro cell UEs.

The complexity of such configuration is represented in the presence of two levels of users' priorities and several types of accessible radio resources. Practically, the CRE region will be further divided into two sub-regions: outer and inner CREs. Therefore, the RBs power allocation and the prioritisation of the users are detailed in the next sections, and both the required algorithms for UEs priorities are discussed later. Furthermore, the implementation of this design is further described using system-level simulation. The next sections discuss all the required modelling calculations thoroughly for the system model and the other simulation assumptions.

4.2 The Proposed Inter-Cell Interference Mitigation Scheme

Inherently, there is a permanent trade-off between ICI mitigation and resource accessibility in LTE heterogeneous networks. For instance, ABS-only configuration can cause waste in frequency/ time resources of the aggressive node, which also leads to throughput degradation and spectrum deficiency. On the other hand, the presence of some data in these special subframes may still cause a negative impact on the SINR of some UEs in the victim cell, or even it may cause an RLF to these users. In the proposed scheme, the special subframes comprise both ABS and RPS (as shown in Figure 4-1) to utilise the available RBs perfectly and to protect the cell-edge users of the Pico cell from the interference coming from the Macro cell. In this way, the performance of the Macro cell will be optimised while keeping the performance of Pico cell intact.

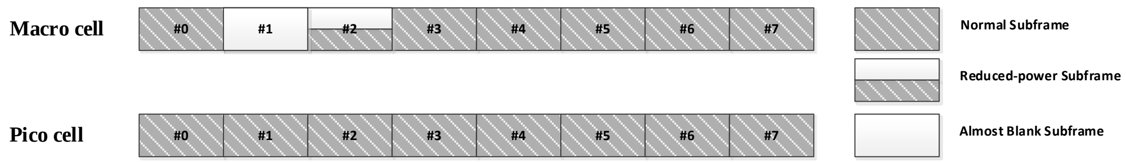


Figure 4-1: Subframe Pattern of the Proposed Scheme

Employing RPS as a TD-ICIC reduces the Pico CRE capability, where data transmission with reduced power on these subframes causes DL interference on PUEs in cell expanded region, which results in shrinkage in CRE region in case of LP-ABS. Therefore, CRE region will be less than that in the case of employing ABS scheme. As a result, Figure 4-2 illustrates that CRE region will be further divided into two regions when employing the proposed scheme: Outer-CRE (δ_j), and Inner-CRE ($\delta_j^{\wedge}$) in case of using ABS and RPS configurations, jointly. In this way, outer CRE region will provide a barrier between the overlapped footprints of both Macro/ Pico cells, because subframes used in this region is totally blanked. On the other hand, inner CRE region can be can be closely isolated from ICI.

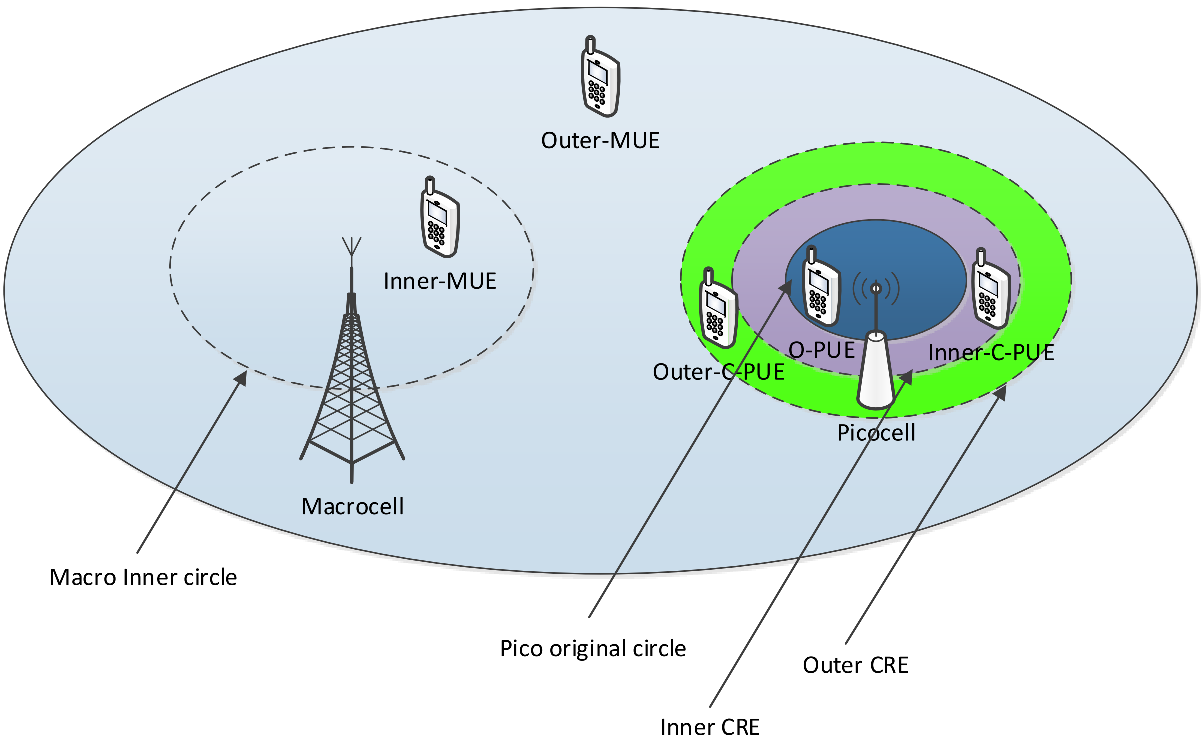


Figure 4-2: CRE Classification

As a result of several regions in such scenario, UEs are classified as follows (as shown in Figure 4-3):

$$UE_k = \begin{cases} MUE, & if\ P_{i,k} > P_{j,k} + \delta_j \\ Outer - C - PUE, & if\ P_{j,k} + \delta_j^{\wedge} < P_{i,k} < P_{j,k} + \delta_j \\ Inner - C - PUE, & if\ P_{j,k} < P_{i,k} < P_{j,k} + \delta_j^{\wedge} \\ O - PUE, & if\ P_{j,k} > P_{i,k} \end{cases}$$

Where$P_{i,k}$, $P_{j,k}$ represent RSRP received by UE_k from $MeNB_i$ and $PeNB_j$, respectively.

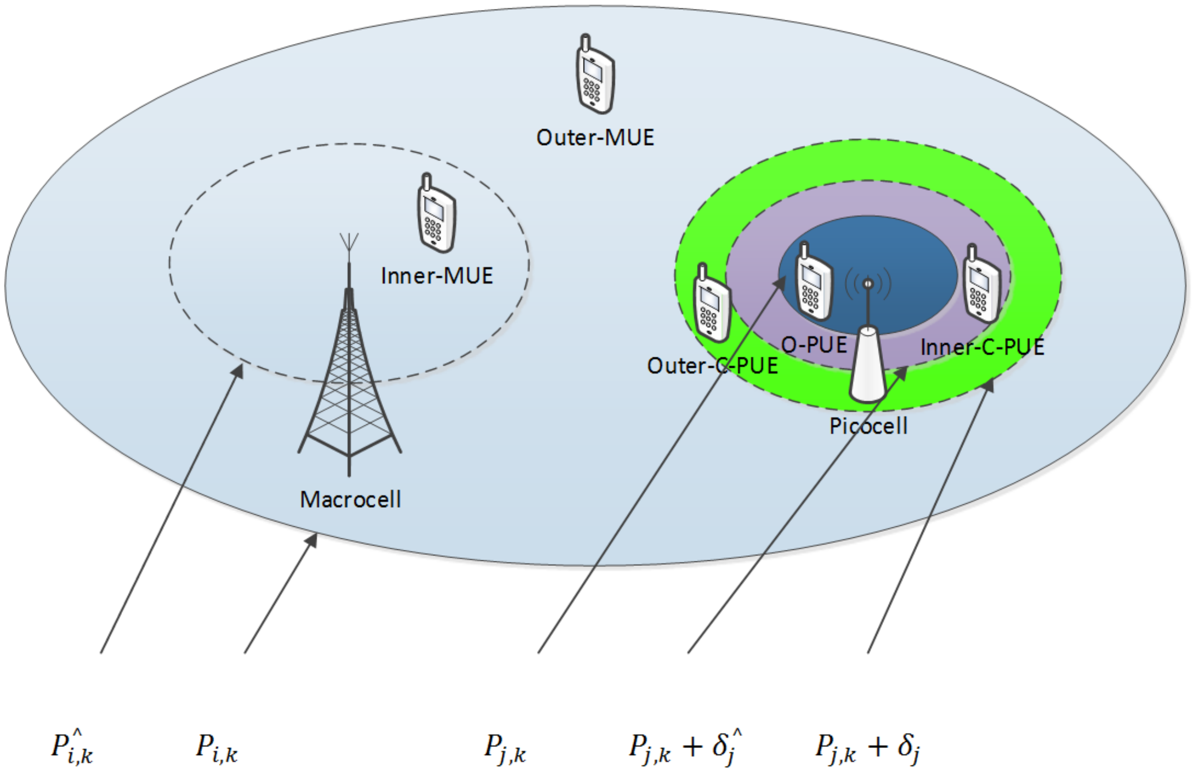


Figure 4-3: Users Classification

For all described notations, refer to Table 4-2.

4.2.1 Physical Resource Blocks Power Allocation

Conventionally, the total transmit power is distributed uniformly among the available physical resource blocks in every transmission period. In addition, only homogeneous power allocation is supported in the recent version of Vienna simulator [109]. However, there is a variable power allocation used in my proposed scheme which needs to modify the power allocation in the simulation tool. Therefore, RB power allocation was modified by accessing the resource block grid file in the simulator to change the power per RB based on the proposed scheme. After the normal power allocation in PRBs, ABS RBs got zero transmit power, while the RPS got half the share of the normal RBs. The reason behind choosing half the share of the transmit power for the RPSs is to maintain an optimum user and cell throughputs of the network. There is a trade of between Pico/ Macro cells performance for both user and cell throughputs when using other levels of PRPs transmit power as illustrated in Appendix I.

On one hand, setting higher transmit power for these subframes improves the signal strength of the Macro cells, which in turn leads to higher throughput and spectral efficiency. On the other hand, higher interference will be received by the edge users of the overlaid Pico cells as a result of the higher transmit power, which degrades both user and cell throughputs of the Pico cells.

Several simulations have been run using different settings of the RPS power distribution utilising 0.25, 0.5, and 0.75 transmit power of the normal RBs for low and high CRE values to examine the impact on both user and cell average throughputs. As a result, better throughputs for the total network have been introduced for the half transmit power of the RPSs according to the simulation results of Appendix I.

4.2.2 Prioritisation of Users

To enable the proposed scheduling algorithms in both Macro cell and Pico cell from working effectively, some users should be prioritised to be scheduled on the various special subframes. Users with lowest received signal from the Pico serving cell are considered cell-edge users (victim users), then they should be scheduled on the ABS and RPS, respectively. Whereas, the users of highest received signal from the Macro serving cell (aggressive users) have to be scheduled on the RPS to avoid any unnecessary interference towards the overlaid Pico cells.

In this way, it is required that all attached UEs to the Pico cell to be sorted ascendingly based on their received signals, while the attached UEs to the Macro cell to be sorted in descending order to filter the prioritised users easily.

4.2.3 The Proposed User Priority Scheduling Algorithms

Proportional fairness schedulers are widely used for resource allocation, which ensures fair resources for all users in the mobile network. However, in our proposed scheme we have two types of special subframes and three types of users with higher prioritisation over the rest of users.

For this reason, it is highly significant to suggest user priority scheduling algorithms for both Macro cells and Pico cells to prioritise these users for scheduling their data first, and to manage the resources effectively among all users.

4.2.3.1 Macro User Priority Algorithm

An enhanced scheduling algorithm is required when implementing such joint configuration, as two usable types of subframes and two types of MUEs are present. Figure 4-4 depicts the proposed scheduling algorithm, where the main function of this algorithm is to prioritise the Inner-MUEs to be scheduled on RPS because these users have better received power than Outer-MUEs. Thus, they still have an acceptable SINR as compared to the target (threshold) SINR when they are scheduled on subframes with reduced power. If all Inner-MUEs are satisfied or there are only a few of them present in the Macro cell's coverage, the remaining MUEs could be scheduled on these subframes if the normal subframes are full to avoid radio link failure for these residual MUEs.

Noting that, there is no resources waste in this algorithm because the LP-ABS subframes are utilised for Inner-MUEs data.

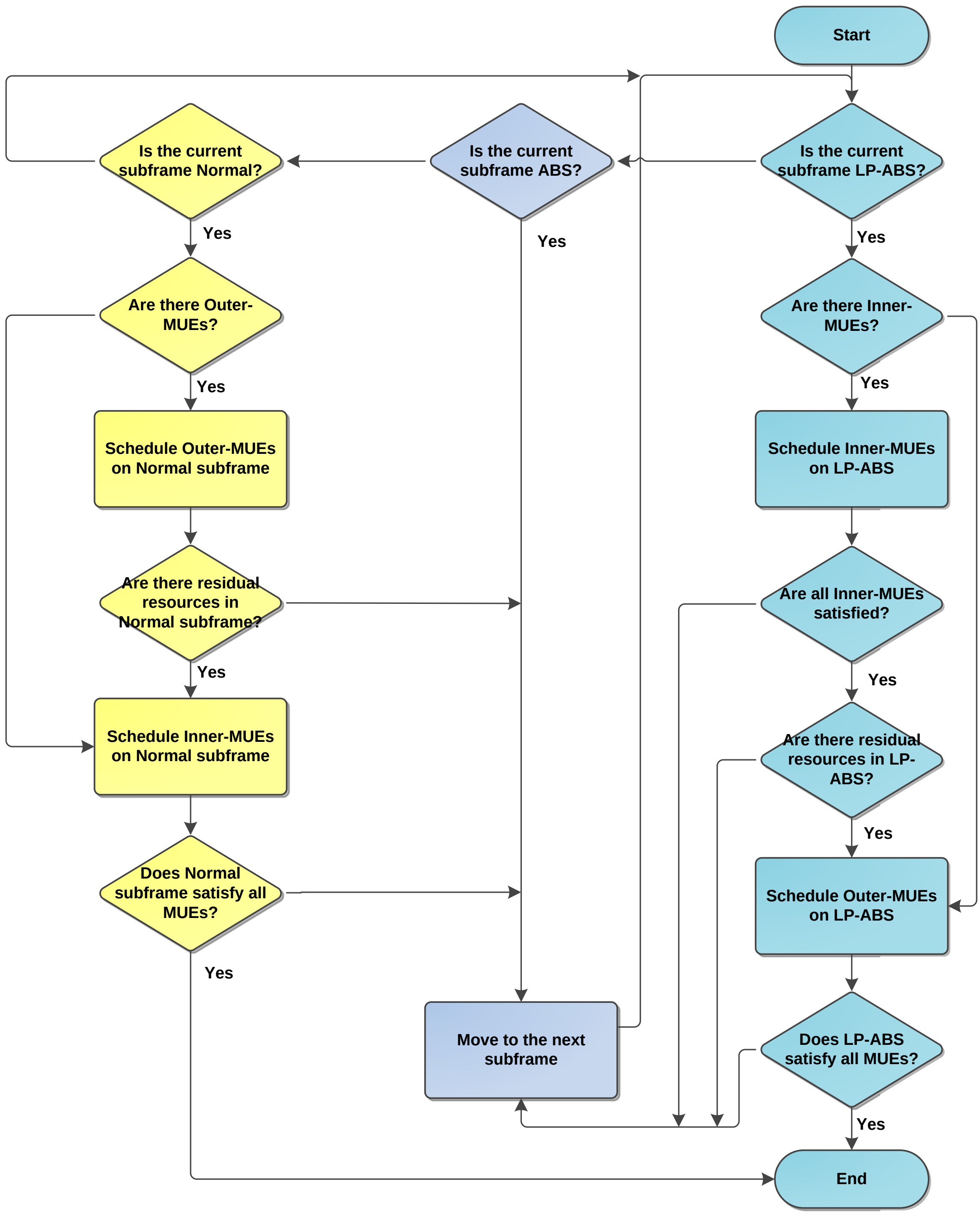


Figure 4-4: MUEs Scheduling Algorithm

4.2.3.2 Pico User Priority Algorithm

PUEs scheduling algorithm mainly depends on RSRP by the UE. As shown in Figure 4-5, it is more complex because three types of subframes are available for three types of PUEs, giving highest priority in scheduling to the Outer-C-UEs on ABS then the second highest priority to the Inner-C-UEs on RPS. Finally, the rest of Pico UEs will be scheduled as normal by the proportional fairness scheduler.

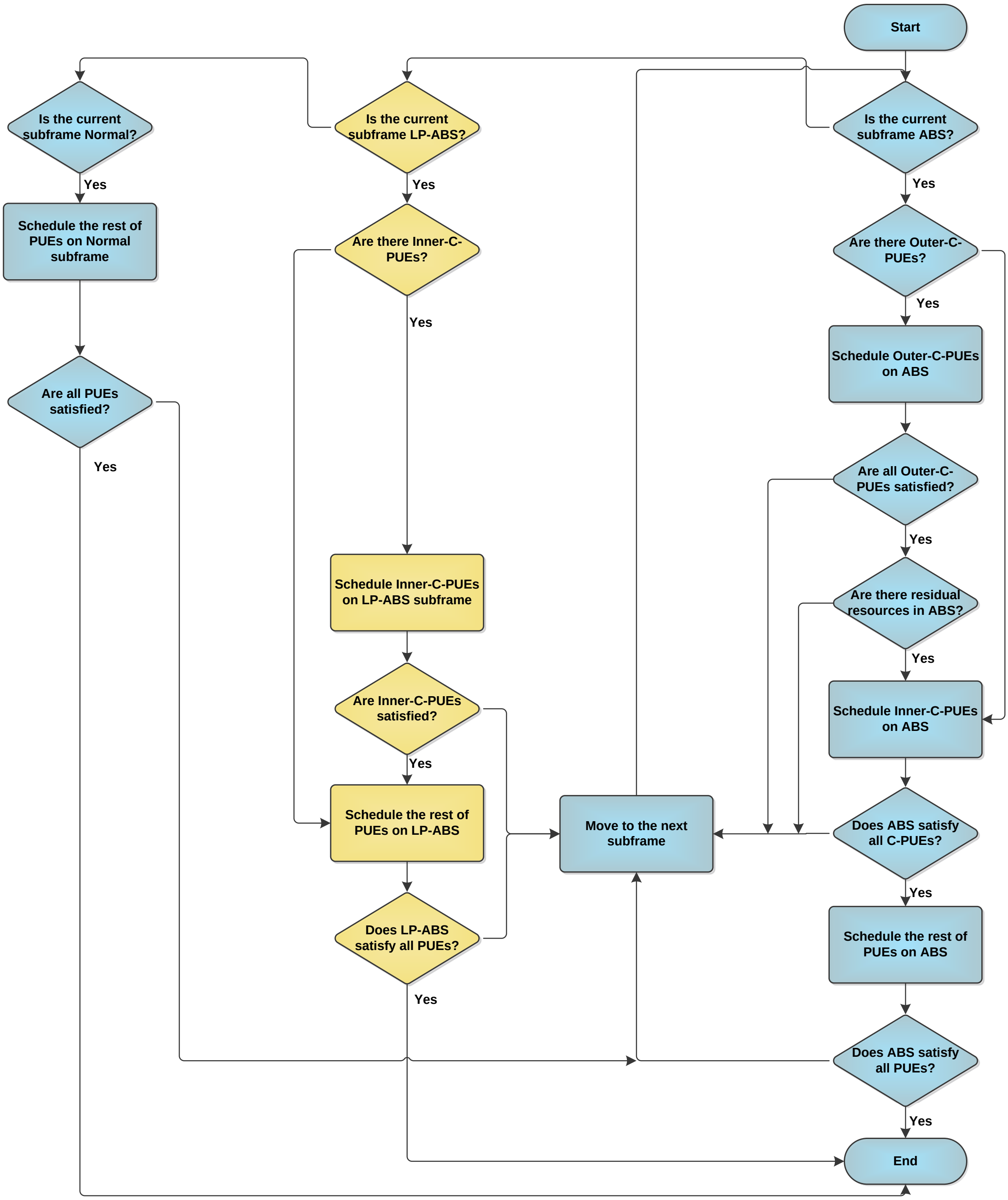


Figure 4-5: PUEs Scheduling Algorithm

4.3 System-Level Simulation of LTE-Advanced Networks

This research was conducted to design a joint scheme for inter-cell interference mitigation in LTE-A heterogeneous networks as an example of Orthogonal Frequency Division Multiple Access (OFDMA). It is also significant to analyse and evaluate the advantage of this proposed scheme over the already employed interference mitigation schemes as a part of research aim and objectives.

System-level simulations are required to create a model of a complex mobile network and to investigate the system performance under certain parameters and assumptions. To achieve this target, Vienna Simulator [110] has been used and modified as a downlink system level simulator to model an LTE-A mobile network with the proposed project. It has been chosen to implement the proposed scheme because it supports the physical layer of the LTE system. Moreover, it is an MATLAB-based LTE-A system-level simulator (supports both uplink and downlink systems), released by University of Vienna under the terms of academic, non-commercial use license. Therefore, there is a great support from the developers of this simulator through an online forum for all raised issues in any stage of the simulation.

4.3.1 Simulation Assumptions

This section introduces some simulation assumptions that have been adopted to model the LTE-A Heterogeneous network, consists of Macro cells and overlaid by several Pico cells as small cells:

- Most studies only take into account one interfering Macro cell to LPCs in HetNets, while few researches [90], [111] include the interference coming from adjacent Macro cells in LTE-Advanced HetNets, which should be involved in this scenario.
- The subframe pattern used in our scenario is depicted in Figure 4-1; where one subframe is totally blanked to for Outer CRE, while another subframe is reserved for

Inner-CRE with a reduced transmit power. Noting that, this pattern is repeated with duration of 8 milliseconds to support HARQ function in case of any radio link failure [112].

- With a bitmap of 40 bit, all possible special subframes configurations aligning with 8 ms uplink HARQ timing can be addressed in FDD deployments of heterogeneous networks [112].
- Assuming that all subcarriers within an RB of normal subframes experience the same radio channel conditions at any given time (i.e. frequency flat-fading in an RB) [113].
- The radio link is subject to propagation loss and log-normally distributed shadowing, while the fast fading is negligible for ease of simulation.
- In the simulations, perfect channel estimation, and perfect synchronisation are assumed. Channel estimation is assumed perfect, and 3GPP extended spatial channel model (SCME) is considered [84].
- Feedback channel delay is 1 Transmission Time Interval (1 TTI), which is the minimum delay for ACK reports [110].
- We assumed two mobility profiles: mobile users with a low speed of 5 km/h and only local mobility, such that no handovers occur [84], and higher vehicular speed of 60 km/h (with handover functionality) to investigate the impact of the high mobility on the proposed scheme. Both mobility profiles imply random routes for the mobile users.
- AWGN noise power is calculated by multiplying the noise power spectral density N_0 by the bandwidth of a unit resource block B/N.
- There are no latency constraints associated with simulated traffic.
- Total simulation time is 40 milliseconds (40 TTIs), and the map resolution is 5 m/ pixels.

- Inter- Macro cell interference is mitigated by FFR scheme or sophisticated frequency allocation [3].
- Each Macro cell is equipped with a single antenna, and the antenna of the Pico cell is Omni-directional.
- All UEs are uniformly distributed within the Region of Interest (ROI), and each UE selects its serving cell according to the maximum RSRP.

Table 4-1: Simulation Parameters

Parameter	Value
Carrier frequency	2.14 GHz
System bandwidth	20 MHz (LTE-Advanced)
MeNB Tx power (P_m)	46 dBm (40 W)
MeNB reduced Tx power (P_{ABS})	23 dBm (200 mW)
PeNB Tx power (P_p)	30 dBm (1 W)
MeNB Pathloss model ($L_{i,k}$)	$128.1 + 37.6\ log_{10}\ R\ (Km)$[114]
PeNB Pathloss model ($L_{j,k}$)	$140.7 + 36.7\ log_{10}\ R\ (Km)$ [114]
Standard Deviation Shadow fading	8 dB
Threshold SINR (γ_{min})	-2dB (0.631 W)
MeNB antenna gain (Urban)	15 dBi
PeNB antenna gain (Urban)	5 dBi
UE antenna gain	0 dBi
UE receive noise figure	9 dB
MeNB height	20 or 32 m (according to 36.814 Table A.2.1.1-2)
User Equipment height	1.5 m
User Equipment speed	5, 60 km/h
Inter-site distance (ISD)	500 m
Distance between MeNB and PeNB	200 m
Noise spectral density	-174 dBm/Hz
Subframe duration	1 ms (11 data +3 control symbols)
Special subframe ratio	2/8 (1 ABS+1 RPS)
Simulation Time	40 TTI
Traffic model	Full buffer, VOIP, FTP
Channel model	Typical Urban (TU)

Scheduler Type	Proportional Fairness with a priority algorithm
Minimum Coupling Loss (MCL) for Macro cell (Urban Area)	70 dB
Minimum Coupling Loss (MCL) for Pico cell (Urban Area)	45 dB
Pico cell wall loss	20 dB
Map Resolution	5 m/pixel
Target BLER	0.1
Feedback Channel Delay	1 TTI (the minimum for ACK reports)

Table 4-2: Notation Description

Notations	**Description**
P_i^M	Macro cell (i) transmit power on normal subframes
P_{RPS}	Macro cell (i) transmit power on RPS subframes
P_j^P	Pico cell (j) transmit power
$L_{i,k}$	Pathloss from UE_k to Macro cell (i)
$L_{j,k}$	Pathloss from UE_k to Pico cell (j)
$P_{i,k}$	RSRP received by UE_k from Macro cell (i) (Full Tx Power)
$P_{i,k}^{\wedge}$	RSRP received by UE_k from Macro cell (i) (Reduced Tx Power)
$P_{j,k}$	RSRP received by UE_k from Pico cell (j)
δ_j	CRE bias value in case of ABS
$\delta_j^{\wedge}$	CRE bias value in case of RPS
γ_k	SINR on RPS subframes
γ_{th}	Minimum SINR threshold for UE PDCCH decoding (target SINR)
N_0	Noise power spectral density

4.3.2 System Model

In this thesis, we consider simulating an LTE-Advanced heterogeneous network of Macro cells and Pico cells , respectively; using Urban settings with Inter-Site Distance (ISD) of 500 m [115]. The network (as shown in Figure 4-6) is composed of a central Macro eNodeB (forming three Macro cells) and six neighbouring Macro eNodeBs which are arranged according to a hexagonal grid [116]. Each Macro cell is overlaid by two Pico cells (6 Pico cells in total) using co-channel deployment for cost-effectiveness and high spectrum efficiency. These Pico cells are placed symmetrically at a distance of R = 200 m from the centre of each Macro cell, and there is an X2 interface between them and each Macro cell for interference coordination and resource sharing.

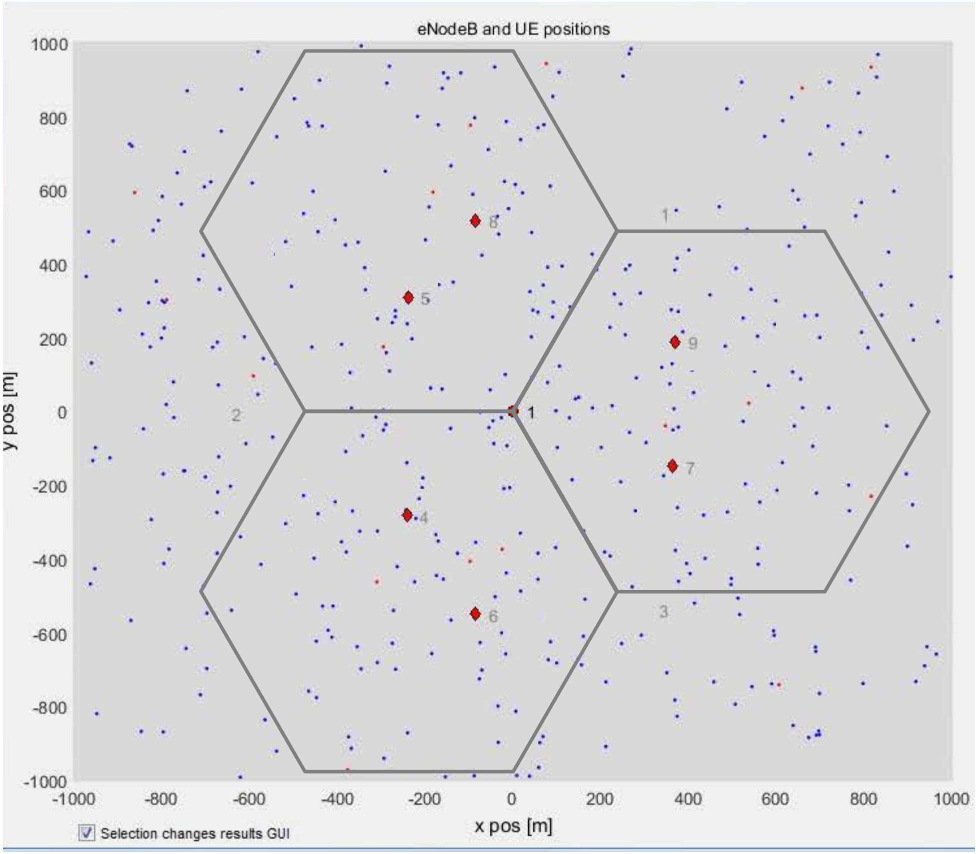


Figure 4-6: Network Scenario

The total channel bandwidth available for each cell is set to 20 MHz, to be compatible with the LTE-Advanced requirements [117]. This means that the total PRBs will be 100, which can be repeated in each cell as we consider co-channel deployment with frequency reuse factor of 1 for cost-effectiveness and high spectrum efficiency. 400 UEs are distributed uniformly within the Region of Interest (ROI) and set to attach the cell with higher RSRP as a serving cell, and starting moving in random routes at certain speeds as mentioned earlier.

Moreover, this simulation also takes into considerations the interference coming from the neighbour Macro cells, which are using frequency reuse factor of 3 to avoid any excessive interference between Macro cells.

In addition, CRE of 3 dB step is also be used to observe the impact of offloaded users towards the Pico cells. Noting that, propagation, traffic, and other models will be further detailed in section 4.3.

- **Network Definition**

To define an LTE-Advanced heterogeneous network, we need to introduce some general notations as follows:

- Macro cells: $M = \{M_1, \ldots, M_m, M_n, \ldots, M_M\}$,
- Where $N_m = \{N_1^m, \ldots, N_b^m, \ldots, N_{N_m}^m\}$ is the set of neighbouring cells of Macro cell M_m,
- Pico cells: $P = \{P_1, \ldots, P_f, P_g, \ldots, P_p\}$,
- Where $N_p = \{N_1^p, \ldots, N_b^p, \ldots, N_{N_p}^p\}$ is the set of neighbouring cell of Pico cell P_p,
- Macro users: M_m: $U^m = \{U_1^m, \ldots, U_u^m, \ldots, U_{U_m}^m\}$,
- Pico users: P_p: $U^p = \{U_1^p, \ldots, U_u^p, \ldots, U_{U_p}^p\}$,
- Subframes: $S = \{1, \ldots, s, \ldots, S\}$,
- Resource Blocks (RBs): $R = \{1, \ldots, r, \ldots, R\}$,

4.3.3 Traffic Model

Full-buffer traffic is considered in this thesis, which may represent the worst case among the other types of traffic models. In the full-buffer model, the number of users in the network is fixed, and each user's session lasts forever to create infinite data volume. In this way, the radio links are always utilised, and all cells are fully-loaded all the times. However, users with different radio conditions spend the same time in the system, in turn, leads to less generated data for users with poor radio conditions. "As a conclusion, full-buffer gives optimistic performance estimation which may deviate from reality" [118].

Noting that other types of traffic (FTP and VOIP) have been simulated for the proposed scheme and the simulation results are shown in Appendix II

4.3.4 Propagation Model

Mainly, heterogeneous networks are deployed in urban environments to cover the highly dense areas. Therefore, the urban model will be the most suitable model used in our simulations to evaluate the propagation path loss due to distance. In such types of models, radio wave propagation has two dominant paths which are over the rooftop and along the street. The first path is more dominant when the user is far from the cell, while the second path is more considerable as long as the user is close to the cell [118].

The received power in both downlink and uplink can be expressed as [114]:

$$RX\_PWR = TX\_PWR - Max(pathloss - G\_TX - G\_RX, MCL) \quad \textbf{(4-1)}$$

Where:

RX_PWR is the received signal power

TX_PWR is the transmitted signal power

G_TX is the transmitter antenna gain

G_RX is the receiver antenna gain

The propagation model for the Macro cell in urban environments can be express as [114]:

$$L = 40 \cdot (1 - 4 \cdot 10^{-3} \cdot Dhb) \cdot \log_{10}(R) - 18 \cdot \log_{10}(Dhb) + 21 \cdot \log_{10}(f) + 80dB \quad \textbf{(4-2)}$$

R is distance between Macro cell and user in kilometres

f is the frequency in MHz

Dhb is the Macro cell antenna height in meters, measured from rooftop level

When considering a carrier frequency of 2 GHz and a Macro cell antenna height of 15 m above rooftop level, the propagation model will be in the following formula:

$$L = 128.1 + 37.6 \log_{10}(R) \tag{4-3}$$

After L is calculated, log-normally distributed shadowing (*Log F*) with a standard deviation of 8 dB should be added [119].

The path loss is given by the following formula:

$$Pathloss\_Macro = L + LogF \tag{4-4}$$

Noting that, this model describes worse case propagation and it is mainly designed for distances ranging from few hundred meters to kilometres and not suitable for short distances.

Furthermore, the propagation model for the Pico cell in 2 GHz carrier frequency (for urban environments) can be express as [115]:

$$L = 140.7 + 36.7 \log_{10}(R) \tag{4-5}$$

4.3.5 Signal to Interference plus Noise Ratio (SINR) Model

The Signal-to Interference plus Noise Ratio (SINR) is a very important metric to be considered in performance evaluation of any mobile networks. It is calculated by the user and sent back to the network [5] to be mainly used for user throughput and cell capacity calculations, taking into account the interference coming from the neighbouring cells/ users.

The general SINR equation for UE_k attached to the cell (i) according to [120] is:

$$\gamma_{i,k} = \left(\frac{P_i \cdot H_{i,k}}{\sum_{q \neq i}^{I} P_q \cdot H_{q,k} + N_0}\right) \quad \textbf{(4-6)}$$

Where P_i represents the transmit power of the desired serving cell (i), and P_q is the transmit power of each neighbouring cell in the set of interferer cells (I) around the UE_k. In the same way, $H_{i,k}$ and $H_{q,k}$ refer to the channel gain from both serving and interferer cells toward the UE_k, respectively, and N_0 is the white Gaussian noise power. Channel gain in this thesis includes both transmit and receive antenna gains, in addition to the path loss gain between the transmitter and receiver.

As a result of having different types of cells in heterogeneous deployment, various types of SINR equations have to be modified to fit the suggested joint scheme with two types of special subframes (RBs).

The SINR equation for UE_k attached to a Macro cell (i) should be written as follows:

$$\gamma_{i,k} = \left(\frac{P_i^M \cdot H_{i,k}}{\sum_{n_m=1}^{N_m} P_{n_m} \cdot H_{n_m,k} + \sum_{n_p=1}^{N_p} P_{n_p} \cdot H_{n_p,k} + N_0}\right) \quad \textbf{(4-7)}$$

Where $P_i^M = \begin{cases} P_m \text{, in case of using normal subframes (Resource Blocks)} \\ P_{RPS}\text{, in case of using Reduced Power subframes (Resource Blocks)} \end{cases}$

Noting that, P_{n_m} and P_{n_p} denote to the transmit power of all neighbouring Macro cells and Low-power cells (Pico cells), respectively. Consequently, $H_{n_m,k}$ and $H_{n_p,k}$ represent the channel gains from both neighbouring Macro and Low-power cells (Pico cells).

On the other hand, a Pico user UE_k attached to a Pico cell (j) can use one of the three following types of SINR based on the used subframe (or RB):

$$\gamma_{j,k} = \left(\frac{P_j^P \cdot H_{j,k}}{\Phi \cdot H_{i,k} + \sum_{n_m=1}^{N_m} P_{n_m} \cdot H_{n_m,k} + \sum_{n_p=1}^{N_p} P_{n_p} \cdot H_{n_p,k} + N_0}\right) \quad \textbf{(4-8)}$$

Where P_j^P represents the transmit power of the serving Pico cell (j) and $H_{j,k}$ is the channel gain towards the Pico user UE_k, and Φ refers to the transmit power of the parent Macro cell where the serving Pico cell is deployed within its coverage area.

$$\Phi = \begin{cases} P_m \text{ , } in\ case\ of\ using\ normal\ subframes\ (Resource\ Blocks) \\ P_{RPS}, in\ case\ of\ using\ Reduced\ Power\ subframes\ (Resource\ Blocks) \\ 0, in\ case\ of\ using\ Almost\ Blank\ Subframes\ (Resource\ Blocks) \end{cases}$$

From the possible values of Φ, it can be clearly noticed that various values with reduced and zero power can result in higher SINR value for the most Pico users, especially that located near the cell edge and CE region. Knowing that the most interference in SINR equation is coming from the parent Macro cell, rather than the neighbouring cells.

Based on this SINR calculation, the user throughput (bit/ sec) obtained by UE_k attached to the cell (i) is calculated by Shannon Hartley theorem as shown in [121]:

$$\boldsymbol{R_i^k = W * log_2(1 + \gamma_{i,k})} \tag{4-10}$$

Where W is the bandwidth (Hertz) allocated for each user.

Generally speaking, the average user throughput is defined as the sum of user throughput of all users in the cell divided by the total number of active users, considering that radio resources are shared equally among these users. Therefore, there is a trade-off between coverage and capacity [122].

As a result, cell throughput is the sum throughput of all active users in that cell:

$$\boldsymbol{R_i = \sum_k^K R_i^k} \tag{4-11}$$

Fairness index is one of the important metrics used to determine whether users are receiving a fair share of the radio resources in the network. Jain's Fairness Index (JFI) is commonly used to determine the radio resources utilisation and defined as [123]:

$$\boldsymbol{JFI}\ (\boldsymbol{R_1}, \boldsymbol{R_2}, \dots, \boldsymbol{R_K}) = \frac{\left(\sum_{k=1}^{K} \boldsymbol{R_k}\right)^2}{\boldsymbol{N_{tot}} * \sum_{k=1}^{K} \boldsymbol{R_k^2}} \qquad \textbf{(4-12)}$$

Where R_k denotes the user throughput, and N_{tot} represents the total number of users attached to the cell.

The result of Jain's Fairness Index ranges from $1/N_{tot}$ (as a worst case) to 1 (as the best case), and it reaches the maximum value when all users share the radio resources equally.

4.3.6 Performance Metrics

In order to evaluate the performance of the proposed scheme in this thesis, Signal-to Interference plus Noise Ratio (SINR), cell and user throughputs, and other indicators (which are outlined in the following paragraphs) are also taken into considerations to estimate the system-level performance.

SINR, throughput, and spectral efficiency at various users' locations are calculated and evaluated by LTE-Advanced system level simulations, validating results from theory.

Here, the most common metrics which have been used to evaluate the performance of LTE-Advanced HetNet under our proposed scheme:

1- ***User Throughput***: Inter-cell interference mainly degrades the system performance of any mobile network in terms of throughput, so the main aim of inter-cell interference mitigation is to improve the network throughput for both users and cells of the mobile network. Both average and edge user throughputs are calculated as part of network performance evaluation. They are calculated for the macro user, Pico user, and the total active users in the network.

2- ***Cell Throughput***: Considering the average and edge cell throughputs in terms of macro cells, Pico cells, and the total cells in the network, respectively. Noting that, the cell throughput equals the sum throughput for all attached users to the cell.

3- ***Average user spectral efficiency***: Spectral Efficiency (SE) is one of the most important metrics to take into consideration when evaluating any mobile network. In our project, we considered spectrum efficiency for Macro, Pico, and total users in the proposed network.

4- ***Average RBs/ TTI/ UE***: In every Transmission Time Interval (TTI), the average number of Resource Blocks (RBs) allocated for each user is considered a significant metric to show the advantages of the scheduling algorithms.

5- ***Fairness index among UEs***: Any user in the network should get a relatively fair share of the available resources, to ensure sufficient experience as compared to the rest of users.

6- ***Number of offloaded users for each CRE value***: It indicates the number of offloaded users towards the Pico cells when for each range expansion value (0, 3, 6, 9, 12, 15), to evaluate the impact of Cell Range Expansion (CRE) on the other performance metrics.

Chapter Five: Simulation Results and Discussion

5.1 Introduction

This chapter evaluates the proposed scheme using system-level simulation (introduced in section 4.3) for full-buffer traffic as a worst case of traffic, based on the system model of section 4.3.2. Section 5.2 discusses the simulation results of the proposed scheme and the impact of increasing CRE values on the system performance because CRE value has a direct relationship with the inter-cell interference, where more CRE value means a higher biased area which results in more interference from the Macro cell toward users in this vulnerable region.

In addition, the evaluation of the scheduling algorithms of both Macro and Pico cells has been done in section 5.3, to test how efficient are the Physical Resource Blocks (PRBs) distributed among users with several types of the special subframes and different levels of users' priorities as suggested earlier.

Moreover, the performance of the proposed scheme was compared with ABS and RPS schemes, to show the advantages of this scheme over the other employed schemes in the literature based on similar system model and simulation assumptions to get an accurate comparison. Finally, section 5.5 summarises the outcomes of the whole results discussed in this chapter.

5.2 Simulation Results of the proposed scheme

This section presents the results of the proposed scheme using a system-level simulation introduced in section 4.3 for full-buffer traffic. In addition, all assumptions and performance metrics discussed in section 4.3.1 were taken into considerations. The proposed scheme was evaluated according to different CRE values (0, 3, 6, 9, 12, 15), to show the impact of these values on the performance of the network under the new scheme.

- **Number of offloaded UEs**

As mentioned earlier, one of Cell Range Expansion (CRE) aims is to offload more users from the possibly congested Macro cell towards the small cells. Figure 5-1 shows the number of offloaded users when applying different CRE values in our proposed scheme.

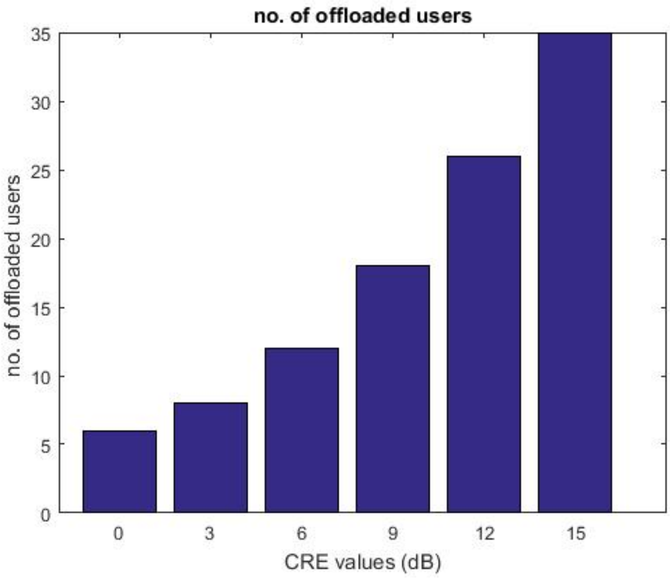
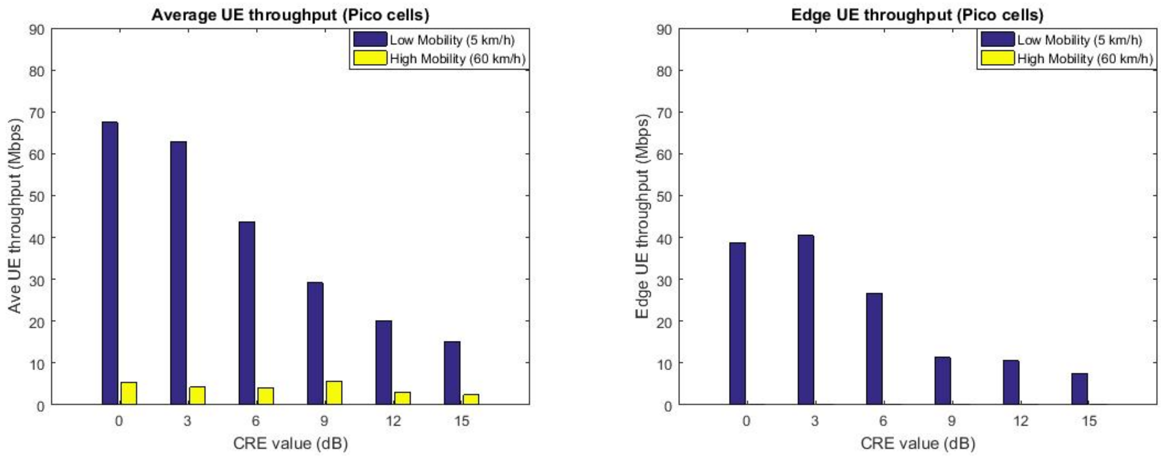


Figure 5-1: Number of offloaded users

It is clearly evident that the number of offloaded users is proportional to the CRE value as a result of increased cell coverage in case of higher (biased) transmit power. For instance, the original number of Pico UEs is 6 when there is no CRE biasing applied, while it increases to 8, 12, 18, 26, 35 for biasing of 3, 6, 9, 12, and, 15 dB, respectively. The reason for this increased offloaded users is the (biased) reference signal received power from the Pico cell becomes higher than that of the Macro cell for the users in the vicinity of the Pico cell.

- **User throughput performance**

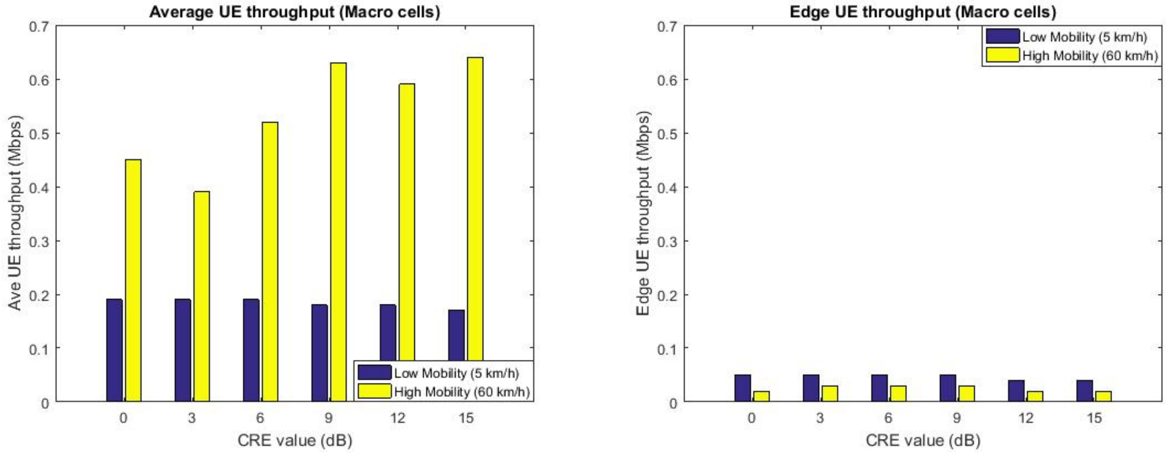
The following three figures show the user throughput (in Mbps) for different CRE Values under the proposed scheme. Figure 5-2 illustrates the average and edge throughput of Pico cell users, respectively. We can notice that these throughputs decreased by CRE increment, which is tightly connected to offload effects. The explanation for this decrement is because more users are offloaded to the Pico cell while the same RBs are shared between them. As a result, less throughput will result for every user. Therefore, a worse throughput (less than 20 Mbps for average and 7 Mbps for edge users) can be experienced for a biasing of larger than 9 dB as shown in Figure 5-2.



A **B**

Figure 5-2: Pico UE Throughput

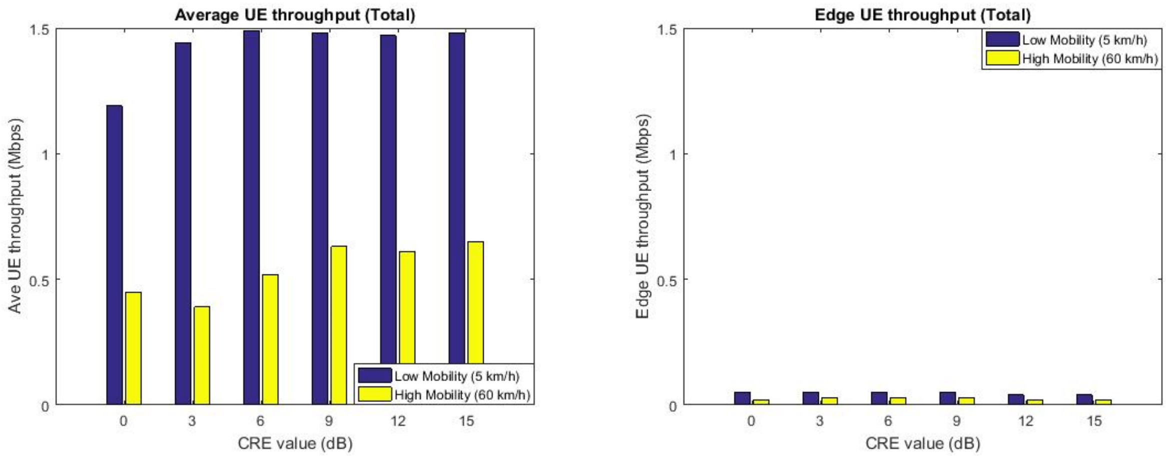
Regarding the Macro cell, we can notice no significant throughput change happens in Figure 5-3 because a small percentage of users are offloaded away as compared to the total number of connected users to the Macro cell. Therefore, steady average throughput (about 0.26 Mbps) can be shown for up to 12 dB biasing, while better edge throughput (0.08 Mbps) can be shown for the 9 dB CRE as clearly illustrated in the aforementioned figure.



A B

Figure 5-3: Macro UE Throughput

The total user throughput is considered as a resultant of both Macro and Pico users' throughputs, so Figure 5-4 shows a steady edge throughput of 0.08 Mbps for up to 12 dB of CRE, whereas better average throughput (about 1.48 Mbps) can be achieved for 3-9 dB.

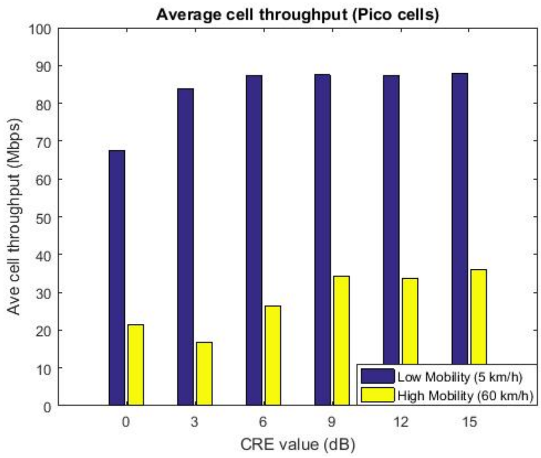


A B

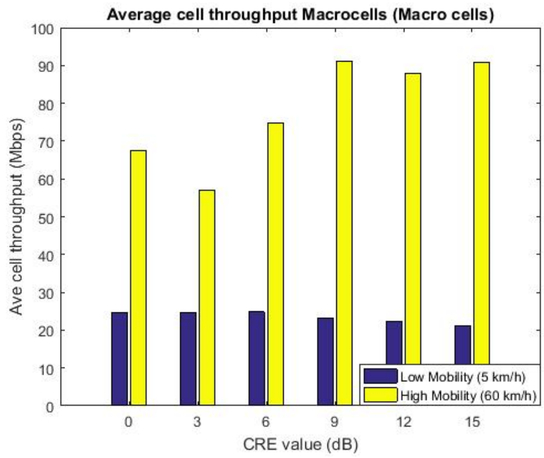
Figure 5-4: Total UE Throughput

- **Cell Throughput**

In theory, cell throughput denotes the sum throughput of all users, to indicate the cell performance under the proposed scheme. Figure 5-5 illustrates the cell throughput for Macro, Pico, and total cells in the network.



A

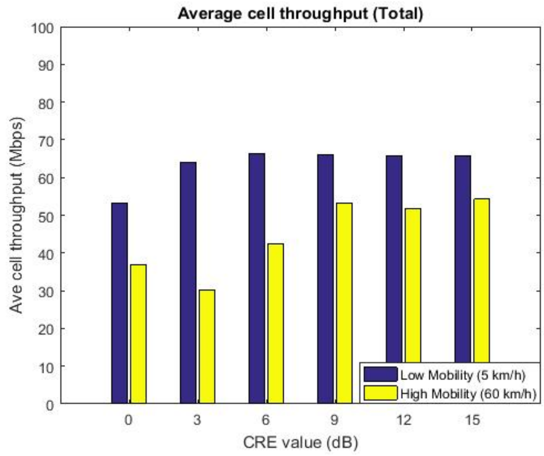


B

A- Average Cell Throughput (Pico cell)

B- Average Cell Throughput (Macro cell)

C- Average Cell Throughput (Total)



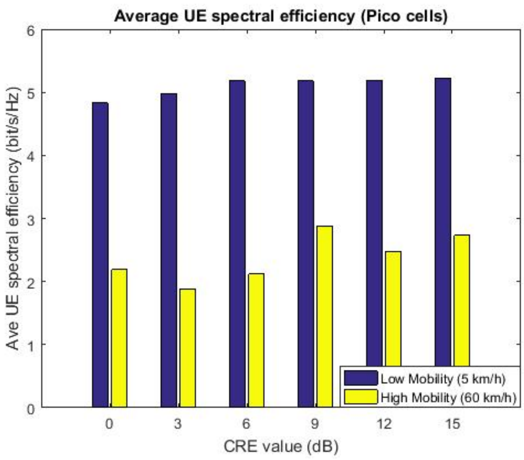
C

Figure 5-5: Cell Throughput

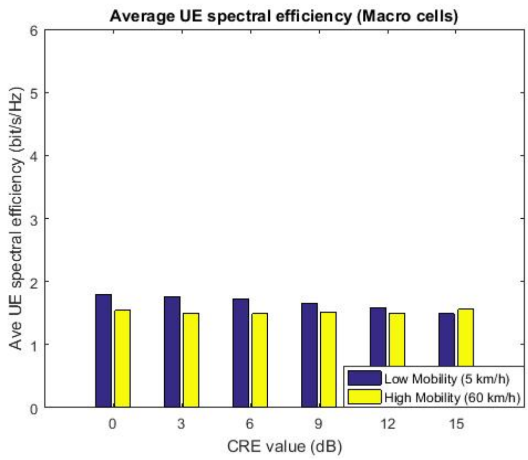
Pico cell shows a uniform throughput of 88.6 Mbps between 9-15 dB of CRE, but Macro cell shows the highest throughput of 34.2 Mbps for 6-9 dB biasing. As a result, the total cell throughput nearly uniform values of about 70 Mbps for a wide range of biasing (3-12 dB).

- **Average User Spectral Efficiency**

Spectral efficiency is one of the important factors to measure the resource allocation performance in any mobile network. It can be clearly noticed in Figure 5-6 a relatively balanced spectral efficiency in the network (about 5.27 and 2.42 bit/s/Hz) for both Pico and total users, respectively. However, the Macro users' spectral efficiency is significantly degraded after 12 dB of CRE, as a result of the unrealistic biased region which requires more protected subframe reserved for Pico cell edge users (victim users).



A

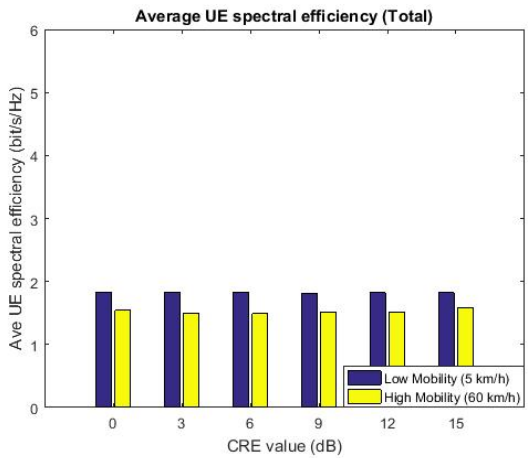


B

A- **Average Spectral Efficiency (Pico cell)**

B- **Average Spectral Efficiency (Macro cell)**

C- **Average Spectral Efficiency (Total)**

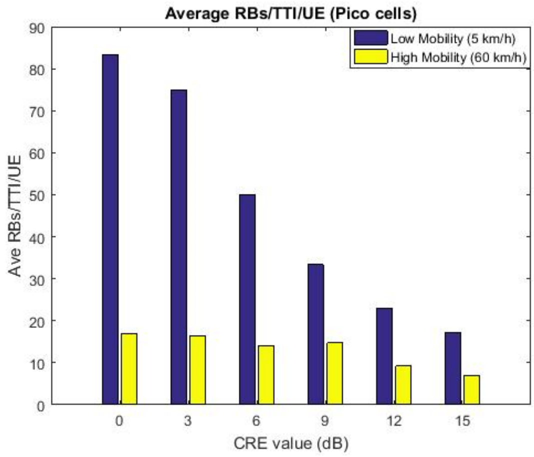


C

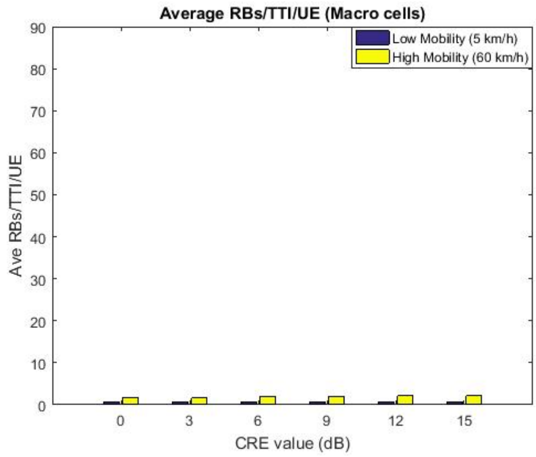
Figure 5-6: Average UE Spectral Efficiency

- **Average RBs/ TTI/ UE**

The spectral efficiency is directly associated with the available resources for each user. It can be depicted in Figure 5-7 that the available RBs for every user in each Transmission Time Interval (TTI) is decreased exponentially for the Pico cell, due to a significant number of users added to the cell as compared to the total number of connected users, which share the same amount of RBs. On the other hand, this impact is trivial for the Macro cell, as a result of a minor change in the number of connected users, which leads in turn to a steady distribution of RBs in the entire network.



A

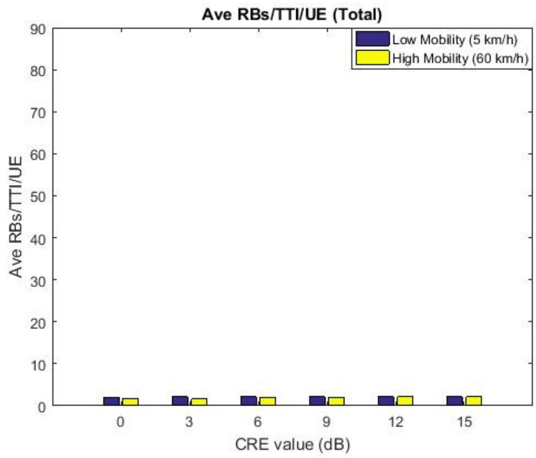


B

A- Average RBs/ TTI/ UE (Pico cell)

B- Average RBs/ TTI/ UE (Macro cell)

C- Average RBs/ TTI/ UE (Total)

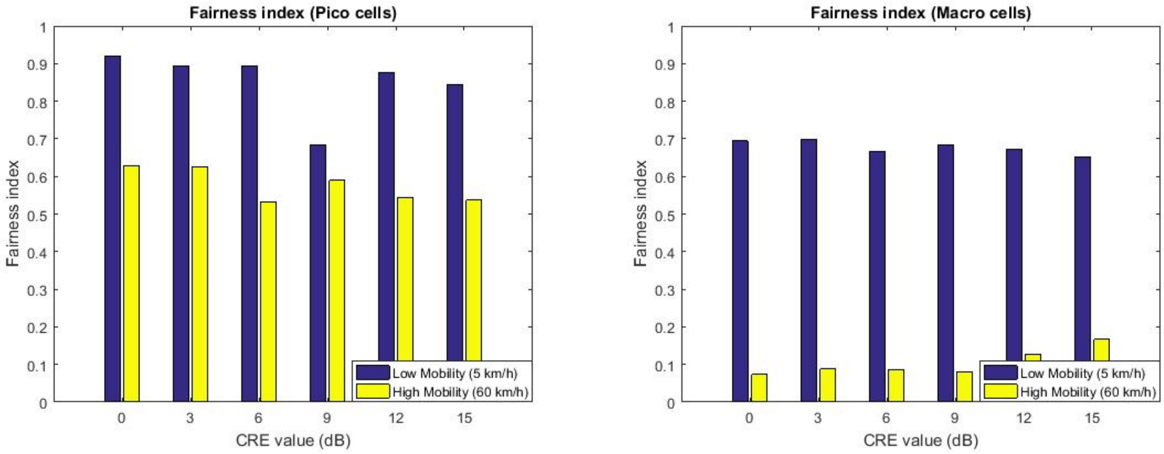


C

Figure 5-7: Average RBs/ TTI/ UE

- **Fairness among Users**

Jain's fairness index (mentioned in section 4.3.5) is considered to evaluate how much fair resources every user gets when employing the proposed scheme. Figure 5-8 illustrates the fairness index for Pico, Macro, and total users, respectively.



A **B**

Figure 5-8: Fairness Index among UEs

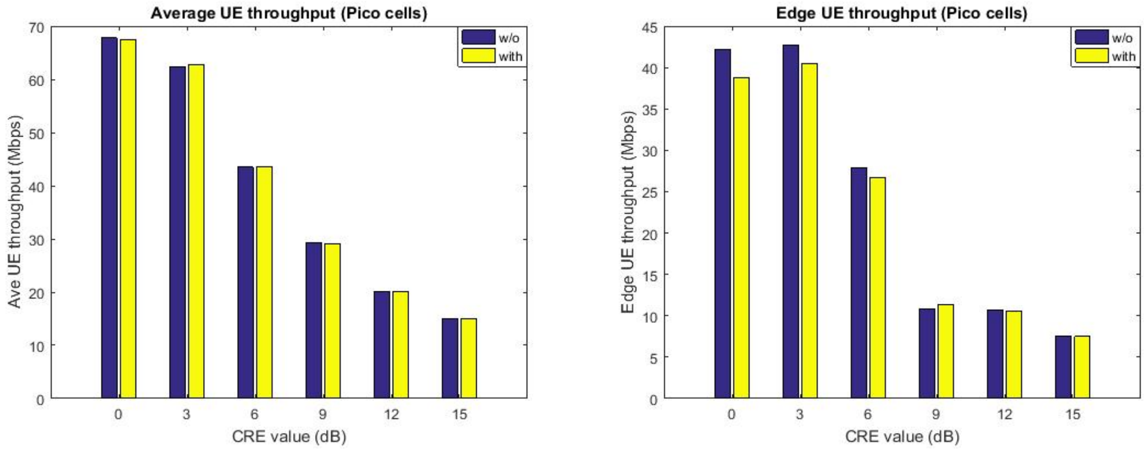
It can show a relatively uniform index among all Macro users, while an alternating index for Pico users. However, fairness index for the total users shows better fairness when increasing the CRE value, which is considered a merit of the scheduling algorithm under the proposed scheme.

5.3 Evaluation of the Scheduling Algorithms

The proposed scheme highly requires powerful priority scheduling algorithms for efficient resource allocation of all users in the network. The reason behind this, we have several types of special subframes and users of different priorities. These algorithms for both Macro cell and Pico cells have been evaluated using system-level simulation to show the importance of such algorithms in this scheme, by comparing the network performance when using these algorithms to that case when the ordinary proportion fairness scheduler is used.

The following simulation results depict the performance of the proposed scheduling algorithms by comparing it with the case without using it, based on the performance metrics suggested in section 4.3.6.

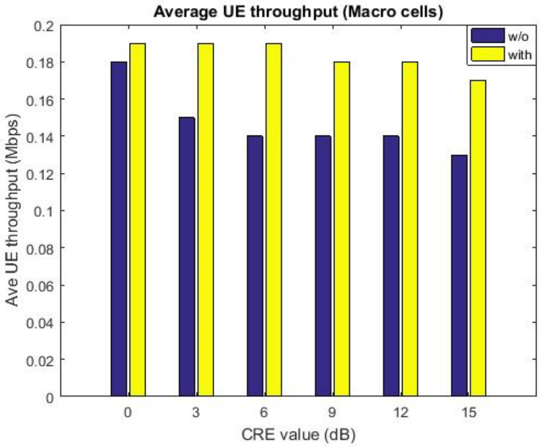
It can be noticed in Figure 5-9 (A) that Pico UE average throughput is going to perform equally for both cases. However, the edge UE throughput in (B) is degraded in small CRE values, while it is close to the case of using proportional fairness scheduler in the higher CRE values.



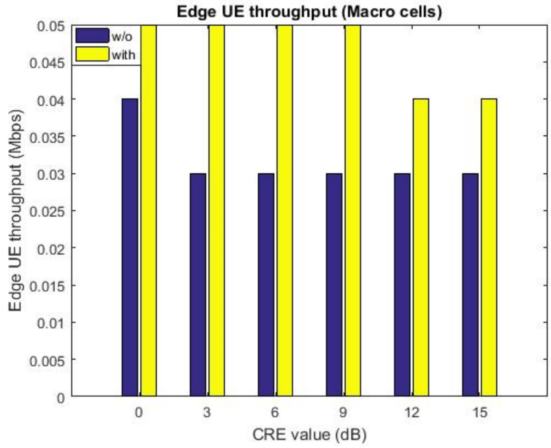
A **B**

Figure 5-9: Pico UE Throughput (Algorithm Evaluation)

Figure 5-10 depicts the performance of Macro UE throughput, where it can be clearly observed that Macro cell scheduling algorithm outperforms in all CRE values for both average and edge UE throughputs, as compared to employed standard scheduler.



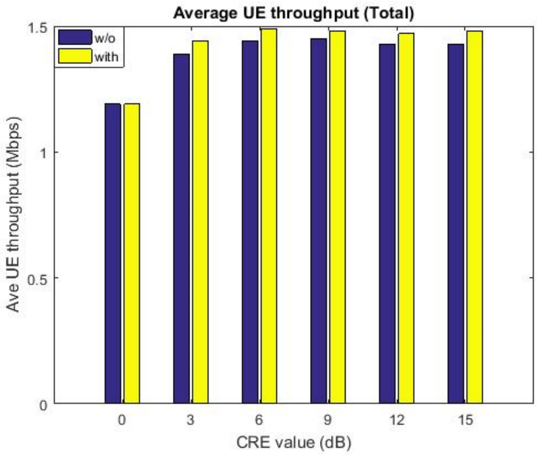
A



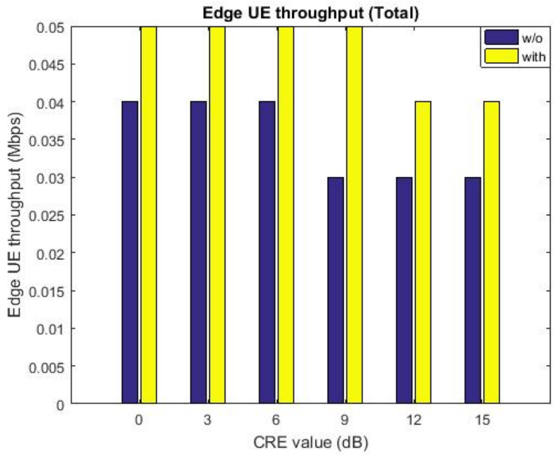
B

Figure 5-10: Macro UE Throughput (Algorithm Evaluation)

Hence, this performance, in turn, is reflected on the total UE throughput as it comprises both Pico and Macro UEs within the network. Figure 5-11 shows total UE performance under the proposed algorithms, which can significantly optimise the edge UE throughput as required to overcome the severe interference on cell-edge users in the simulated network.



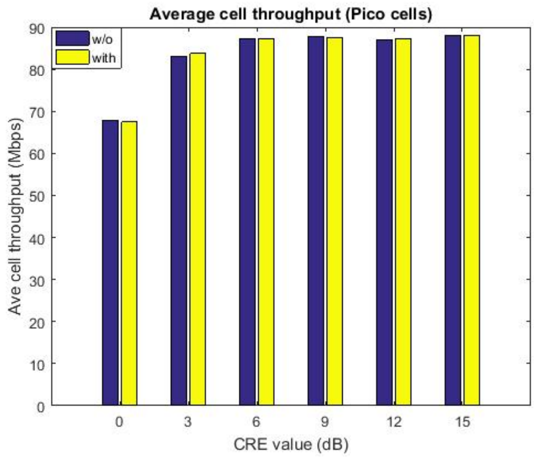
A



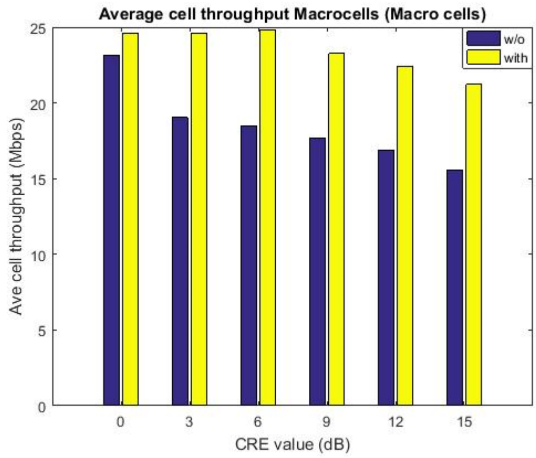
B

Figure 5-11: Total UE Throughput (Algorithm Evaluation)

It is common sense that cell throughput is the sum throughput of user throughput. So, Figure 5-12 illustrates cell throughput for Pico, Macro, and total cells, respectively. According to the previous figures for UEs throughputs, a significant improvement in Macro cell throughput can be achieved when using the proposed Macro cell scheduling algorithm, which in turn leads to better total cell throughput as shown below.



A

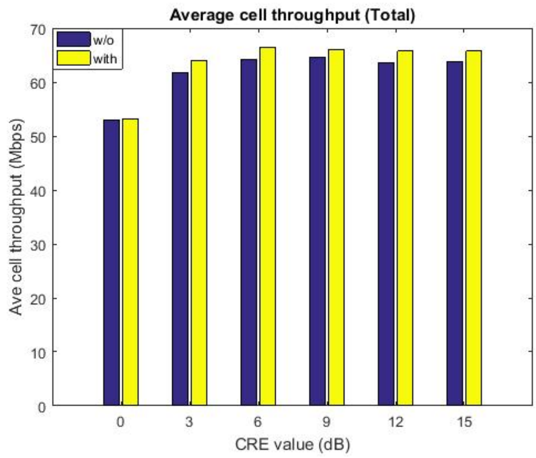


B

A- Average Cell Throughput (Pico cell)

B- Average Cell Throughput (Macro cell)

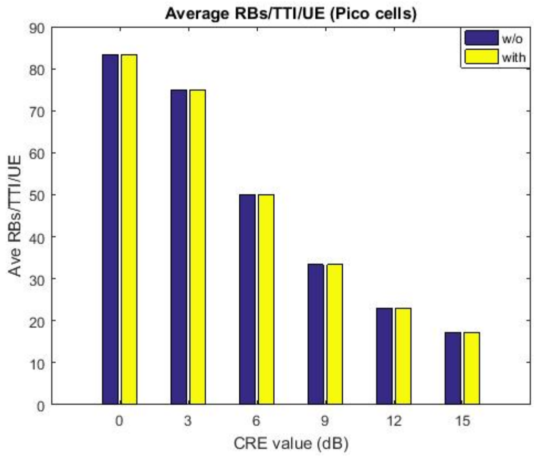
C- Average Cell Throughput (Total)



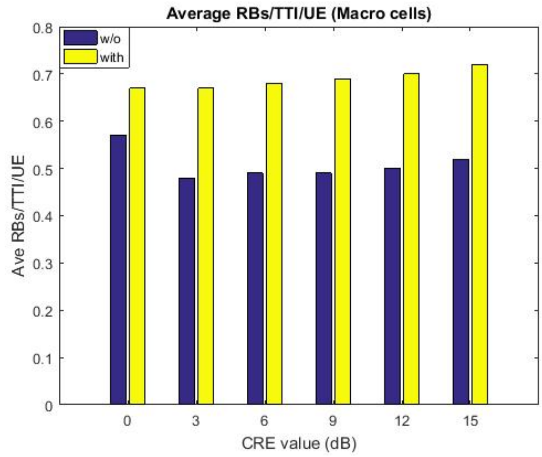
C

Figure 5-12: Average Cell Throughput (Algorithm Evaluation)

As we know that power of the proposed algorithm is mainly associated with the efficient resource allocation for all users in the network. Therefore, it is important to illustrate the average Resource Blocks (RBs) available for each UE for every Transmission Time Interval (TTI). Figure 5-13 depicts that for Pico, Macro, and the total UEs, respectively. It can be clearly noticed that the resource allocation in Macro scheduling algorithm outperforms that in Pico algorithm, which also has a positive impact on the total resource allocation in the network.



A

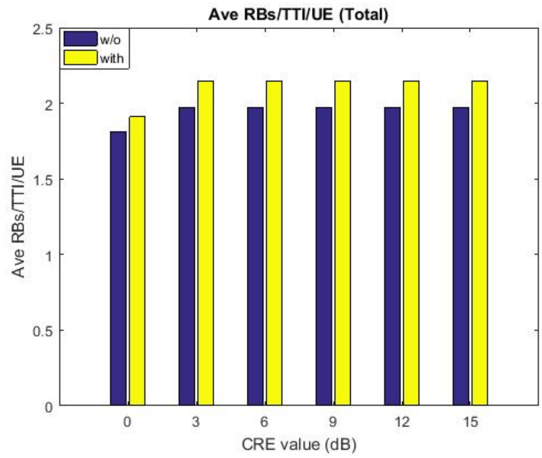


B

A- Average RBs/ TTI/ UE (Pico cell)

B- Average RBs/ TTI/ UE (Macro cell)

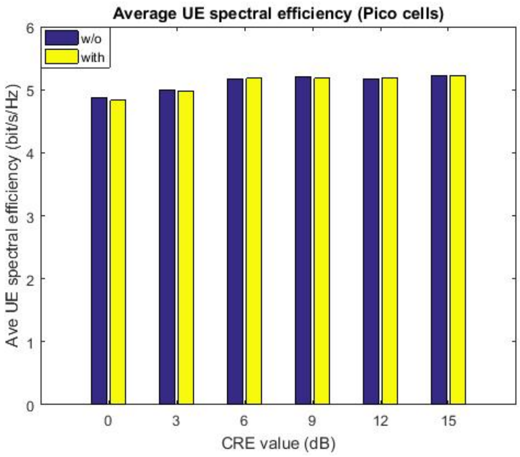
C- Average RBs/ TTI/ UE (Total)



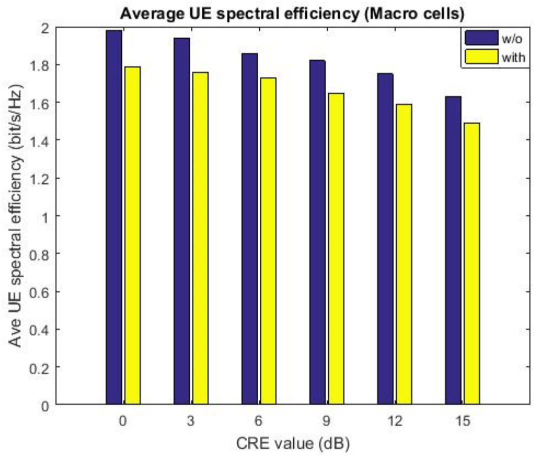
C

Figure 5-13: Average RBs/ TTI/ UE (Algorithm Evaluation)

The average spectral efficiency is an important factor to evaluate the performance of any mobile network; especially it is related to the UE throughput and the available resources. It represents the relationship between the throughput and the used bandwidth. Figure 5-14 (A) shows spectral efficiency closer to that of using proportional fairness scheduler in the case of Pico cell UEs. On the other hand, Macro UE (B) and total UE (C) spectral efficiency is less in our proposed algorithm, as a result of more resources available for UEs (as shown in Figure 5-14) to achieve the same throughput, which reduces the resulted spectral efficiency when compared to the standard case.



A

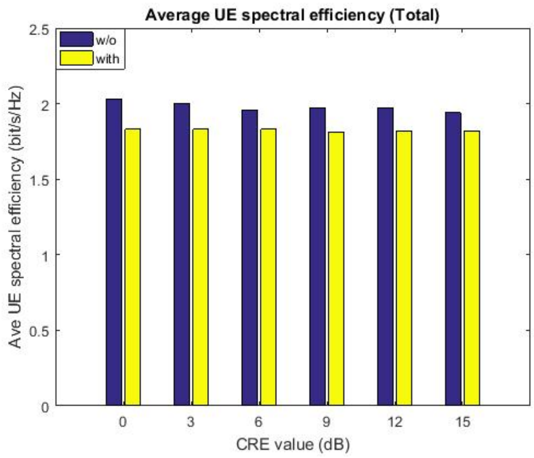


B

A- **Average Spectral Efficiency (Pico cell)**

B- **Average Spectral Efficiency (Macro cell)**

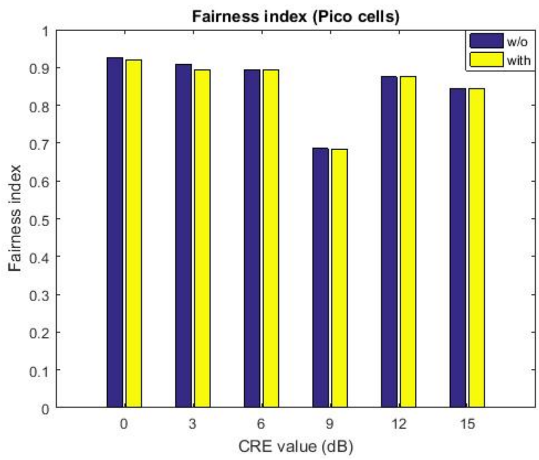
C- **Average Spectral Efficiency (Total)**



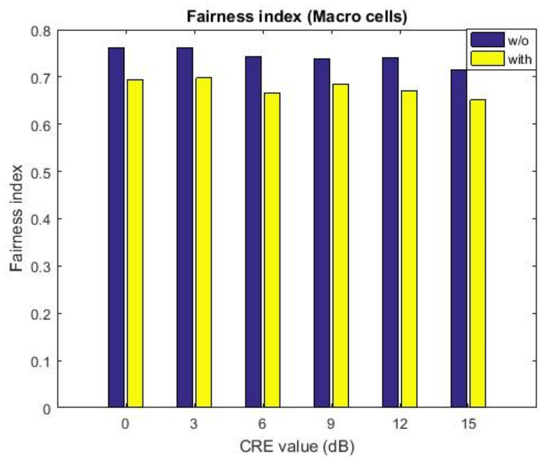
C

Figure 5-14: Average Spectral Efficiency (Algorithm Evaluation)

Fairness Index is another important factor to compare the performance of scheduling algorithms; it can reflect how much fair share available for every user in the network. Figure 5-15 depicts the fairness index for Pico UEs (A), Macro UEs (B), and Total UEs (C), respectively. The best fairness can be shown among the total UEs, while it has less value in case of Macro UEs and equal performance in Pico UEs, as compared to the regular PF scheduler.

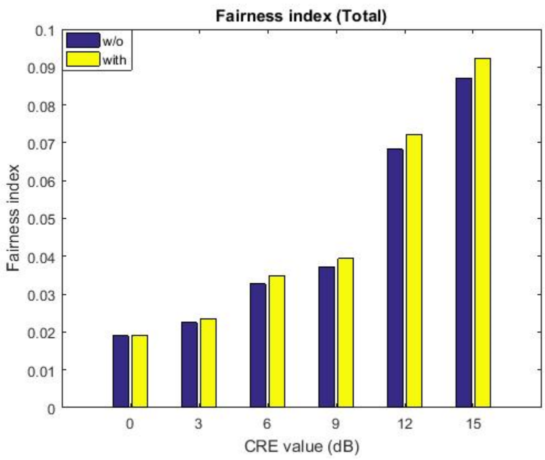


A



B

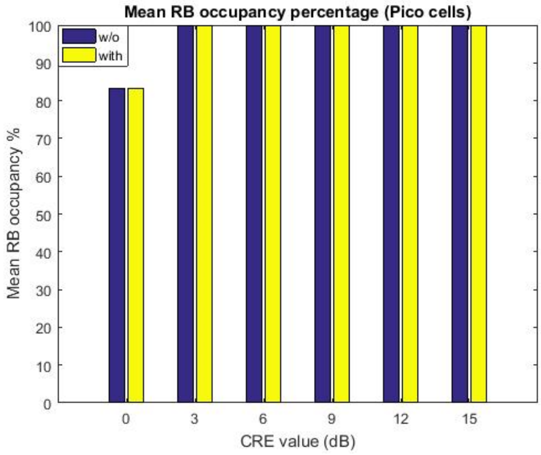
- **A-** **Fairness Index (Pico cell)**
- **B-** **Fairness Index (Macro cell)**
- **C-** **Fairness Index (Total)**



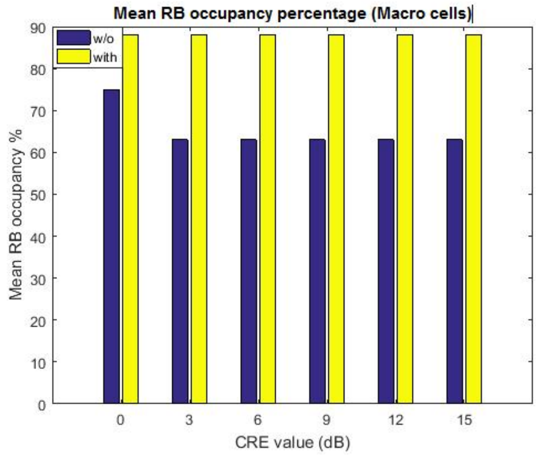
C

Figure 5-15: Fairness Index (Algorithm Evaluation)

One of the main objectives of our research is to utilise the frequency spectrum effectively, by avoiding RBs waste as a result of more blanked subframes in the Macro cell as an aggressive node. Figure 5-16 (B) shows that Macro cell scheduling algorithm is leveraging more usable RBs, which is considered a significant achievement in the whole algorithm. Moreover, it has a good impact on the total RB occupancy (C) as well. On the other hand, there is no change in mean RB occupancy for Pico cell (A) because in either case all RBs in the Pico cells are occupied.



A

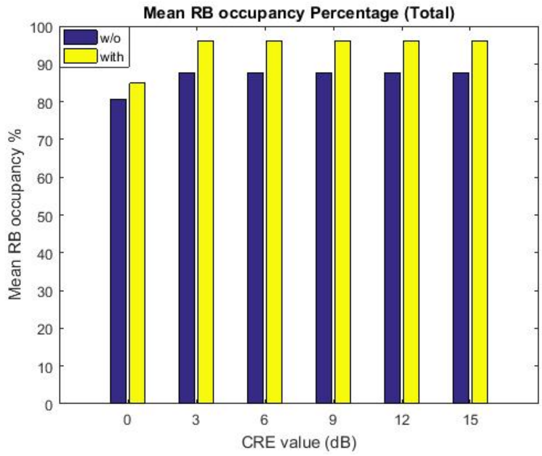


B

A- Mean RB Occupancy Percentage (Pico cell)

B- Mean RB Occupancy Percentage (Macro cell)

C- Mean RB Occupancy Percentage (Total)



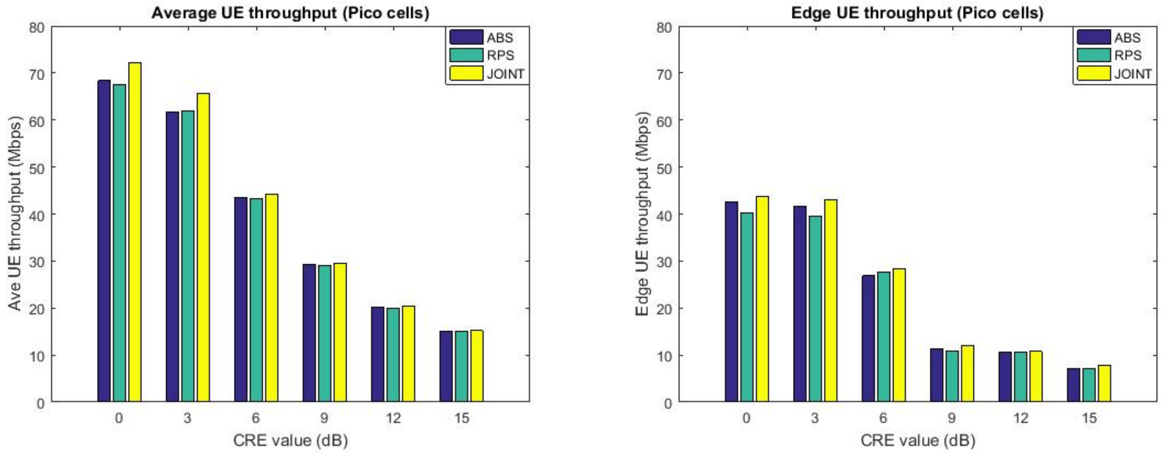
C

Figure 5-16: Mean RB Occupancy Percentage (Algorithm Evaluation)

5.4 Comparison with other works in the literature

It is vital to compare the performance of the proposed scheme with the other works in literature, to show the advantage of this scheme over the other employed schemes based on performance metrics of section 4.3.6. Therefore, the proposed scheme performance can be compared with two other schemes of using Almost Blank Subframes (ABS) and Reduced Power Subframes (RPS) as they are suggested and standardised by 3GPP for ICIC in LTE-Advanced Heterogeneous mobile networks. Figure 5-17 illustrates both average (A) and edge (B) UE throughputs (in Mbps) of the Pico cells in the simulated network, respectively.

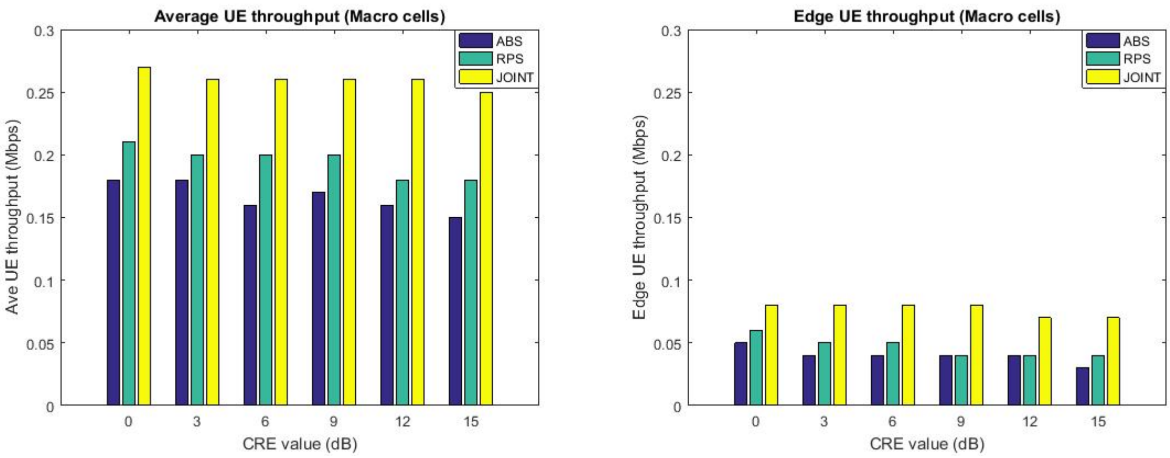
It can be noticed from the figure that the proposed scheme outperforms (about 6.5-8.5 %) the other schemes more in low CRE values (3-6 dB) for both average and edge throughputs, while it achieves a slightly higher throughput in higher CRE values (9-15 dB).



A B

Figure 5-17: Pico UE Throughput (Comparison with other Schemes)

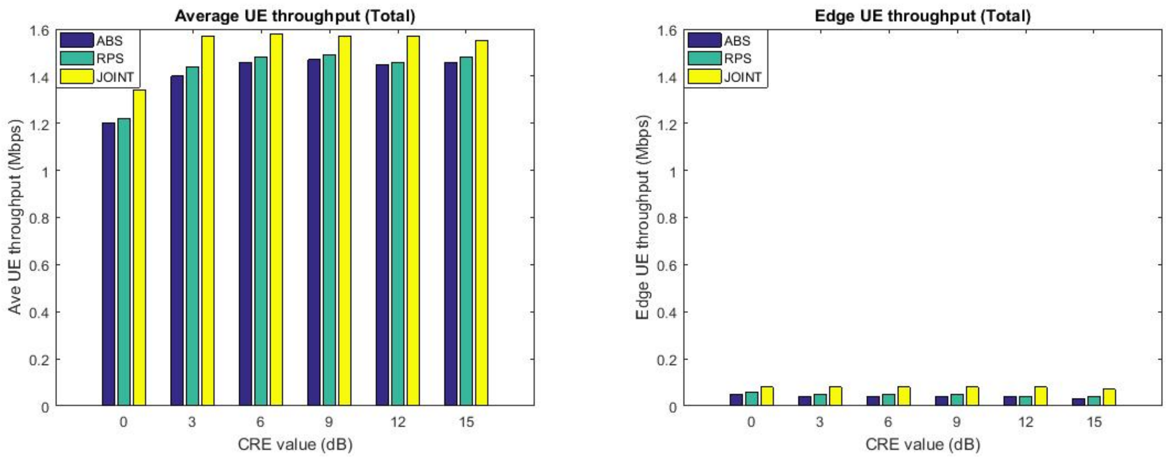
It was concluded from scheduling algorithms performance in section5.3, the performance of the Macro cell scheduling algorithm is higher as compared to the Pico cell scheduling algorithm, which was noticed clearly in Figure 5-9 and Figure 5-10, respectively. Hence, Figure 5-18 (A) illustrates that our scheme shows about 33% and 22% higher average Macro UE throughput, as compared to ABS and RPS schemes, respectively. On the other hand, Figure 5-18 (B) depicts edge UE throughput for the Macro cells, where we can achieve up to 50% higher throughput in higher CRE values.



A **B**

Figure 5-18: Macro UE Throughput (Comparison with other Schemes)

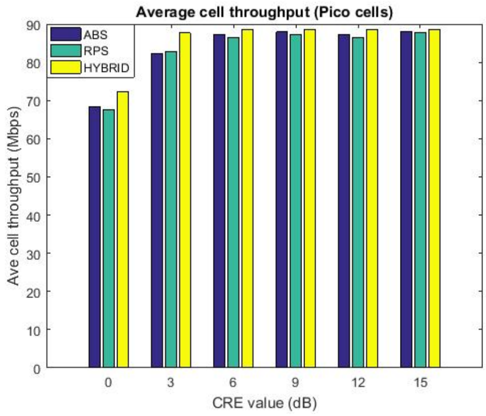
As a result of the aforementioned Macro and Pico cells performance under our proposed scheme, there is still better performance in average UE throughput in the whole network, and significant performance in edge UE throughputs (37.5% and 50%) as compared with RPS and ABS, respectively as shown in Figure 5-19.



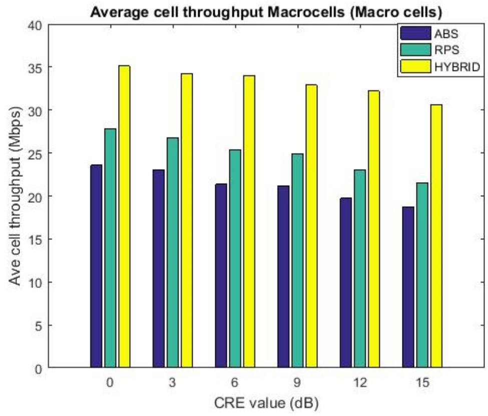
A **B**

Figure 5-19: Total UE Throughput (Comparison with other Schemes)

Figure 5-20 depicts the average cell throughput for Pico cells (A), Macro cells (B), and the total cells in the network (C), respectively. As mentioned earlier, average cell throughput equals the sum throughput of each UE in the cell. Therefore, the highest performance can be expected in the average Macro cell throughput (more than 20% higher), based on discussion of Figure 5-18.



A

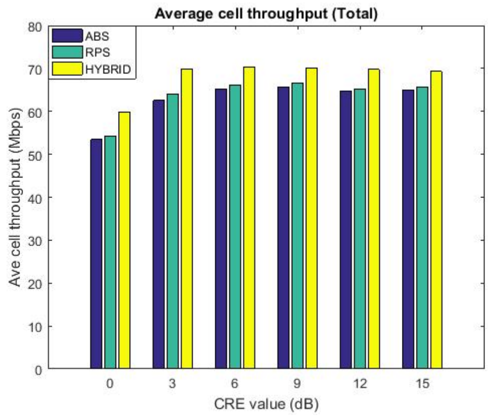


B

A- Average Cell Throughput (Pico cell)

B- Average Cell Throughput (Macro cell)

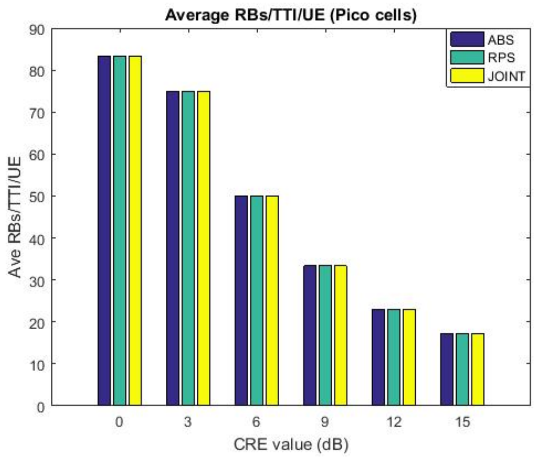
C- Average Cell Throughput (Total)



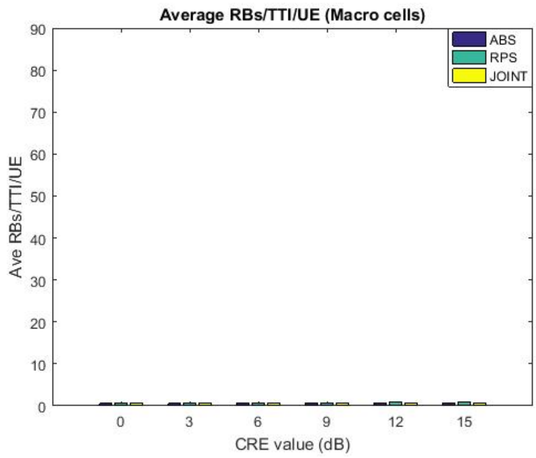
C

Figure 5-20: Average Cell Throughput (Comparison with other Schemes)

One of the most important factors to determine the performance of the proposed scheme over the other employed schemes is the number of Resource Blocks (RBs) available for each UE in every Transmission Time Interval (TTI), which has a significant impact on all other performance metrics. Figure 5-21 depicts that for Pico, Macro, and the total UEs, respectively. In (A) we can be clearly observed that all the three schemes perform equally because in each of these schemes all allocated RBs are available for the Pico cells. However, Figure 5-21 (B) shows significant disparity in the available RBs for the Macro cell in each scheme, as a result of different types of special subframes reserved for the edge users of the victim cell(s). These subframes can be totally blanked or partially used by the Macro cell (aggressor) which directly affects the available RBs in that cell when applying different schemes.

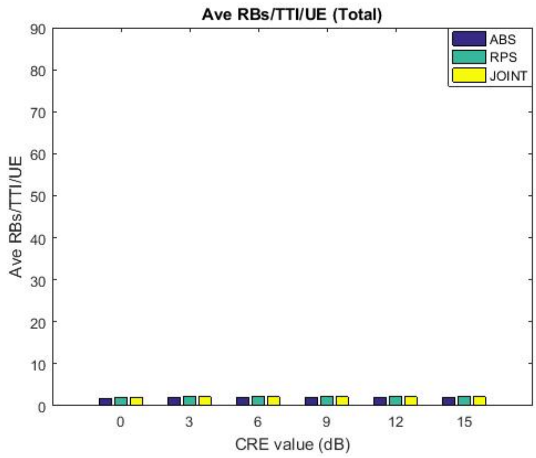


A



B

- **A- Average RBs/ TTI/ UE (Pico cell)**
- **B- Average RBs/ TTI/ UE (Macro cell)**
- **C- Average RBs/ TTI/ UE (Total)**



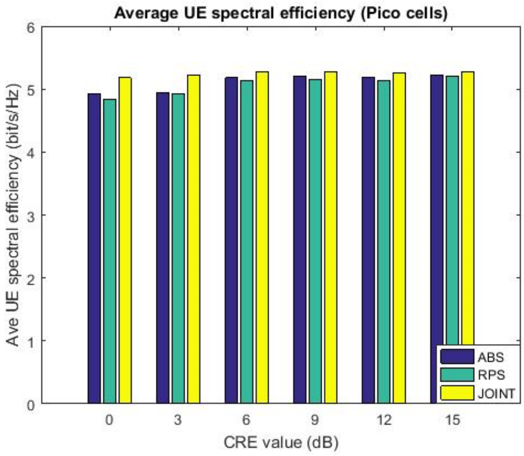
C

Figure 5-21: Average RBs/ TTI/ UE (Comparison with other Schemes)

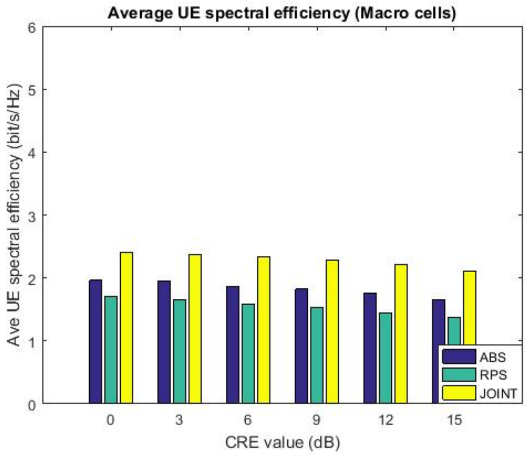
It can be clearly seen that our scheme provides a compromise between ABS and RPS in terms of the available RBs, while it achieves higher throughputs compared to the standard ICIC schemes.

Spectral efficiency is another important factor used to evaluate the performance of the simulated network under the proposed inter-cell interference coordination scheme. It is tightly associated with user throughput and the available RBs for each user in the network.

Therefore, Figure 5-22 shows that the network experiences higher spectral efficiency in the Macro cell, as a result of higher average UE throughput (depicted in Figure 5-18), and more available RBs for Macro users as shown in Figure 5-21.



A

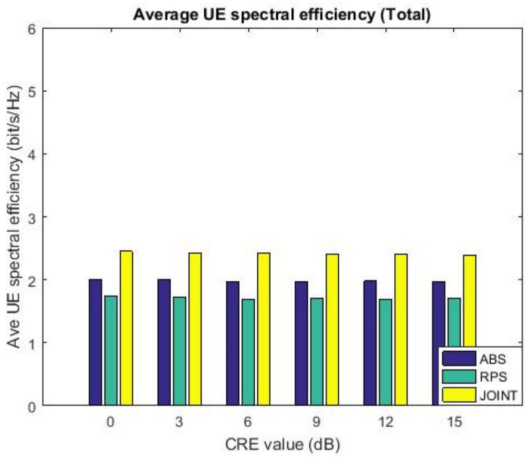


B

A- Average Spectral Efficiency (Pico cell)

B- Average Spectral Efficiency (Macro cell)

C- Average Spectral Efficiency (Total)



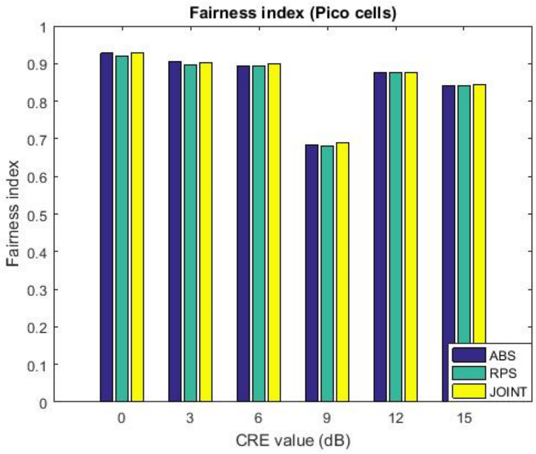
C

Figure 5-22: Average Spectral Efficiency (Comparison with other Schemes)

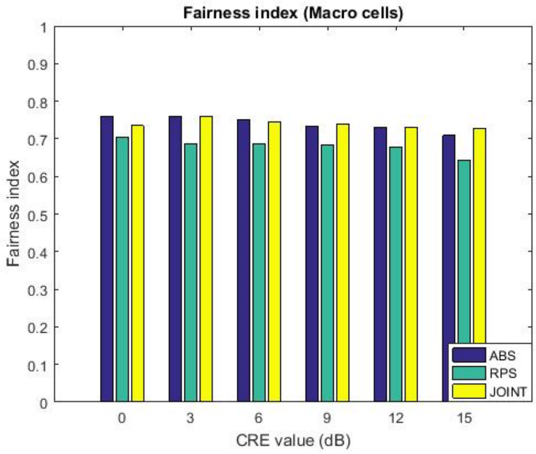
The proposed scheme shows about 20% and 30% higher spectral efficiency as compared with ABS and RPS schemes, respectively.

Jain's fairness index (defined in section 4.3.5) has been used to show how fair the RBs are distributed among all users. It is clearly shown in Figure 5-23 (A) that all three schemes perform slightly same in terms of fairness among Pico users. However, it is one of our scheme's merits that it can achieve (6.5-8.5%) higher throughput for both average and edge

Pico users (as depicted in Figure 5-17) while it keeps relatively same fairness among users, despite the fact it is hard to keep the same fairness with two types of priorities between Pico cell users as described in section 4.2.2.



A

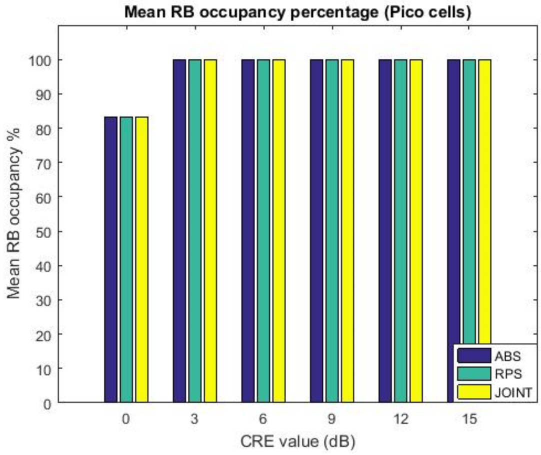


B

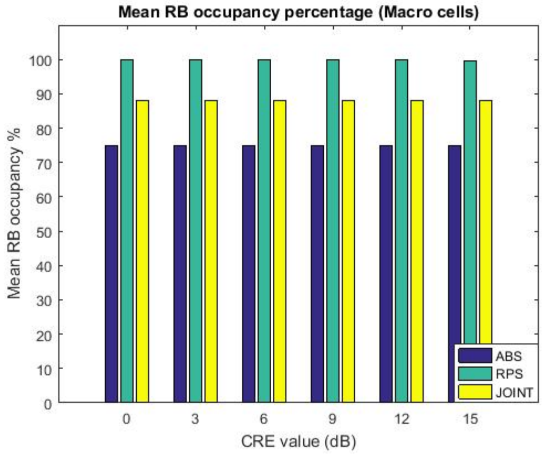
Figure 5-23: Fairness Index (Comparison with other Schemes)

In addition, Figure 5-23 (B) illustrates significant improvements compared to RPS scheme and a slight higher fairness over ABS scheme when employing higher CRE values. As a result, the total fairness among network users will be improved to show better performance as in Figure 5-23 (C).

Figure 5-24 shows the mean RBs occupancy percentage for Pico, Macro, and the total UEs, respectively. In (A) we can clearly observe that all the three schemes perform equally because in each of these schemes all allocated RBs are available for the Pico cells. However, Figure 5-21 (B) shows significant disparity in the available RBs for the Macro cell in each scheme, as a result of different types of special subframes reserved for the edge users of the victim cell(s). These subframes can be totally blanked or partially used by the Macro cell (aggressor) which directly affects the available RBs in that cell when applying different schemes.



A

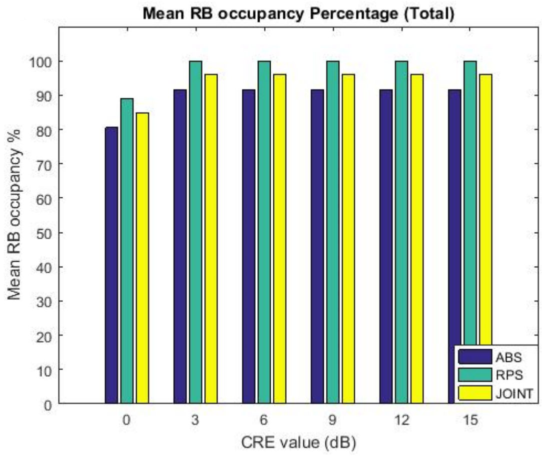


B

A- Mean RB Occupancy Percentage (Pico cell)

B- Mean RB Occupancy Percentage (Macro cell)

C- Mean RB Occupancy Percentage (Total)



C

Figure 5-24: Mean RB Occupancy Percentage (Comparison with other Schemes)

5.5 Discussion

This section discusses the simulation results of the proposed inter-cell interference mitigation scheme in LTE-Advanced as an example of OFDMA cellular network. It aims to improve the performance of heterogeneous deployment of LTE-Advanced in terms of user throughput (both average and edge users), cell throughput, spectral efficiency, fairness among users, and the mean resource blocks occupancy for all cell as performance metrics.

Conventionally, increasing the CRE value results in degradation of throughput for the UEs in Range Expanded (RE) region, as a result of the severe interference coming from Macro cell towards these users.

However, it can be concluded that the proposed scheme can offer higher CRE without having a negative impact on the network performance, thanks to the variety of special subframes used to protect these vulnerable users while yielding of offloading more users to the small cells to balance the load among all cells.

By using this scheme, simulation results show optimum radio resources utilisation for Macro users' throughput in both average and edge users. Likewise, the Macro cell throughput behaves the same because it represents the sum throughput of all users in their coverage area.

On the other hand, the Pico users do not experience significant improvements as it has been already protected by using the special subframes since the first ICIC schemes.

When comparing the proposed ICI mitigation scheme with both ABS and RPS schemes, higher scheduling opportunities can be achieved for the Macro users/ cells (up to 50% as compared with ABS), which leads to higher cell throughput as a result.

The proposed scheme shows about 20% and 30% higher spectral efficiencies in Macro users as compared with ABS and RPS schemes, respectively.

Regarding the impact of CRE increments on the network performance under the proposed scheme:

- The number of offloaded users toward the Pico cells is proportional to the CRE value as a result of increased (biased) cell coverage.
- Pico user throughput decreased because more offloaded users will share the same radio resources, which has a direct impact on the cell throughput. In contrast, Macro cell does not experience significant change because the percentage of offloaded users is still trivial as compared to the total number of connected users.
- Worse Pico user throughput can be experienced for a biasing of larger than 9 dB, and steady Macro user throughput for up to 12 dB biasing.
- Pico user throughput performs equally in high CRE values as compared with the case of using only proportional fairness scheduler, while it clearly shows higher performance in all CRE values for both average and cell-edge Macro user throughput as compared to the standard scheduler.

It is vital to compare the performance of the proposed scheme with other TD-ICIC schemes to show the advantages of this scheme as part of the proposal evaluation. Therefore, the comparison with ABS and RPS can be summarised as follows:

- the proposed scheme outperforms (about 6.5-8.5 %) the other schemes more in low CRE values (3-6 dB) for both average and edge throughputs of the Pico cells, while it achieves a slightly higher throughput in higher CRE values (9-15 dB).
- 33% and 22% higher average Macro UE throughput, as compared to ABS and RPS schemes, respectively. Also, the edge UE throughput for the Macro cells can achieve up to 50% higher throughput in higher CRE values.

- As a result of the aforementioned Macro and Pico cells performance under our proposed scheme, there is still better performance in average UE throughput in the whole network, and significant performance in edge UE throughputs (37.5% and 50%) as compared with RPS and ABS, respectively.
- As mentioned earlier, average cell throughput equals the sum throughput of each UE in the cell. Therefore, the highest performance can be expected in the average Macro cell throughput, which in turn has a positive impact on the average cell throughput of the whole network.

As a conclusion, simulation results of the proposed scheme show optimum radio resources utilisation for Macro users' throughput in both average and edge users. Likewise, the Macro cell throughput behaves the same because it represents the sum throughput of all users in their coverage area.

On the other hand, the Pico users do not experience significant improvements as it has been already protected by using the special subframes since the first ICIC schemes.

When comparing the proposed ICI mitigation scheme with both ABS and RPS schemes, higher scheduling opportunities can be achieved for the Macro users/ cells (up to 50% as compared with ABS), which leads to higher cell throughput as a result. The proposed scheme shows about 20% and 30% higher spectral efficiencies in Macro users as compared with ABS and RPS schemes, respectively.

5.6 Summary

Chapter 5 evaluates the proposed scheme using system-level simulation, based on the system model of section 4.3.2. It mainly investigates the simulation results of the proposed scheme and the impact of increasing CRE values on the system performance as a consequence of the direct relationship with the ICI. Furthermore, section 5.3 discusses the evaluation of the priority scheduling algorithms on both Macro and Pico cells, to test how efficient are the RBs distributed among users with different levels of priorities and several types of radio resources. After that, the performance of the proposed scheme was compared with the other TD-ICIC configurations (section 5.4) to show the advantages over the other employed schemes based on the similar system model and simulation assumptions to get an accurate comparison. Finally, section 5.5 outlines the discussion of the simulation results obtained by the system-level simulation of the whole chapter.

Chapter Six: Conclusions and Future Work

This thesis investigates the interference mitigation in LTE-Advanced Heterogeneous Networks (HetNets) and contributes to mitigating the inter-cell interference (ICI) in macro cell- Pico cell scenarios. It provides increased downlink network performance in terms of user and cell throughputs, which results in total network improvements. The next subsections summarise the research contribution of this thesis and give a direction for the future work.

6.1 Summary of Thesis Contribution

Despite the significant benefits of deploying LTE-Advanced HetNets to increase the network capacity or to extend the coverage in a cost-effective way, Inter-cell interference is one of the largest challenges in such networks when utilising co-channel deployment. This type of interference results from the transmit power disparity in cells of different classes. On one hand, Cell Range Expansion (CRE) concept has been already employed to solve the uplink ICI, and to offload more data connections toward the Low-Power Cells (LPCs), achieving higher load balance in LTE-A HetNets. On the other hand, several types of ICIC schemes have been utilised to mitigate the downlink ICI. These schemes have been classified into Power-Domain (PD-ICIC), Coordinated Multipoint (CoMP), Frequency-Domain (FD-ICIC), and Time-Domain (TD-ICIC). In the light of this, the latter scheme has been chosen for further improvements in this thesis as a result of its higher spectral utilisation by sharing the whole available bandwidth between the Macro cell and the LPCs, and the capability of employing higher CRE values which in some cases are necessary to achieve proper load balance in the HetNets. The key design of TD-ICIC relies on reducing the transmission activity on certain subframes of the aggressor cell (e.g. Macro cell), to provide protected subframes to schedule the data of the cell-edge users of the victim cell (e.g. Pico cell). Therefore, these subframes could be totally blanked from user data in the aggressor cell

(Almost Blank Subframes-ABSs), or they could still be used with reduced transmit power (Reduced Power Subframes-RPSs) for better radio resources utilisation in the Macro cell layer.

Generally speaking, there is a permanent trade-off between ICI mitigation and resource accessibility in LTE-Advanced HetNets. ABS-only configuration can cause waste in the radio resources available for the aggressor cell, which leads to lower throughput and spectrum utilisation. In contrast, the presence of some data in these special subframes still has a negative impact on the SINR of some users in Cell Expanded (CE) region of the victim cell, or even it may cause a radio link failure to these users. As a result, a joint configuration utilising both ABS and RPS in the same scheme has been proposed in chapter 4 of this thesis, to achieve a balance between the performance of cell-edge users of the Low-Power Cell (LPC) and that of the Macro cell UEs. In this way, the performance of the Macro cell will be optimised while keeping the performance of Pico cells intact, which in turn results in a higher network performance. The complexity of such configuration is represented in the presence of two levels of users' priorities and several types of accessible radio resources. Practically, the CRE region will be further divided into two sub-regions: outer and inner CREs. In that way, the Pico UEs with the lowest received power will be scheduled on the ABS RBs to provide an interference-free barrier between the overlapped footprints of Macro- Pico cells, while the other CRE UEs can be scheduled on the RPSs. Therefore, these procedures entail setting highest priority for the outer-CRE UEs, and second priority for the inner-CRE UEs. On the other hand, the Macro UEs with the highest received power should be scheduled on the reduced-power RBs, to provide more usable radio resources for the Macro cell. As a result, powerful scheduling algorithms (described in section 4.2.3) for both aggressor and victim cells have been developed to prioritise these UEs before the remaining users. The proposed scheme with the priority scheduling algorithms have been evaluated against the other TD-ICIC (ABS and RPS) schemes, and it shows better performance as it will be further discussed in the next section.

6.2 Recommendations for Further Research

Network densification mainly relies on the small cells deployment to offer higher spectrum utilisation, which in turn leads to higher data rates. Therefore, the current trend is going towards network densification of mobile systems, and small cells deployment has got more attention, especially in 5G mobile networks. Furthermore, the Orthogonal Frequency Multiplexing (OFDM) is one of the possible main players in the 5G mobile networks. As a result, OFDM-based mobile networks with small cells deployment have a great role in the recent researches in both academia and industries. In the next mobile generations, the presence of the regular Macro cells is still required to support backwards compatibility with the old versions of users and to provide anchor connection to the mobile, especially with high speeds. As a conclusion, the OFDM-based HetNets should be further developed to satisfy the future demands of mobile networks. Some of the recommendations for further research could be:

- The practical deployment of LTE-Advanced HetNets involves several types of cells of different characteristics and access modes, so when the number of Low-Power Cells (LPCs) increases, the static configuration will be costly, and the ICIC will be more challenging. Therefore, a central autonomous solution for resource allocation is essential to manage the ICI in the whole network, especially when every small cell has a different CRE biasing to maintain the load balance among all cells. In addition, the amount of information exchanged for coordination should be taken into further considerations.

- Due to the importance of CRE concept of mitigating the UL interference and achieving more load balance in the HetNets, the relationship between CRE values and the load balance in the network should be further investigated, especially when the increment in this value results in more traffic included in the cells which have a significant impact on cell capacity. Furthermore, the impact of limited backhaul of the Pico cell in higher CRE values should be taken into account, which has a negative effect on the Pico cell functionality in most mobile networks.
- The increasing demands for mobile data and the expanding use of smart devices entail services of various traffic requirements and different priorities which should be taken into considerations in the future designs of ICIC schemes.

6.3 Reflection on the PhD Research

During my journey through the four-year PhD project, many skills have been learned and several challenges have been tackled. Choosing an up-to-date research problem and investigating the potential benefits of the proposed solution for the future research are tasks that should be carefully considered and analysed, as hundreds of research studies are being carried out in similar fields and so new and different systems are emerging every year. This choice was further discussed with the supervisors to get their advice based on the wide academic experience they have. In addition, time management was a vital issue which can have a significant impact on the research progress.

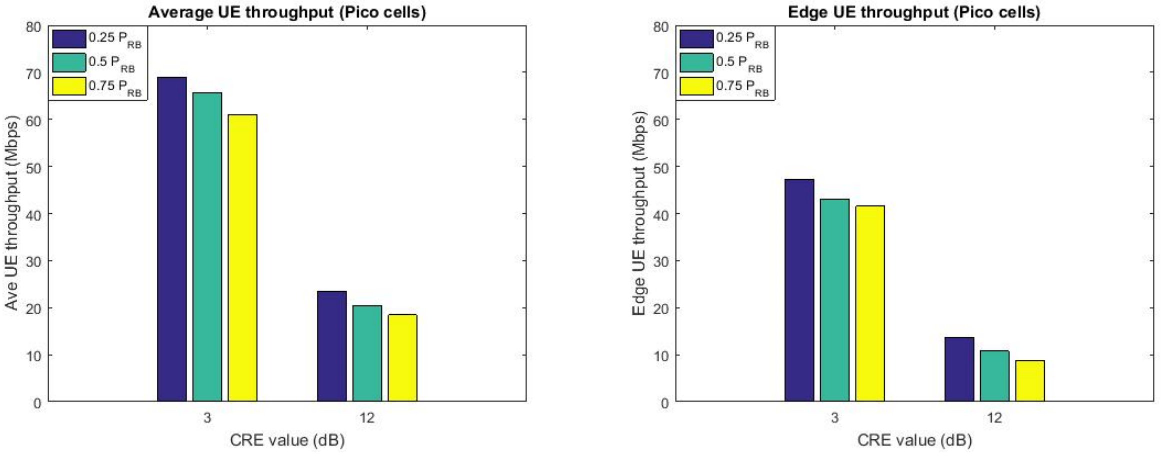
Several skills are necessary for any researcher in this field, namely those related to programming skills and presentation skills, which have been learned by the aid of my supervisor, Salford University, and the other researchers. Many challenges have also been faced, which had a negative impact on the research project. The most important challenge for this research was finding the appropriate simulation tools which could fully support the proposed solution and the possibility of adapting this tool to simulate different scenarios. Most commercial simulation tools have strict modification capabilities and they have high license costs. On the contrary, the open-source tools are free and easy to modify but there is less support available when facing some difficulties in implementation. I have struggled to find the suitable simulation tools for my research project and much time was lost on this matter.

One of the most challenging issues in this research is the intensive research of this field, which makes the novelty of the proposal more challenging because hundreds of publications were showing detailed investigation and saturated ideas in inter-cell interference coordination of LTE-A mobile systems.

Appendix I

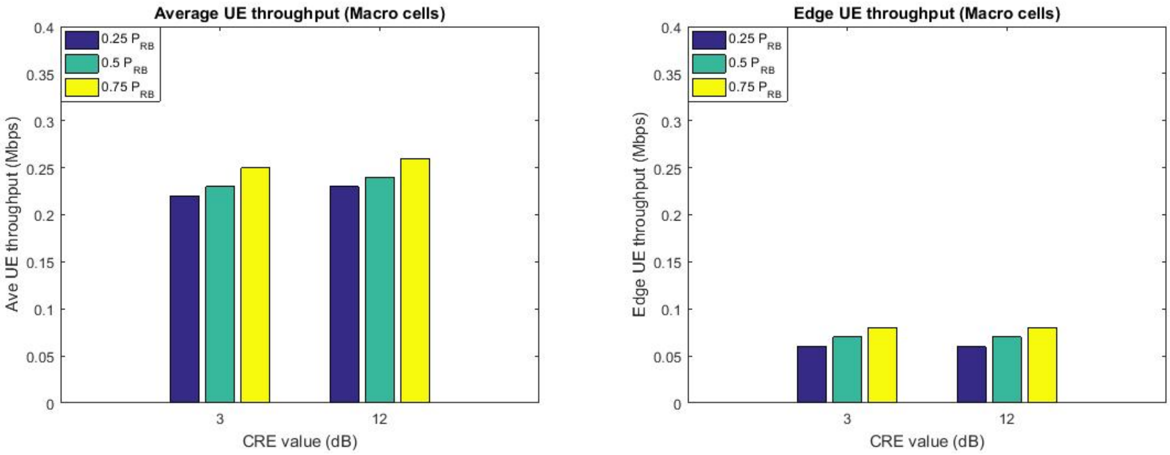
Simulation Results of the proposed scheme using different Transmit Power Rates of the Reduced-Power Subframes

The following results show the simulation of the proposed scheme for several transmit power share of the Reduced-Power Subframes (RPSs) using 0.25, 0.5, and 0.75 the power share of the normal RBs to test the network performance under these settings. Knowing that the performance metrics used to test the scheme are the user and cell throughputs, the spectral efficiency, because the other metrics show the same performance for all settings.



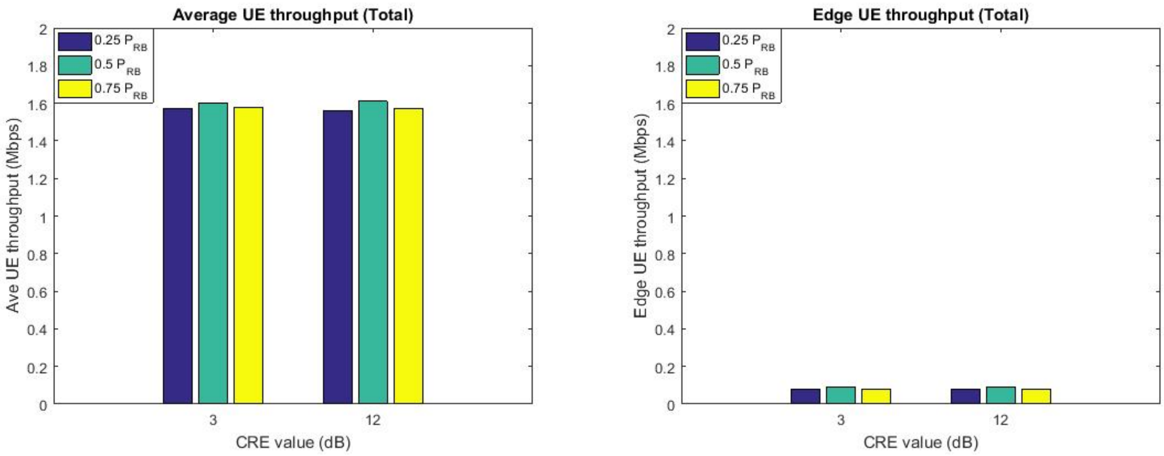
A B

Figure I-1: Pico UE Throughput



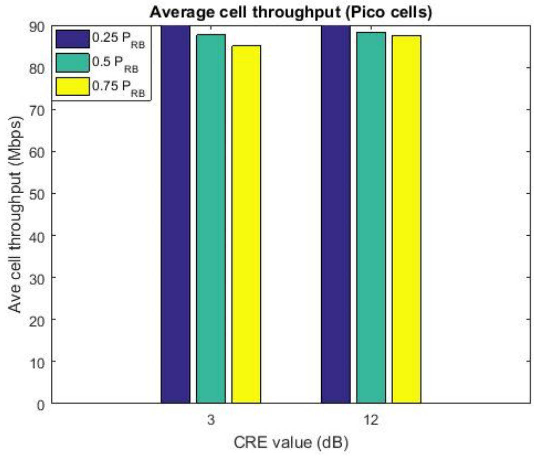
A **B**

Figure I-2: Macro UE Throughput

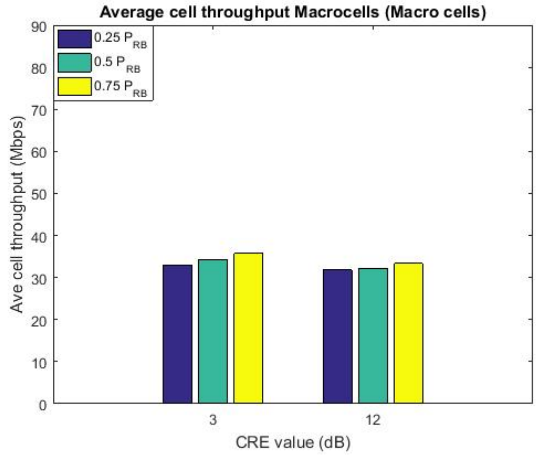


A **B**

Figure I-3: Total UE Throughput



A

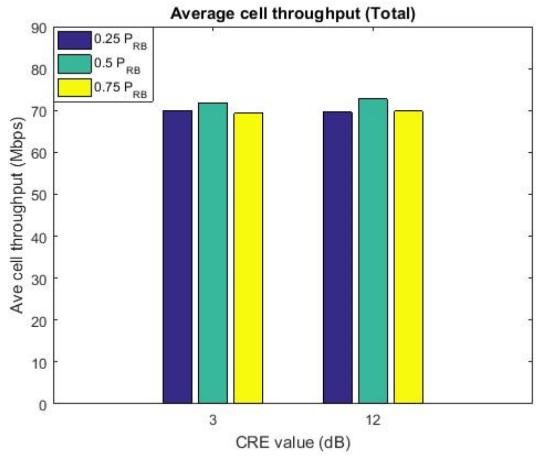


B

A- Average Cell Throughput (Pico cell)

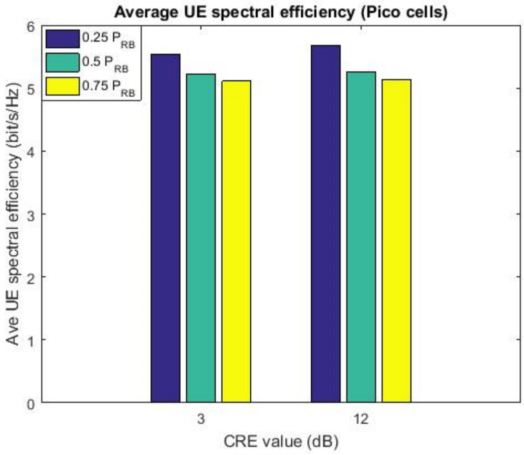
B- Average Cell Throughput (Macro cell)

C- Average Cell Throughput (Total)

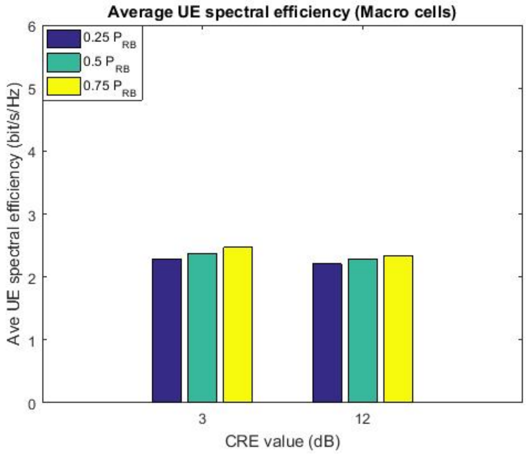


C

Figure I-4: Average Cell Throughput



A

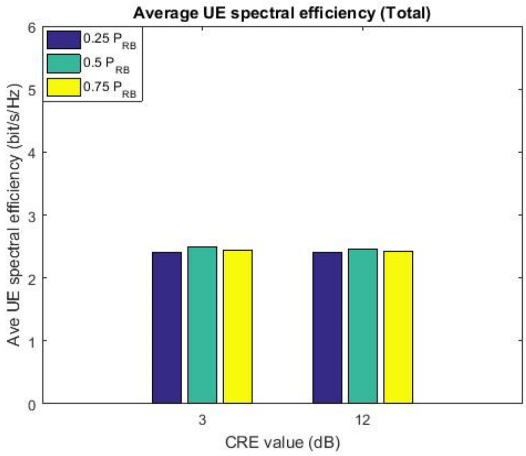


B

A- Average Spectral Efficiency (Pico cell)

B- Average Spectral Efficiency (Macro cell)

C- Average Spectral Efficiency (Total)



C

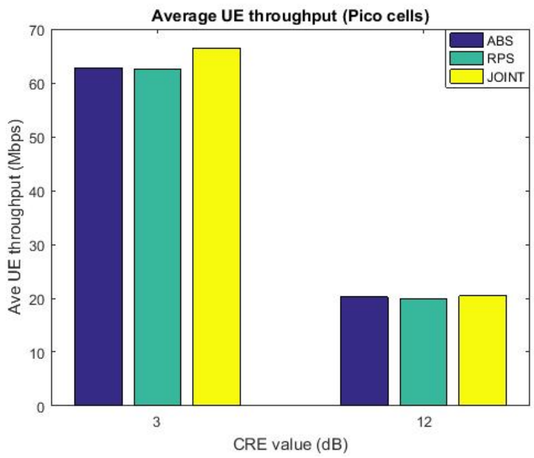
Figure I-5: Average Spectral Efficiency

Appendix II

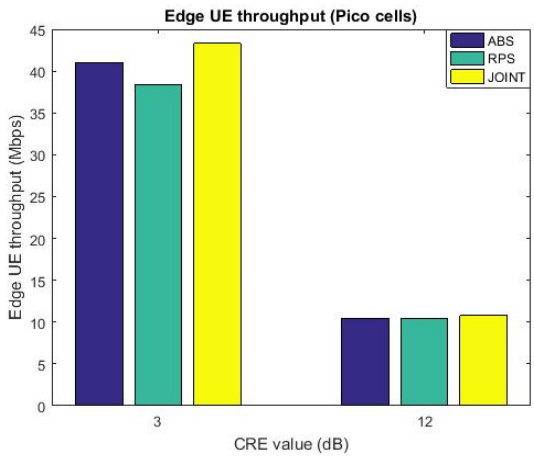
Simulation Results of the proposed scheme using different types of Traffic

This appendix explores the proposed scheme against the two other employed ICI schemes (ABS and RPS) under two types of traffic: Voice over IP (VOIP) traffic, and File Transfer Protocol (FTP) traffic. The comparison of these schemes has been done for two different CRE values: 3 dB and 12 dB to study the network behaviour for low and high biasing.

1- VOIP Traffic

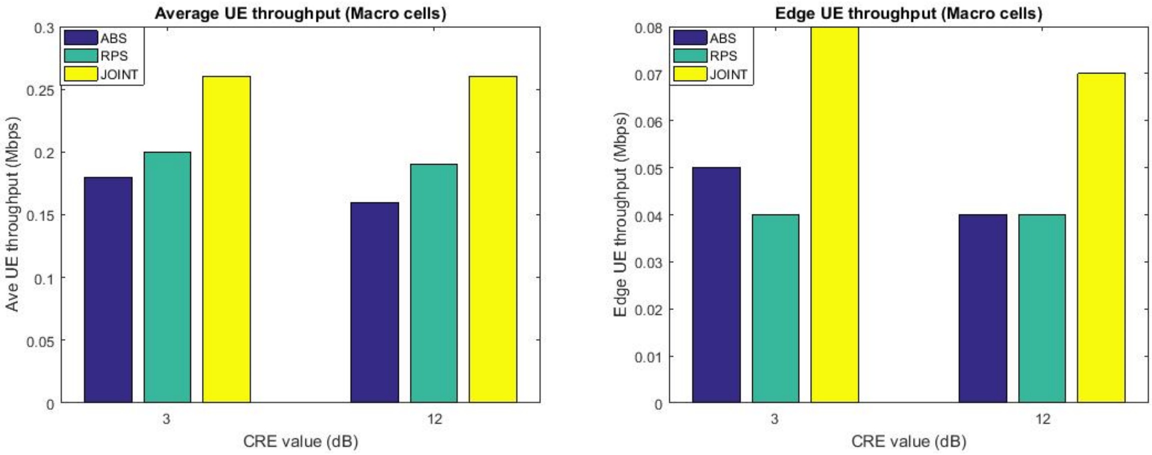


A



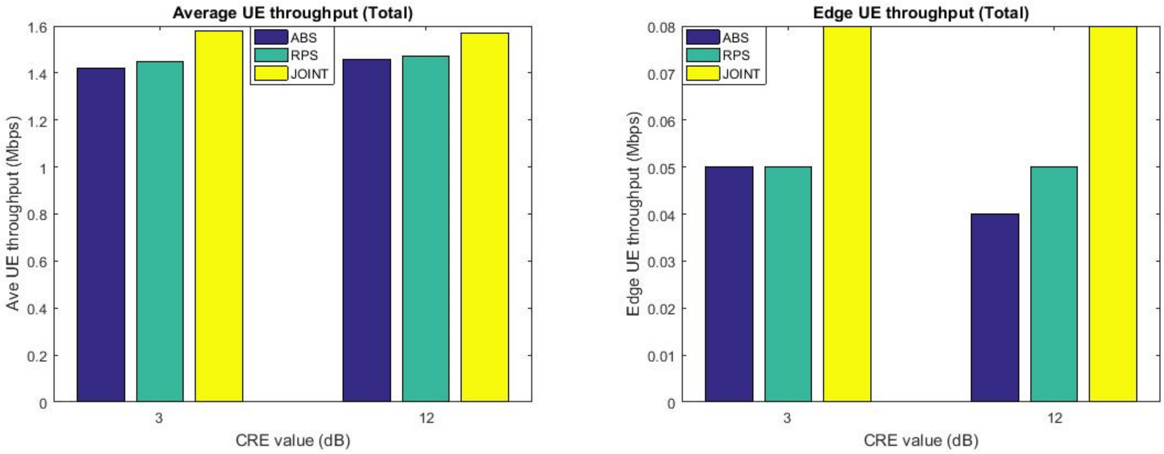
B

Figure II-1: Pico UE Throughput



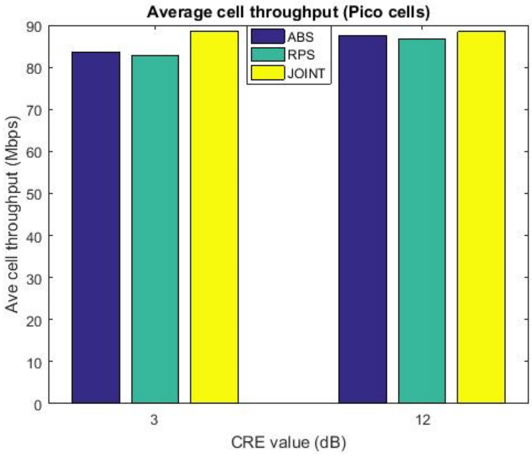
A **B**

Figure II-2: Macro UE Throughput

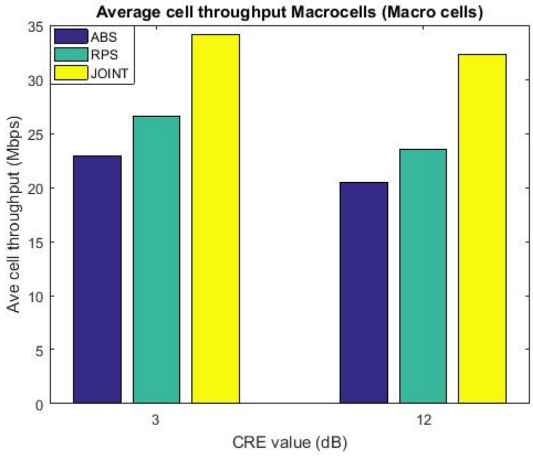


A **B**

Figure II-3: Total UE Throughput



A

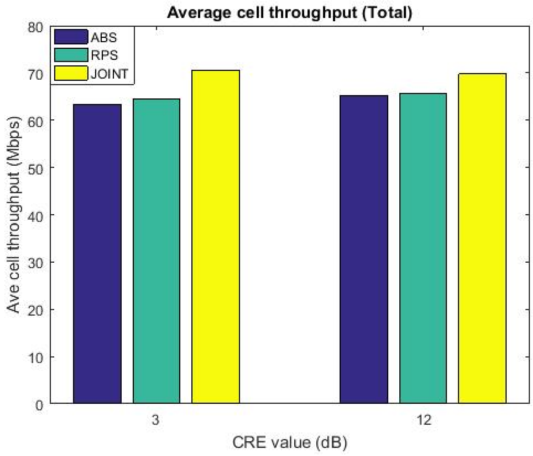


B

A- Average Cell Throughput (Pico cell)

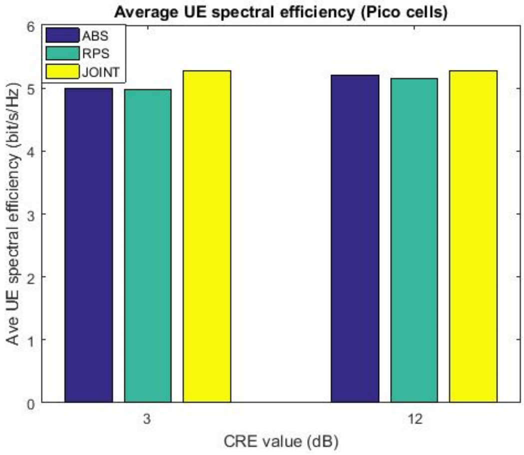
B- Average Cell Throughput (Macro cell)

C- Average Cell Throughput (Total)

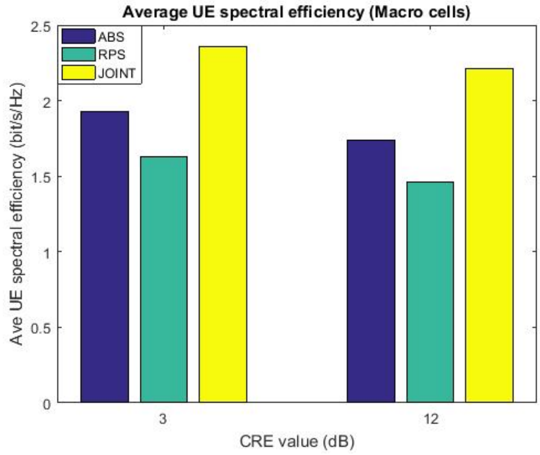


C

Figure II-4: Average Cell Throughput



A

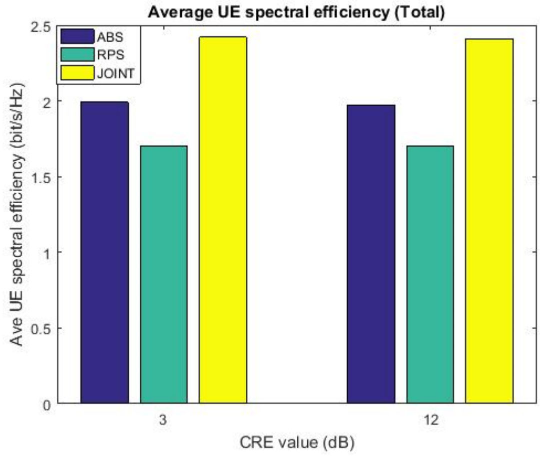


B

A- Average Spectral Efficiency (Pico cell)

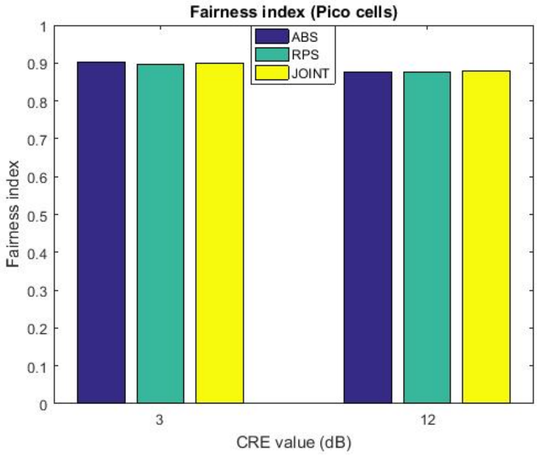
B- Average Spectral Efficiency (Macro cell)

C- Average Spectral Efficiency (Total)

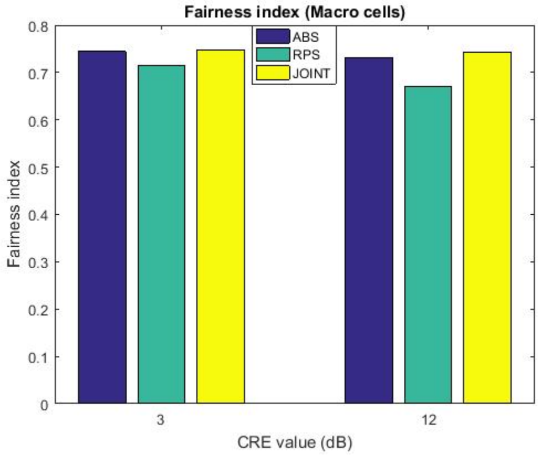


C

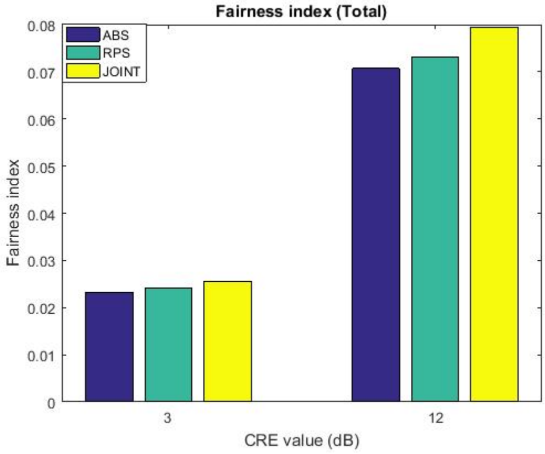
Figure II-5: Average Spectral Efficiency



A



B



C

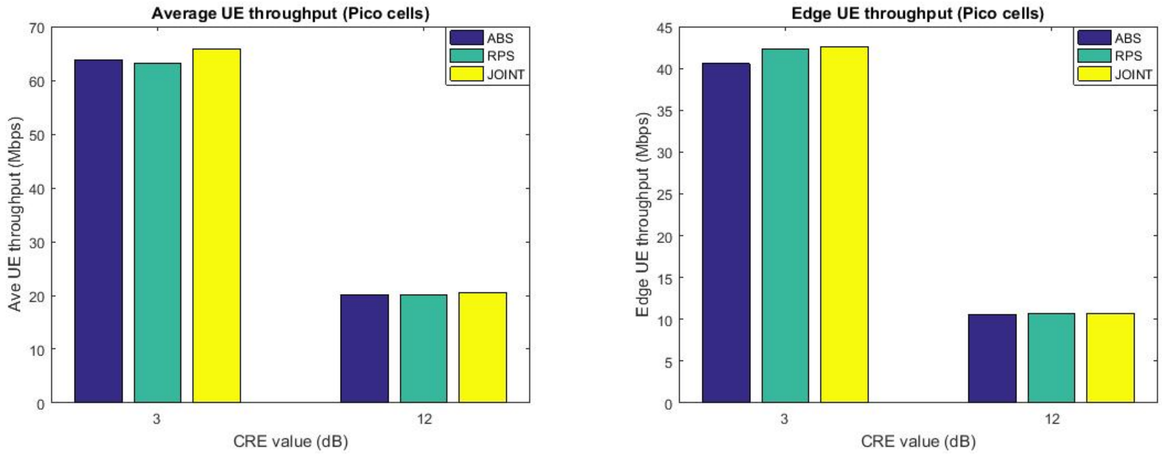
A- Fairness Index (Pico cell)

B- Fairness Index (Macro cell)

C- Fairness Index (Total)

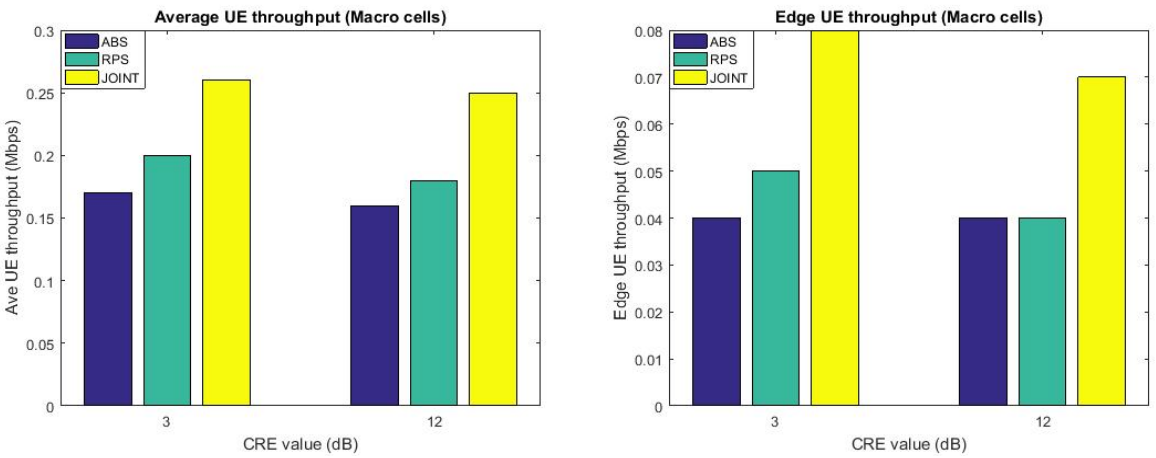
Figure II-6: Fairness Index

2- FTP Traffic



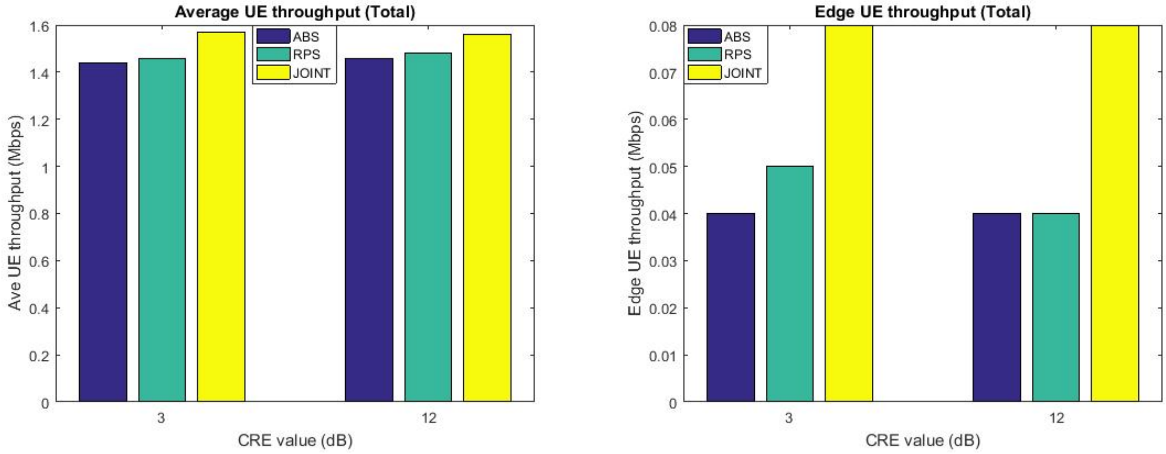
A **B**

Figure II-7: Pico UE Throughput



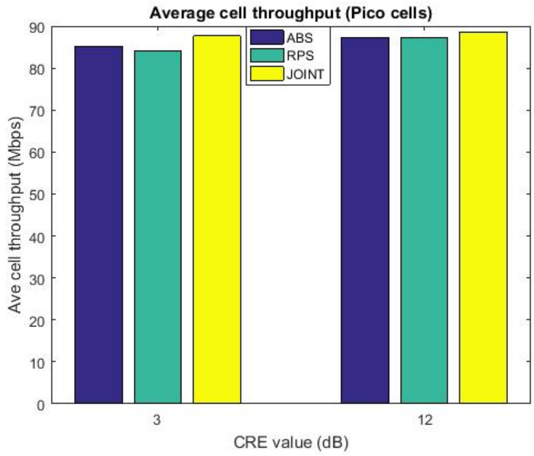
A **B**

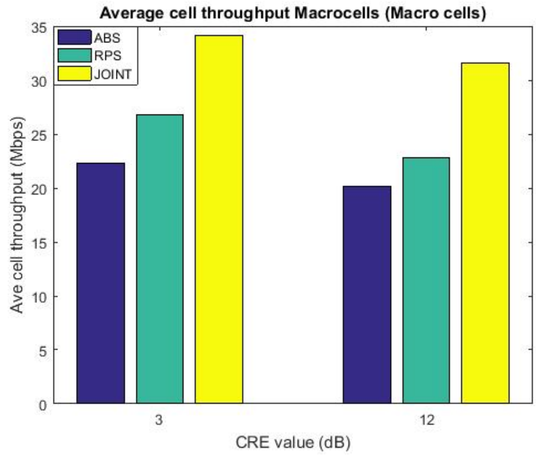
Figure II-8: Macro UE Throughput



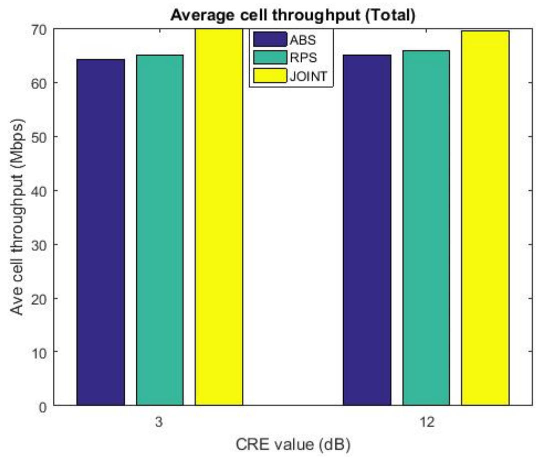
A **B**

Figure II-9: Total UE Throughput





A **B**



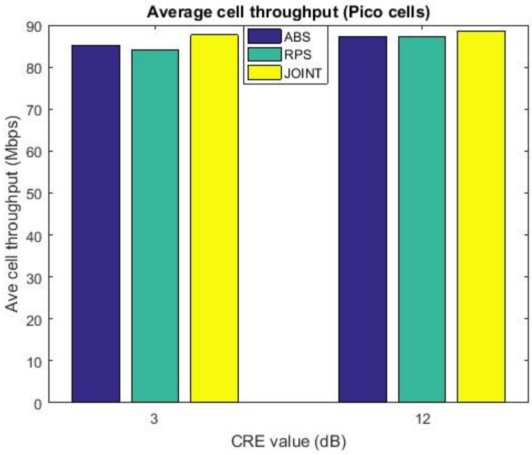
A- **Average Cell Throughput (Pico cell)**

B- **Average Cell Throughput (Macro cell)**

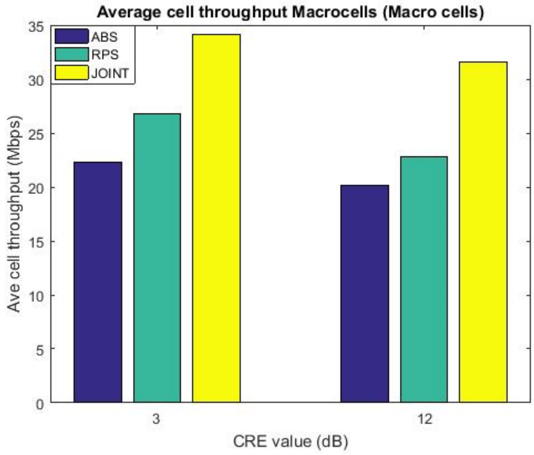
C- **Average Cell Throughput (Total)**

C

Figure II-10: Average Cell Throughput



A

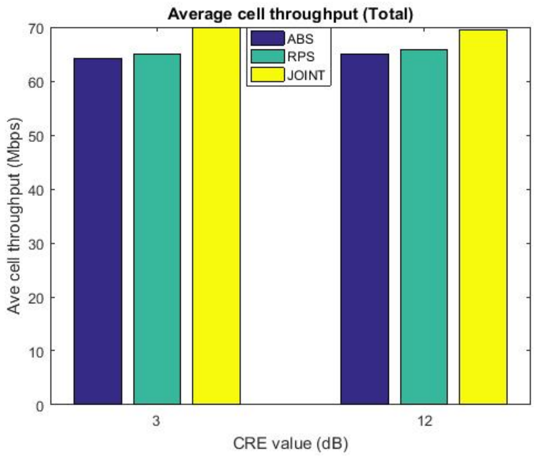


B

A- Average Cell Throughput (Pico cell)

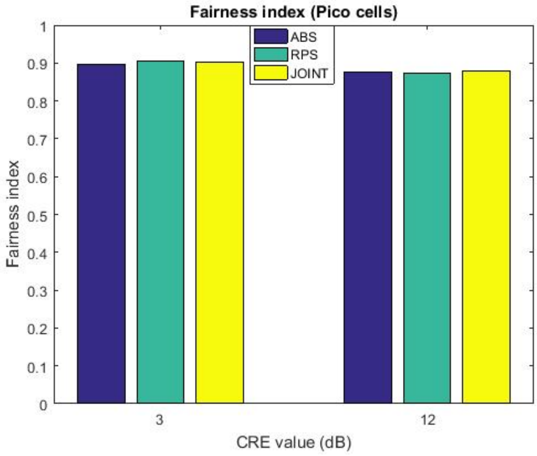
B- Average Cell Throughput (Macro cell)

C- Average Cell Throughput (Total)

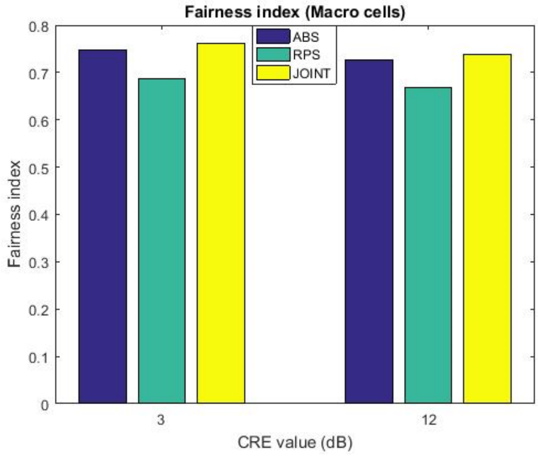


C

Figure II-11: Average Spectral Efficiency



A

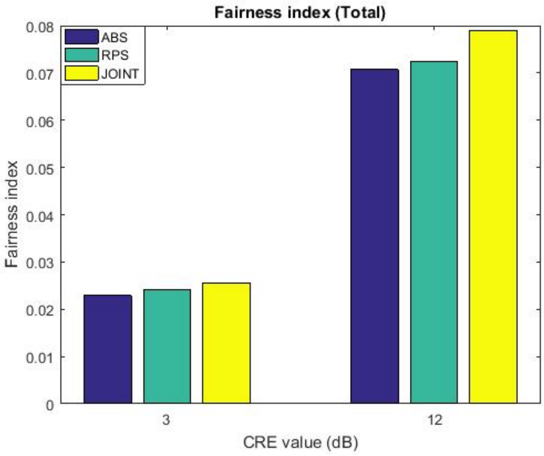


B

A- Fairness Index (Pico cell)

B- Fairness Index (Macro cell)

C- Fairness Index (Total)



C

Figure II-12: Fairness Index

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