EFFICIENT RADIO RESOURCE MANAGEMENT THROUGH COORDINATED MULTIPOINT TRANSMISSION AND CARRIER AGGREGATION FOR LTE-ADVANCED

MUHAMMAD HASIBUR RASHID CHAYON

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Passport No:

Matric No: **KHA130149**

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EFFICIENT RADIO RESOURCE MANAGEMENT THROUGH COORDINATED MULTIPOINT TRANSMISSION AND CARRIER AGGREGATION FOR LTE-ADVANCED

ABSTRACT

The demand of high data rate services for mobile user increases sharply nowadays. It is difficult for Long Term Evolution (LTE) to cope up with this current and future requirement. Hence, Long Term Evolution-Advanced (LTE-A) introduces several new technologies to improve the performance of the user. However, poor received signal and interference from adjacent cells in the cell-edge area can reduce the efficiency of using the individual technology. Therefore, the cell-edge users experience lower throughput compared to the LTE-A standard which leads to overall poor system performance. This thesis proposes an efficient downlink radio resource management scheme by implementing Coordinated Multipoint (CoMP) transmission and reception along with Carrier Aggregation (CA) technique to achieve better performance for cell-edge user as well as cell-center user. The proposed method, jointly transmits multiple Component Carriers (CCs) to the cell-edge user from different cells in order to increase the bandwidth, strengthen the received signal and reduce the interference while it satisfies several constraints. The cell-center user gets multiple CCs from the same attached eNodeB (eNB). Modified Largest Weighted Delay First (MLWDF) algorithm is deployed for resource allocation which considers queuing delay, the probability of packet loss, the instantaneous and previous data rate of the user. Extensive system-level simulations for different network scenarios have been performed by a MATLAB based simulator to evaluate the performance of the proposed method. The obtained results show that the proposed method significantly enhances the spectral efficiency, fairness index, cell-edge user throughput and average user throughput compared with the existing conventional

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methods. The simulation results also illustrate that the proposed method performs better than individual techniques and can be implemented in different network conditions.

Keywords: LTE-A, Resource Allocation, COMP, CA, MLWDF.

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PENGURUSAN SUMBER RADIO EFISIEN MELALUI PENGHANTARAN MULTIPOINT YANG DIPERBADANKAN DAN PENGANGKUTAN PENYELESAIAN UNTUK LTE-ADVANCED

ABSTRAK

Permintaan kadar data tinggi menservis kerana pengguna mudah alih meningkatkan dengan tajam sekarang ini. Adalah sukar untuk Long Term Evolution (LTE) untuk mencapikerluan masa kini dan masdepan ini. Lantarannya, Long Term Evolution-Advanced (LTE-A) memperkenalkan beberapa teknologi baru untuk meningkatkan prestasi pengguna. Bagaimanapun, isyarat rendah yang diterima dan gangguan dari sel-sel yang berdekatan dalam kawasan pinggir sel boleh mengurangkan kecekapan menggunakan teknologi individu. Lantarannya, pengguna-pengguna pinggir sel mengalami daya pemprosesan lebih rendah berbanding dengan standard LTE-A yang membawa ke prestasi sistem yang keseluruhan miskin. Tesis ini mencadangkan pengurusan sumber radio downlink cekap skim dengan melaksanakan penghantaran Coordinated Multipoint (CoMP) dan penerimaan bersama dengan teknik Carrier Aggregation (CA) mencapai daya pemprosesan lebih tinggi untuk pengguna pinggir sel serta pusat sel pengguna. Cadangan kaedah bersama menghantar Component Carriers (CCs) berbilang kepada pengguna pinggir sel dari sel lain untuk meningkatkan lebar jalur, mengukuhkan isyarat yang diterima dan mengurangkan gangguan sementara ia memuaskan beberapa kekangan. Pengguna sel pusat menenma CCs berbilang dari eNodeB (eNB) yang dilampirkan bersama. Modified Largest Weighted Delay First (MLWDF) algorithm digunakan untuk peruntukan sumber yang menganggap beratur kelewatan, kebarangkalian kehilangan paket, data terdahulu dan serentak kadar pengguna. Beberapa simulasi peringkat sistem untuk senario-senario rangkaian yang berbeza telah dipersembahkan oleh MATLAB untuk menilai prestasi cadangan kaedah. Hasil yang diperolehi menunjukkan bahawa kaedah yang dicadangkan meningkatkan

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dengan ketara kecekapan spektrum, indeks keadilan, throughput pengguna sel-sel dan purata penggunaan pengguna berbanding dengan kaedah konvensional yang sedia ada. Hasil simulasi juga menggambarkan bahawa kaedah yang dicadangkan ini lebih baik daripada teknik individu dan boleh dilaksanakan dalam keadaan rangkaian yang berbeza.

Kata Kunci: LTE-A, Pembahagian Sumber, COMP, CA, MLWDF.

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University of Malaya

TABLE OF CONTENTS

University of Malaya

University of Malaya

University of Malaya

University of Malaya

LIST OF FIGURES

University of Malaya

University of Malaya

LIST OF TABLES

University of Malaya

LIST OF SYMBOLS AND ABBREVIATIONS

e	:	eNB
i	:	User
j	:	CC
k	:	RB
l	:	MCS index
m	:	Maximum number of CC can be assigned to a user
n	:	Maximum number of eNB can be attached to a user
t	:	Time (TTI index)
B	:	Total number of eNB
Q	:	Total number of user
R	:	Total number of CC
S	:	Total number of RB
T	:	Total number of MSC index
r_i	:	Instantaneous throughput
V	:	Currently attached eNB
L	:	Set of attached and adjacent eNBs
ε	:	Error probability
λ	:	Probability from success state to failure state
C_{sum}	:	Sum of coefficient
β	:	Arrival rate
η_i	:	Average throughput of user i
N_{RT}	:	Number of RT packets
$\varphi_{e,i,j,k,l}$	:	A variable to denote whether or not CC j, RB k and MCS l of eNB e is assigned to user i

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$Z_{e,i,j,k,l}$	:	Weighted transmission rate of eNB *e*, user i, CC *j*, RB *k* and MCS *l*
$D_{e,i,j}$	:	Head of line Delay of eNB *e*, CC *j*, user *i*
$\xi_{e,j}$	:	Queue length of eNB *e*, CC *j*
δ_i	:	Probability of packet loss of user *i*
α_i	:	The variable which distributes the packet delay
τ_i	:	Delay threshold
$\Gamma_{i,j}$	:	Spectral efficiency
σ^2	:	Additive noise
$\Omega(e, j, k)$	:	Transmission rate of user currently being allocated with CC *j* and RB *k* of eNB *e*
$g\ (e, i, j, l)$	:	The gain after assigning eNB *e*, CC *j,* and MCS to user *i*
$\omega\ (e, i, j, k, l)$	:	Weighted transmission rate metric with the and Delay
$P_{e,i,j,k}$		Transmit power
$G_{e,i,j,k}$	:	Large-scale gain
$H_{e,i,j,k}$	:	Complex channel gain
$X_{e,i,j,k}$	:	Transmit signal from eNB e to user *i*
$Y_{e,i,j,k}$	:	Received signal
$\gamma_{e,i,j,k}$	:	SINR

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3GPP	:	Third Generation Partnership Project
4G	:	Fourth Generation
BW	:	Bandwidth
CA	:	Carrier Aggregation
CC	:	Component Carrier
CLSM	:	Closed Loop special Multiplexing
CoMP	:	Coordinated Multipoint
CQI	:	Channel Quality Index
CS/CB	:	Coordinate Scheduling/ Coordinate Beamforming
CSI	:	Channel State Index
D2D	:	Device-to-Device
DPS	:	Dynamic Pont Selection
eNB	:	Evolved NodeB
EPC	:	Evolved Packet Core
EUTRAN	:	Evolved Universal Terrestrial Radio Access Network
EXP/PF	:	Exponential Proportional Fairness
FTP	:	File Transfer Protocol
HetNet		Heterogeneous Network
HOL	:	Head of Line Delay
HSS	:	Home Subscriber Server
HTTP	:	Hyper Text Transfer Protocol
ICI	:	Inter-Cell Interference
IMT	:	International Mobile Telecommunication
JT	:	Joint Transmission
LTE	:	Long Term Evolution
LTE-A	:	Long Term Evolution-Advanced

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MAC	:	Medium Access Control
MCS	:	Modulation and Coding Scheme
MIMO	:	Multiple Input Multiple Output
MLWDF	:	Modified Largest Weighted Delay First
MTC	:	Machine-Type Communication
NRT	:	Non-Real-Time
OFDMA	:	Orthogonal Frequency Division Multiple Access
PF	:	Proportional Fair
PL		Pathloss
QoS	:	Quality of Service
RA	:	Resource Allocation
RB	:	Resource Block
RE	:	Resource Element
RI	:	Rank Indicator
RR	:	Round Robin
RRH	:	Remote Radio Head
RRM	:	Radio Resource Management
RSRP	:	Reference Signal Receiving Power
RT	:	Real-Time
SINR	:	Signal to Interference Noise Ratio
TTI	:	Transmission Time Interval
VoIP	:	Voice over Internet Protocol

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LIST OF APPENDICES

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CHAPTER 1: INTRODUCTION

LTE is introduced as Fourth Generation (4G) mobile communication by Third Generation Partnership Project (3GPP) in Release-8 (Rel-8) which is based on the Orthogonal Frequency Division Multiple Access (OFDMA) technology. LTE has set a benchmark in achieving peak downlink data rate of 300 Mbps and uplink data rate of 150Mbps with some modification in Rel-9. However, current forecast of future demand indicates that the immense challenge is far beyond the initial establishment of 4G. Due to both the explosion of mobile data traffic along with new services and applications, it is necessary to upgrade the LTE system.

1.1 LTE-A System

The 3GPP standardizing body introduces LTE-A in Rel-10 which meets the requirements of International Mobile Telecommunication-Advanced (IMT-Advanced) set by the International Telecommunication Union (ITU) and upgrades in later releases (Rel-11/12/13) (*4G Mobile Broadband Evolution Release 11 & Release 12 and Beyond, Tec. Rep. FINAL v2*, February, 2014). LTE-A can enhance the spectral efficiency and maximizes the throughput of the user up to 1 Gbps in downlink and 500 Mbps in uplink by using maximum 100MHz of bandwidth.

1.1.1 Background of LTE-A

3GPP upgrades the LTE system with new features in updated releases and announces LTE-A with several new technologies such as CoMP, CA, Heterogeneous Network (HetNet), Machine-type communication (MTC) and Device-to-device (D2D) communication (Akyildiz, Gutierrez-Estevez, Balakrishnan, & Chavarria-Reyes, 2014; "Requirements for Further Advancements for Evolved Universal Terrestrial Radio Access (E-UTRA) (LTE-Advanced)," September 2012). The basic structure of LTE-A is based on LTE structure and LTE-A upgrades the capability of LTE by incorporating new

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technologies. LTE-A is both forward and backward compatible which means that LTE devices (Rel-8/9) will work on LTE-A network and vice-versa.

The network structure of LTE-A is divided into two basic parts- Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and Evolved Packet Core (EPC). E-UTRAN contains evolved NodeB(eNB) and user whereas, EPC contains several nodes such as Mobility Management Entity (MME), Home Subscriber Server (HSS) and other gateways ("Network Architecture, Release 11, Section 4.1.4," June 2013). Resource Block (RB) in OFDMA system is the basic resource unit which is defined by the time and frequency domain in X and Y axis, respectively. A 10ms long radio frame in time domain is divided into 10 sub-frames each with 1ms duration. Each sub-frame consists of two equal-sized time slots with the duration of 0.5 ms. Each slot is composed of 6 or 7 OFDMA symbols for extended and normal cyclic prefix respectively ("Physical Channels and Modulation, Release 11, Section 4,," September 2013). In frequency domain, one RB is 180 kHz long with 12 subcarriers where each subcarrier has 15 kHz bandwidth ("Physical Channels and Modulation, Release 11, Sections 5.2, 6.2," September 2013).

1.1.2 Coordinated Multipoint Transmission

The basic concept of CoMP is to provide coordinated services of multiple eNBs or remote radio head (RRH) to the cell-edge user in order to mitigate Inter-Cell Interference (ICI) and strengthen the desired signal (Irmer et al., 2011). A cell-edge user can be connected with multiple eNBs or RRHs at a given time and these cooperative serving nodes communicate and coordinate with each other to serve the user. Two types of CoMP architecture can be considered depends on the place of the cooperation happens. Communication of Intra-Cell CoMP takes place within the same eNB of the same cell and no backhaul involvement is needed. Inter-cell CoMP involves a backhaul communication as multiple eNBs from different cells interact with each other to serve a user. There are also different downlink CoMP transmission approaches with different

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requirements, complexity, and level of coordination. Joint transmission (JT), dynamic point selection (DPS) and coordinated scheduling/coordinated beamforming (CS/CB) are the most promising CoMP transmission approaches (Sawahashi, Kishiyama, Morimoto, Nishikawa, & Tanno, 2010). In JT, data is simultaneously transmitted from multiple eNBs in a same frequency for a particular user to improve the desired signal coherently or non-coherently. Cooperative eNBs connected with fast backhaul link decide centrally or in distributed approach on the transmission scheme. This thesis implements the centralized coherent JT transmission to mitigate the ICI and to strengthen the received signal of the cell-edge user.

1.1.3 Carrier Aggregation

To reach out with the high throughput demands and to implement the IMT-Advanced requirements, LTE-A introduced CA in Rel-10 with wider bandwidth up to 100 MHz ("Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (Release 11)," December 2012). This technology is also known as channel aggregation, which uses multiple (maximum 5) CCs of different frequencies joined together to form a higher overall transmission bandwidth and is used to provide an improved throughput as required for LTE-A system. Each CC may appear as LTE carrier to the legacy users while LTE-A users are able to transmit and receive on several CCs simultaneously. CA is designed to be backward compatible which means that legacy Rel-8 and Rel-9 users can co-exist with LTE-A users on part of the total bandwidth. The scheduler can allocate resources on any available CCs with different bandwidth (maximum 20 MHz) to Rel-8 and Rel-9 users. CA will allow the operator to provide additional capacity without causing any unfavorable impact on the legacy LTE (Rel-8/9) users. There are three types of CA, namely Intra-band contiguous, Intra-band non-contiguous and Inter-band. This thesis incorporates the Inter-band CA (of maximum 4 CCs) technique with the CoMP to avoid

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the ICI and to increase the downlink bandwidth of the cell-edge user as well as the cell-center user.

1.1.4 Radio Resource Management

The packet scheduler in LTE-A system calculates the metric of all users according to the corresponding algorithm. It considers various factors, such as instantaneous and previous throughput, spectral efficiency, head of line (HOL) packet delay, the number of packets waiting in the queue and several other scheduling constants. The user with higher metric value will be in front of the queue to get the service. An efficient packet scheduler can reduce the traffic congestion in the network by efficiently allocate RBs to the user. Different downlink scheduling algorithms have different approaches to determine the user priority. The basic schedulers such as Proportional fairness (PF) (Choi & Bahk, 2007) and Round Robin (RR) (Capozzi, Piro, Grieco, Boggia, & Camarda, 2013) do not consider any kind of packet delay or queue length. Therefore, real-time data experiences low QoS and high rate of packet loss. The QoS aware MLWDF algorithm ensures ideal throughput to the system and to maintain fairness to all users (Basukala, Mohd Ramli, & Sandrasegaran, 2009). This scheduler largely depends on QoS and packet delay. MLWDF has less complexity among all other QoS and channel aware scheduling algorithms and it considers the real-time traffic by prioritizing those users who has larger HOL delay and high probability of packet loss. The primary goal of this scheduler is to provide better QoS, to enhance the throughputs, spectral efficiency and to provide good fairness to the user.

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1.2 Problem Statement

To meet the higher demand of the mobile user, LTE-A introduces several new technologies such as CoMP and CA. However, due to the low signal to interference noise ratio (SINR) and extensive ICI in the cell-edge area, cell-edge user has higher delay and lower throughput than the cell-center user (Mahmud, Hamdi, & Ramli, 2014). CoMP is designed to improve the SINR of the cell-edge user but narrow bandwidth and inefficient eNB coordination scheme can cause low throughput and longer delay (Elfadil, Ali, & Abas, 2015). On the other hand, CA technique can increase the bandwidth of the cell-edge user. However, only allocating high number of RBs to the cell-edge user is waste of resources which can be cost inefficient. Therefore, CoMP or CA technique individually cannot improve the throughput of the cell-edge user as well as the overall performance. Moreover, inefficient CC selection for CA also causes low throughput for all users in the cell (W. Fu, Kong, Zhang, & Yan, 2013). A combined method is required to address these issues with an efficient packet scheduler. Existing packet scheduling methods for CoMP or CA do not consider the delay parameters and probability of packet loss (Z. Li, Liu, Zhang, & Wu, 2016). Thus, the user experiences low throughput, higher waiting time in the queue and excessive packet drop.

1.3 Objectives

The primary focus of this thesis is to propose, simulate and analyze the resource allocation scheme which combines the CoMP and CA techniques with efficient eNB coordination method and MLWDF packet scheduling algorithm to improve the cell-edge user throughput along with overall system performance. The objectives of this thesis are given below.

1. To design a novel method for implementing CoMP with CA for cell-edge user to enhance the cell-edge user throughput as well as the system performance.
2. To develop an eNB coordination scheme for efficient resource allocation through centralized CoMP to improve the overall performance.
3. To design an efficient CC selection method with maximum 4 CCs for all users to increase the available RBs.
4. To implement MLWDF scheduling algorithm for CoMP and CA by considering delay parameters and the probability of packet loss.

1.4 Scope of the Study

This thesis analyzes the problem of downlink radio resource management by implementing CoMP with CA to enhance the cell-edge user throughput as well as the overall system performance. An efficient resource scheduling method with effective eNB coordination scheme for centralized CoMP and an efficient CC selection method has been proposed to address the issue. The proposed scheduling method considers that a cell-center user can attach with one eNB and a cell-edge user can receive the CoMP transmission signal from maximum three eNBs of the adjacent cells along with CA technique for all users. The adjacent cooperative eNBs can combinedly serve a particular cell-edge user by multiple CCs based on the available resources and the channel condition of that user. The cooperative eNBs communicate with each other by a fast backhaul connection to share the user data and control data. The signal from adjacent eNBs to the cell-edge user is coherent so that the user can receive stronger signal and thus can achieve higher throughput. The proposed scheduling method which is based on MLWDF algorithm calculates the gain of all user by considering delay threshold of different application, HOL delay, probability of packet loss, available CCs, MCS index and the queue length of each CC for each adjacent eNB. The higher the gain of a user, higher are the chances for the user to get the required RBs. The packet loss probability is calculated by the two-state Markov chain model where error rate and probability from success state to failure state are considered.

1.5 Outline of the Thesis

The remaining thesis is organized as follows.

- Chapter TWO (2) describes the background information of the LTE-A structure, implementation challenges, CoMP, and CA. Previous studies related to CoMP scheduling algorithms and CA selection methods for downlink radio resource management are also included. In addition, this section gives a brief description of different types of packet scheduling algorithms.
- Chapter THREE (3) elaborates the proposed radio resource management through CoMP and CA for LTE-A. It describes the proposed network structure where multiple eNBs transmit multiple CCs to the cell-edge user and an efficient CC select method for all user by considering delay parameters and probability of packet loss. This section also provides the derivation of the Markov chain model used in this thesis to calculate the probability of packet loss.
- Chapter FOUR (4) describes different simulation scenarios and the corresponding parameters this thesis used to implement the proposed method along with QTPF and JT-RR methods. This chapter shows the simulation results of average user throughput, cell throughput, cell-edge throughput, fairness, spectral efficiency and RBs per TTI per user where the proposed method is compared with QTPF and JT-RR methods.
- Chapter FIVE (5) concludes the study of this thesis by summarizing the overall work. It also describes the potential future work based on the research and findings of this thesis.

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CHAPTER 2: LITERATURE REVIEW

2.1 Background of LTE-A

2.1.1 From 1G to LTE-A

First digital mobile communication system launched in early 1990s based on Global System for Mobile communication (GSM) as Second Generation (2G) system after the analog system of First Generation (1G) (Mouly, Pautet, & Foreword By-Haug, 1992). Universal Mobile Telecommunication System (UMTS) was developed from GSM in 2000 to introduce the Third Generation (3G) system. The basic technology of 3G is Wideband Code Division Multiple Access (WCDMA) and 3G meets the ITU recommended requirements of IMT-2000 (Dahlman, Gudmundson, Nilsson, & Skold, 1998). 3GPP continued the study based on UMTS to enhance the user throughput with lower latency and introduced the LTE as 4G system in 2010. Initially, ITU suggested that LTE should not be called 4G as it does not follow the requirements of IMT-Advanced. However, the marketing community continuously use the 4G term for LTE and there is a significant technical transformation from UMTS to LTE. Therefore, finally, the ITU accepted the 4G term for LTE in December 2010 (Cox, 2012).

The explosion of both smartphone subscription and the volume of mobile data forces the researchers and the standardizing bodies to constantly upgrade the LTE system. Therefore, 3GPP continues its study and upgrades work to meet the user demand and the ITU requirements. 3GPP announces new and updated specifications of LTE into its later releases where stable features are clearly defined. Further enhancement based on LTE Rel-8/9 leads to the introduction of LTE-A in Rel-10 ("International Telecommunication Union Requirements, Evaluation Criteria and Submission Templates for the Development of IMT-Advanced.," 2008). The ITU also acknowledges that LTE-A meets the requirements of IMT-Advanced. LTE-A(Rel-10/11) extend the capacity of LTE Rel-8/9 by adding in new features and with updated specification. Since LTE-A system is

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developed based on the LTE system, the basic network and protocol structure of LTE-A is same as LTE ("International Telecommunication Union Guidelines for Evaluation of Radio Interface Technologies for IMT-Advanced," 2008).

2.1.2 Basic Requirements and New Technologies of LTE-A

Driven by the requirements of IMT-Advanced, LTE-A is required to provide various IP-based services and application with wide range of data rates, different QoS requirements and various user mobility condition in multi-user environments ("International Telecommunication Union Requirements Related to Technical Performance for IMT-Advanced Radio Interface(s)," 2008). LTE-A is expected to provide a maximum data rate of 1Gbps in downlink and 500Mbps in uplink by using maximum bandwidth of 100 MHz. Moreover, LTE-A system has been developed to enhance the data rate up to 3Gbps and 1.5Gbps, respectively. The requirements also include the spectral efficiency which can be 4.5 – 7 times higher in downlink and 3.5- 6 times higher in uplink than the Rel-6 specifications (Cox, 2012). LTE-A is backward and forward compatible with LTE system which means LTE devices can work in LTE-A system and vice-versa (Baker, 2012). The performance comparison among IMT-Advanced, LTE, and LTE-A shows that LTE-A can meet the IMT-Advanced target. (Akyildiz, Gutierrez-Estevez, & Reyes, 2010).

It is a major challenge for mobile operators and standardizing bodies to face the user demand and the evolving new applications. Current LTE system is not capable of solving these issues. Therefore, several new technologies have been introduced in Rel-10/11/12/13 to enhance the capability of LTE and to cope with the demands (*4G Mobile Broadband Evolution Release 11 & Release 12 and Beyond, Tec. Rep. FINAL v2*, February, 2014; Roessler, 2015). Figure 2.2 shows the evolution of LTE-A through different releases (*Wireless technology evolution towards 5G: 3gpp release 13 to release*

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15 and beyond, February, 2017). CA is the most prominent technique in LTE-A which can enhance user throughput by using up to 100 MHz bandwidth with maximum 5 CCs (Bhat et al., 2012). CoMP helps the cell-edge user to strengthen the received signal and avoid the ICI by connecting multiple eNBs at the same time. Enhanced Multiple Input Multiple Output (MIMO) technique can use maximum 8x8 antennas to increase the cell coverage and to improve the SINR of the user (Akyildiz et al., 2014). MTC is also known as machine-to-machine (M2M) technology which can connect and manage thousands of nodes smartly to provide specific services such as smart transportation, grid, healthcare and home system (Ahmadi, 2013). D2D communication allows different devices to communicate with each other directly without having any conventional network system for coverage extension (Roessler, 2015).

2.1.3 Network Architecture

The network architecture of LTE-A is divided into two functional entities namely EPC and E-UTRAN. Figure 2.1 shows the network architecture of LTE-A. This network is less complex with fewer nodes than previous 2G/3G systems, ensures seamless mobility experience and supports handover as well as connection to other technologies (Dahlman, Parkvall, & Skold, 2013). User is the main communicating device which is also known as User Equipment (UE) or Mobile Equipment (ME). The user can be mobile phone, tablet or PCs/laptops with LTE-A module. eNB is another key node in LTE-A structure. The overall performance of LTE-A system largely depends on the capacity and performance of the eNB. The services provided by the eNB includes RRM, MME selection, routing user data, controlling the paging messages, managing the broadcast messages, mobility management by doing handover, admission control, power control and managing MME emergency messages. Moreover, relay/RRH enabled eNB also

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coordinates the other nodes inside its cell area (Ahmadi, 2013). The stability and reliability of each network element can provide service continuity with wide range of new and enhanced services. The EPC is also connected with other Packet Data Network (PDN) and Public Land Mobile Network (PLMN) ("Service Requirements for the Evolved Packet System (EPS), Release 11," September 2012). The main responsibility of the LTE-A core network is to request and receive data from those networks. Unlike the 2G/3G systems, LTE-A has only packet switch domain to transmit/ receive data including all voice calls. However, LTE-A can also use circuit switch fall back or VoLTE for voice call services ("Circuit Switched (CS) Fallback in Evolved Packet System (EPS); Stage 2, Release 11," September 2012). Data is transferred through Service data flows (SDF) which are carried over several bearers with QoS parameters. The overall structure can be summarized as follows (Lucent, 2009).

- E-UTRAN and EPC divide the LTE-A network based on functionalities
- EPC has fewer network nodes than previous 2G/3G system to reduce the complexity and to provide faster services
- User and control data are logically separated
- Packet switch domain is implemented for both data and voice
- IP-based LTE-A structure supports both IPv4 and IPv6
- Ensure QoS requirements for different types of data
- eNB in LTE-A structure is now more powerful and less dependent to core network than the previous legacy
- eNB has now full control over Radio Resource Management (RRM)
- The interfaces of LTE-A structure are based on logical connection between two network nodes.
- Multiple network nodes can be implemented in a single physical node
- Ensures end-to-end security for all network entities

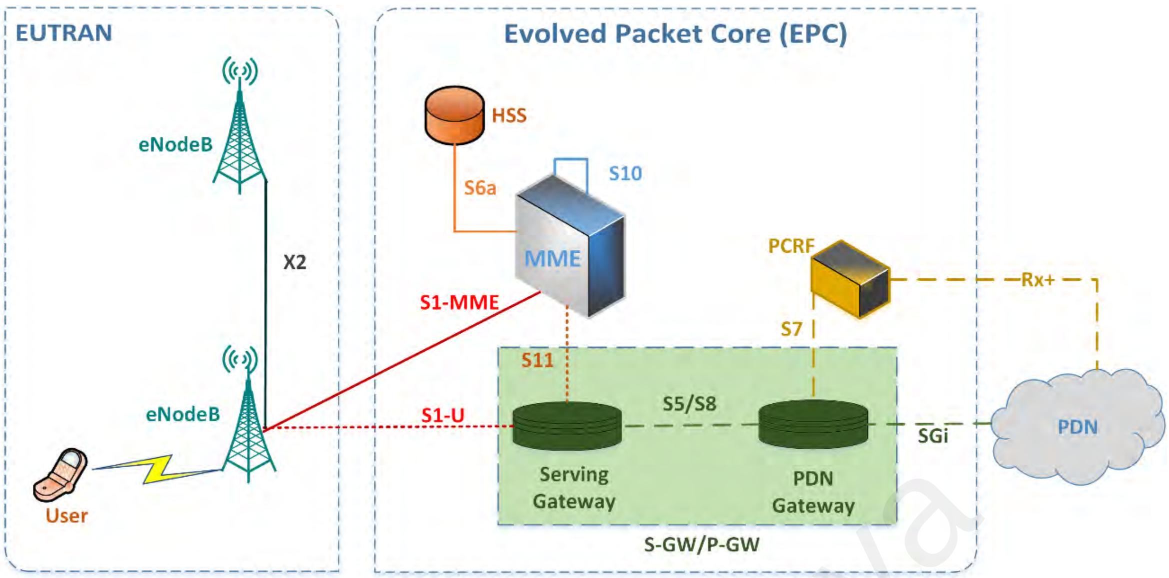

Figure 2.1: Network Architecture of LTE-A

2.1.4 Frame Structure

LTE-A designs the physical signals by using OFDMA symbols and sub-carriers. Data is exchanged between two nodes by a function of time and frequency which is called Resource Grid (RG) ("Physical Channels and Modulation, Release 11, Sections 5.6, 6.12," September 2013). Figure 2.2 shows the RG with 7 OFDMA symbols (normal cyclic prefix). The basic unit of RG is called Resource Element (RE) which is one symbol and one sub-carrier long. Each RE can transfer two, four or six bits of data depending on the modulation type ("Physical Channels and Modulation, Release 11, Sections 5.2, 6.2," September 2013). REs are combined into RB which spans 180kHz and one time-slot (0.5ms) in frequency and time domain, respectively. RB is further divided into 12 subcarriers in the frequency domain. The width of a subcarrier is 15kHz long which is called subcarrier spacing. Each subcarrier can send and receive data independently. The subcarrier spacing is small enough to not overlap each other. The eNB allocates minimum of 180kHz to the user up to any frequency bandwidth depends on the availability.

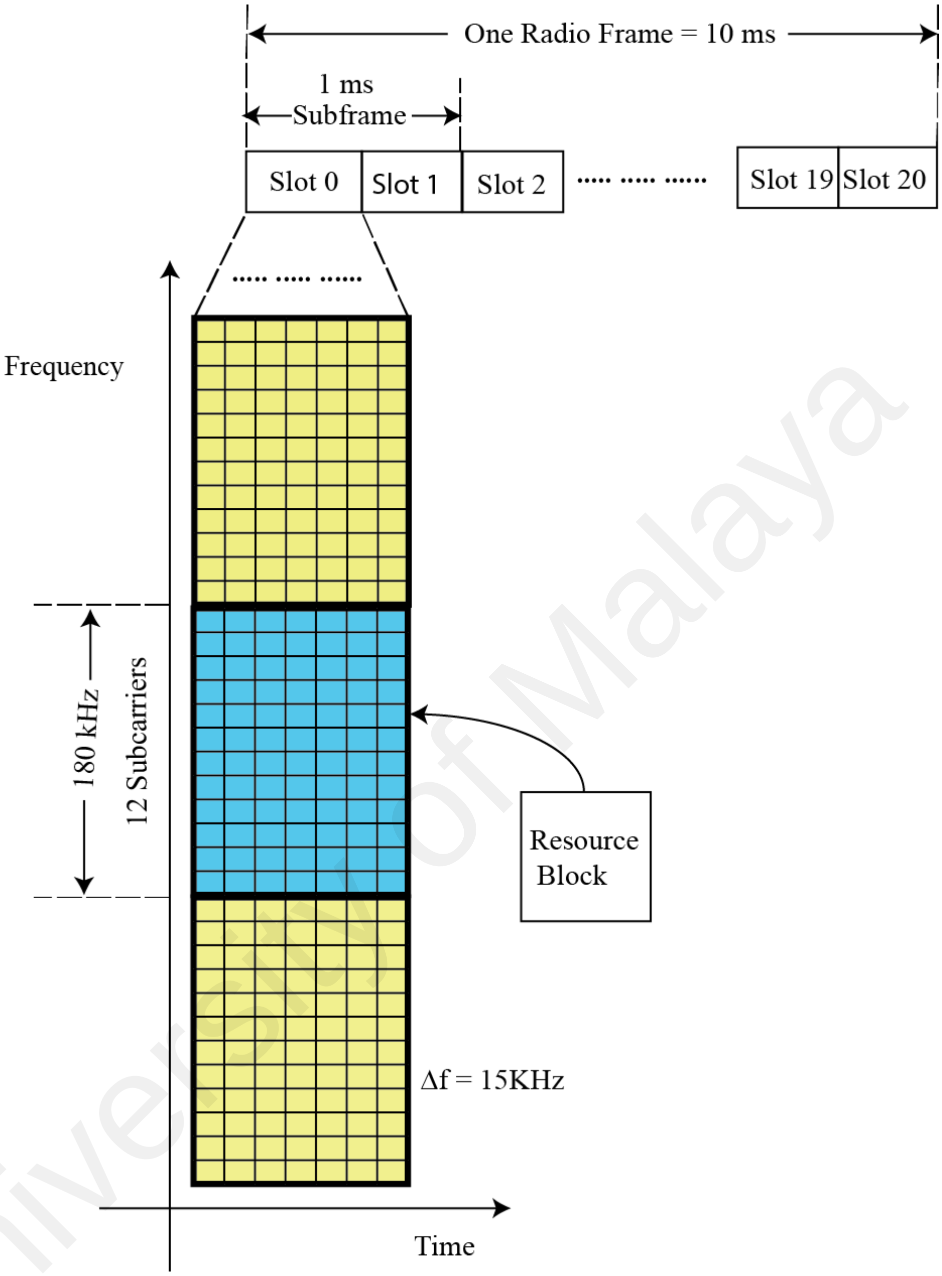

Figure 2.2: Time-frequency resource block structure of LTE-A

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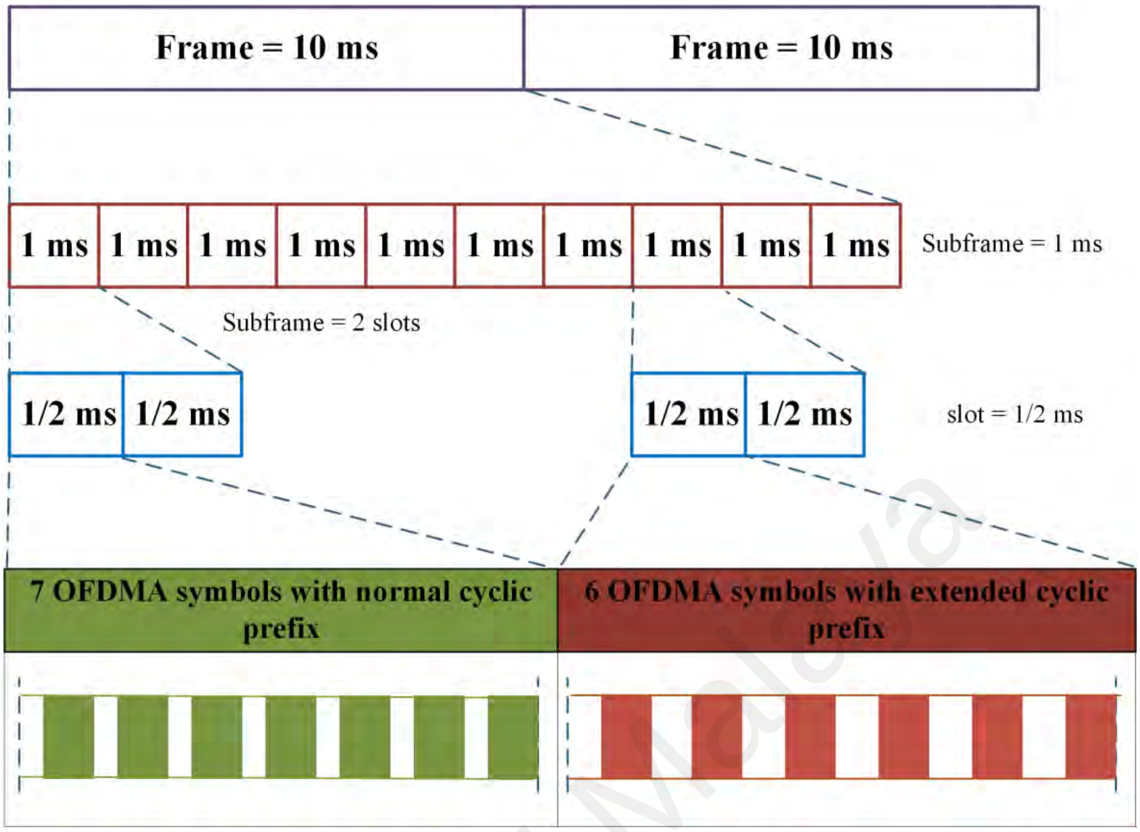

Figure 2.3: Time Domain structure with OFDMA Symbols

In the time domain, two-time slots make one subframe which is 1ms long. Consecutive 10 subframes grouped into one frame. Figure 2.3 shows the time domain structure of LTE-A ("Physical Channels and Modulation, Release 11, Section 4,," September 2013). The eNB needs to allocate minimum of two RBs to a user in a scheduling cycle. This means a user can get minimum 180kHz of frequency and 1ms of time from eNB at a given time. Although cyclic prefix does not contain any important data for the user, it is required to avoid inter-symbol interference during transmission. LTE-A supports two types of cyclic prefix namely normal and extended. One time-slot contains 7 OFDMA symbols in

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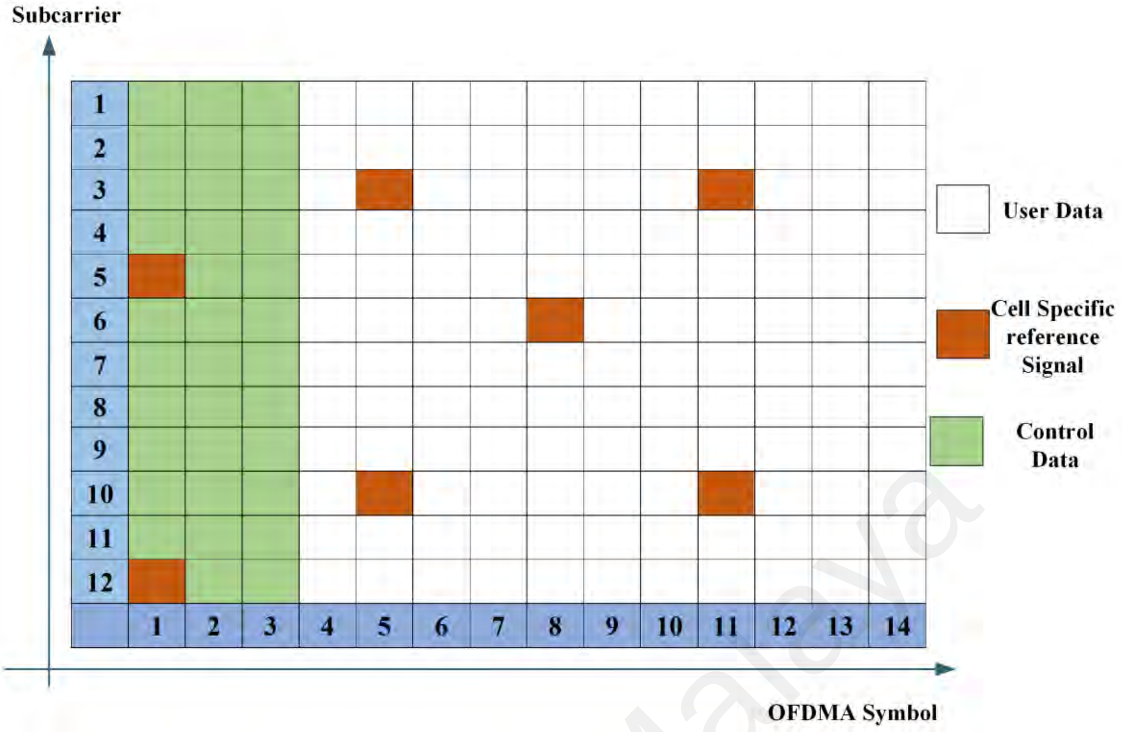

Figure 2.4: Signal Content of Downlink Subframe

normal cyclic prefix whereas there are 6 OFDMA symbols in case of extended cyclic prefix. Figure 2.4 shows the combined structure of a LTE-A subframe with normal cyclic prefix. The first three symbols are dedicated to control data. Some symbols are for cell-specific reference signal which are used to estimate the CQI, Rank Indicator (RI) and Precoding Metric Indicator (PMI) as well as to perform the demodulation (Ghosh & Ratasuk, 2011). Rest of the symbols are user data.

2.1.5 Protocol Structure

The protocol stack in LTE-A architecture consist of the Physical (PHY), Medium Access Control (MAC), Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP), and Radio Resource Control (RRC) ("Long Term Evolution Protocol Overview," October, 2008). A brief description is given below.

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- **PHY**: The LTE-A PHY layer is the medium where data physically transmitted to the user. Generally, it is full duplex. Several physical channels are responsible to transmit and receive data ("Evolved Universal Terrestrial Radio Access (E-UTRA), Physical Layer Procedures," September 2012).
- **MAC**: The MAC layer controls the hybrid ARQ (HARQ) function, which is responsible for automatic packet retransmission. Another significant function of this layer is the packet scheduling. The top of the MAC layer contains logical channels which defines the types of data in the transmission block. Transport channels exists in the bottom of this layer which defines how data is carried, type of encoder and modulation. ("Medium Access Control (MAC) Protocol Specification, Release 11," July 2013).
- **RLC**: The RLC layer has three modes: unacknowledged mode, acknowledged mode and transparent mode. Different radio bearers use these modes for different purposes. The RLC performs duplicate detection, sequential delivery reassembly, and segmentation ("Radio Link Control (RLC) Protocol Specification, Release 11,," September 2012).
- **PDCP**: PDCP performs ciphering (encryption and decryption), header decompression, packet sequencing, integrity protection and duplicate removal. Each radio bearer attaches with one PDCP instance ("Packet Data Convergence Protocol (PDCP) Specification, Release 11," March 2013).
- **RRC**: RRC is in layer 3 of the protocol stack which has several key responsibilities such as managing paging messages, controlling system broadcast information, managing the RRC connection between the E-UTRAN and user, controlling radio bearers and QoS requirement ("Radio Resource Control (RRC); Protocol Specification, Release 11," September 2013).

2.1.6 Key Implementation Challenges of LTE-A

- **Insufficient Bandwidth**

With the fast lifestyle change and advancement of mobile technologies, mobile data traffic has rapidly increased. According to (Heuveldop, June 2017), the mobile data traffic increased 70% between 2016 and 2022. Moreover, the traffic is expected to grow 8 times of current data traffic in 2022. To cope up with this explosive traffic demand, mobile operators need more bandwidth. More low-band, low-to-mid band, and mid-band spectrum are needed to provide better coverage and more capacity ("Future spectrum requirements estimate for terrestrial IMT," December, 2013; *Whitepaper on Spectrum*, February, 2013). At this time, these bandwidths are shared by that regional countries depend on their demands (Table 2.1). However, all these bandwidths are not identified by the IMT to be utilized them in user level. The comparison in Table 2.2 shows that the identified spectrum is much less than the required spectrum, which led to low QoS for the user (*Mobile Spectrum Requirement Estimates: Getting The Inputs Right*, August 2014). If IMT needs to meet the demand of excessive traffic in 2020, it still need to identify more than 500 MHz of spectrum which is a real challenge.

Table 2.1: Typical regional spectrum availability

Region	Total spectrum available for IMT (MHz)
Asia	510
Arab	630
Africa	370
Europe	590
North America (CITEL)	478
Latin America (CITEL)	360

Table 2.2: Global requirement and identified IMT spectrum

Year	Estimated spectrum Requirement by year in MHz	Estimated spectrum Identified by year in MHz
2010	840	625
2015	1300	1172
2020	1720	N/A

- **Complex Mobile Devices**

3G enabled devices need to support 26 frequency band whereas LTE and LTE-A use 44 frequency band to execute the mobile communication. Moreover, IMT is planning to identify new 500 MHz spectrum and will extend it up to 1 GHz by 2020 for LTE-A (*Whitepaper on Spectrum*, February, 2013). Therefore, LTE supported devices need to support a wide range of spectrum from 470 MHz band to 6 GHz band. There are some technical difficulties to develop a mobile device for low spectrum (below 400 MHz) and it will be a great challenge to support the existing and future proposed spectrum. In addition to that, the mobile terminal will be more complex and expensive. From a user point of view, they must change their mobiles to use the LTE/LTE-A services as the 3G supported devices are not compatible with LTE technology. In the business perspective, mobile manufacturing companies and operators need to invest huge amount of money to upgrade from 3G to LTE/LTE-A.

- **Insufficient MIMO Technologies**

Although MIMO is a widely used and well-studied technique, it needs to be updated further as the demand is increasing rapidly. Massive MIMO and Full dimension MIMO (FD MIMO) technique is introduced in LTE-A to improve the coverage, reduce the

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interference and increase of throughput (Lu, Li, Swindlehurst, Ashikhmin, & Zhang, 2014). Nevertheless, the massive MIMO system faces some challenges that require further investigation (Aragon-Zavala, 2008). The pilot contamination problem is the major issue for limited performance of massive MIMO (Hien Quoe Ngo, Marzetta, & Larsson, 2011). This interference appears when the number of antenna increases without constraint, clears the fast fading and uncorrelated noise. Moreover, complexity of massive MIMO increase exponentially with the number of users (Marzetta, 2010). As the massive MIMO can perform very narrow beamforming, it cannot easily track the users when they are moving. It is a challenge to develop an efficient and reliable 3D channel model which considers azimuth and elevation direction regarding signal propagation (Rusek et al., 2013). Finally, channel condition feedback, reference signals, and precoding codebooks need further optimization to enhance the performance of any MIMO scheme.

- **Poor Resource Allocation Technique**

Radio resource management especially scheduling algorithm plays a vital role to ensure enhanced services to the user. Different algorithm has different approach to allocate the resources (Capozzi et al., 2013). Therefore, no scheduler is suitable for every network scenario. Standardizing body leave this area to the network providers and researchers to develop the efficient algorithms. Many researchers have studied and considered different key parameters to develop the scheduler for LTE-A system. Deep investigation and further study are needed to enhance the spectral efficiency of LTE-A network and to improve the throughput and fairness index of the user.

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- **ICI and Mobility Management in HetNet**

HetNet deployment strategy helps LTE-A to solve several issues, i.e., better coverage area, higher throughput, and enhanced the QoS for cell-edge user (Ramazanali, Mesodiakaki, Vinel, & Verikoukis, 2016). However, it faces some challenges which still need further investigation. Cell association and ICI in HetNet are major issues to consider. These are coupled problems and it would be better to solve concurrently. Although cell association problems can be solved by considering network load, uplink data and backhaul capacity and ICI can mitigate by using different carrier frequencies for different cell (Boudreau et al., 2009), it will be more effective for the joint solution which can consider the interference before assigning any user to a particular cell. A detailed study shows that the handover failure rate in HetNet is far greater than homogeneous network (López-Pérez, Guvenc, & Chu, 2012). The reasons behind this are the insufficient mobile state estimation and the ineffective small cell discovery method over different carrier frequencies. Therefore, a better small cell discovery technique along with recovery process are required to reduce the effect of failed handover.

- **Implementing CoMP**

CoMP is included in the LTE-A system to improve the efficiency, cell-edge user throughput, and the cell coverage. However, there are some challenges to implement CoMP (Irmer et al., 2011; Qamar, Dimyati, Hindia, Noordin, & Al-Samman, 2017). Backhaul connection between several eNodeB (eNB) is an important aspect in CoMP. Although there is no efficient backhaul communication strategy, specific control and signaling protocol for different scenarios have yet to be developed. As CoMP heavily relies on channel information feedback, scheme with smart resource allocation, improved pilot signal, antenna configuration and improved uplink reference signals need to be developed.

- **Implementing Relay**

LTE-A introduced relays in Rel-10 to enhance the coverage area, cell-edge user throughput and data rate in special areas i.e. underground, indoor environment. There are several issues need to be solved within the scope of Rel-12 (Coletti, Mogensen, & Irmer, 2011). First, the deployment of mobile relays increases the coverage and boosts the QoS in high-speed transportation like trains, but due to high speed and penetration loss severe, Doppler Effect and low signal strength limit the network performance and increases the power consumption. Second, efficient deployment strategies are needed for different scenarios. Third, interference to the nearby users and eNBs caused by the transmission of relay node (RN) can drastically reduce the performance. An efficient technique to coordinate the RNs' transmission is required to avoid this kind of interference. Finally, a reliable and dedicated backhaul connection between the RN and eNB is needed for better connectivity and efficient resource allocation (Yang, Hu, Xu, & Mao, 2009).

- **High Attenuation and Poor QoS of Cell-Edge User**

To meet the IMT-Advanced requirement, LTE-A need to improve spectral efficiency, cell capacity, and cell edge user throughput. As LTE-A uses larger bandwidth, higher frequency (more than 6GHz) spectrum is the best option to facilitate it due to the high availability. However, this high-frequency spectrum is highly affected by attenuation and fading due to absorption by water and oxygen molecule (resonance frequency) in the air (Colombo & Cirigliano, 2011). Bad weather can increase the fading effect and heavy rain can even cause signal loss for this range of high frequency. Cell-edge users are most likely the victim of this issue. Although carrier aggregation can aggregate different low band frequencies, it is a real challenge to improve the capacity of the cell and QoS of the cell-edge user by using higher frequencies.

2.2 Coordinated Multipoint Transmission

Generally, a cell-edge user has low SINR due to the distance from the attached eNB and interference from the adjacent cells. LTE-A system introduces the CoMP transmission to improve the cell-edge user throughput and system capacity (Marsch & Fettweis, 2011). This new technique enhance the performance by turning ICI into a useful signal and/or avoiding the ICI using directional coordinated beamforming ("Further advancements for E-UTRA physical layer aspects," 2010). The main idea of CoMP is that a cell-edge user can receive signals from multiple eNBs of adjacent cells as shown in Figure 2.5 ("Technical specification group radio access network; coordinated multi-point operation for LTE physical layer aspects (release 11).", 2011). The eNBs are connected to each other by a backhaul link (X2 interface) to exchange the information.

2.2.1 CoMP Categories

There are different downlink CoMP transmission approaches with different requirements, complexity, and level of coordination. The LTE-A system implements one of the CoMP types based on the degree of eNB coordination and current traffic load. However, it is possible to combine multiple types of CoMP (Osseiran, 2011). Initially, CoMP is divided into 'Coordinated Scheduling and/or Beamforming' (CS/CB) and 'Joint Processing' (JP) depending on the type of transmission. JP is further divided into Dynamic Point Selection (DPS) and Joint Transmission (JT) (Pateromichelakis, Shariat, ul Quddus, & Tafazolli, 2013). A brief description of different CoMP type is given in the next sections.

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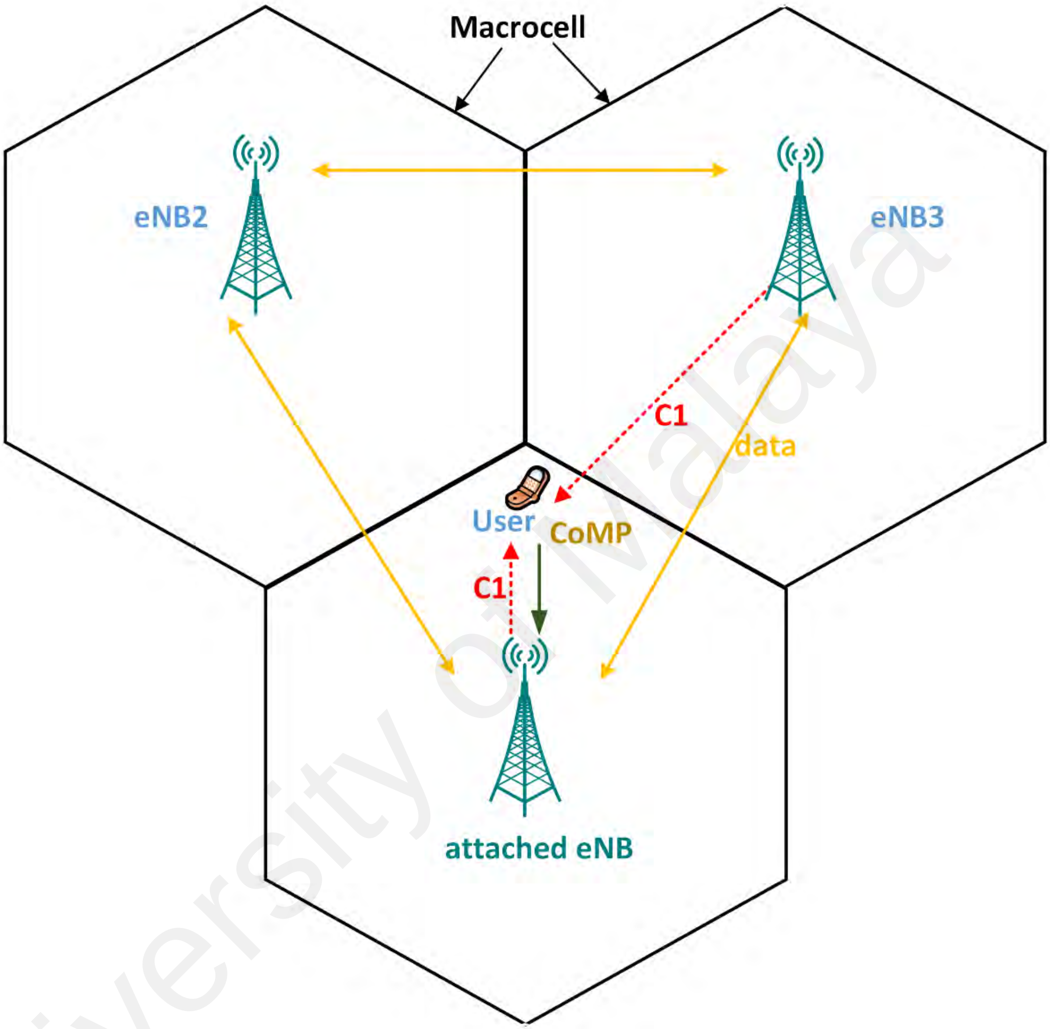

Figure 2.5: General architecture of CoMP

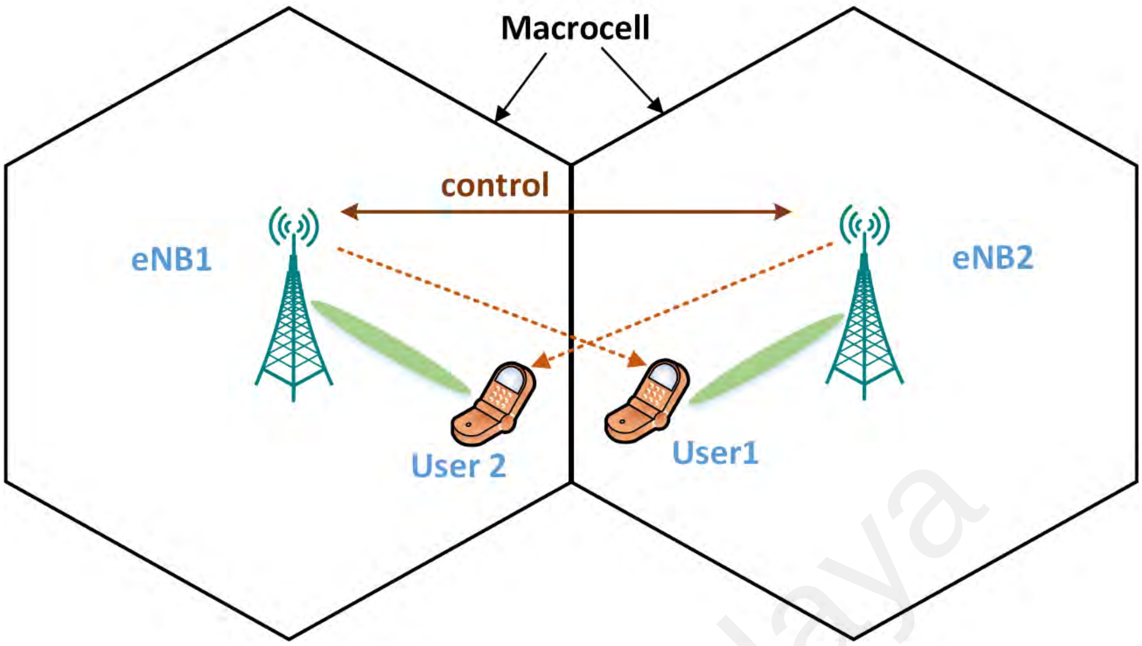

Figure 2.6: Coordinated scheduling/Coordinated beamforming

2.2.1.1 Coordinated Scheduling and/or Beamforming

This method serves a user by coordinating the serving point and the signals to enhance the cell-edge throughput as shown in Figure 2.6. CS/CB can be considered as extended ICIC as it combines the dynamic ICIC (DICIC) and coordinates multiple eNBs (Boujelben, Benrejeb, & Tabbane, 2014). CS/CB performs efficient and fast eNB coordination with the capability of beamforming by using MIMO. Although the scheduling decision and beamforming are coordinated among a cluster of eNBs, a cell-edge user is served by a single eNB at a given time. Dynamic Point Blanking (DPB) can be the example of CS/CB where one transmitter switches on or off based on the possible effect of the interference (Osseiran, 2011; Svedman, Wilson, Cimini, & Ottersten, 2007).

Channel State Information (CSI) of the user based on the SINR is a significant feedback report in multi eNB coordination. Both the transmitter and receiver use a predefined matrix to identify the channel state at a given time. Therefore, the user sends feedback to the serving eNB with Precoding Matrix Index (PMI), CQI and RI. eNB can

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mitigate the ICI by using the PMI assuming that both user and eNB have a knowledge of codebook matrix. User suggests the eNB to either recommend or restrict a PMI based on the possible interference if it is used to transmit the signal. eNB considers this suggestion to coordinate with the adjacent cell before using a specific PMI for downlink transmission (Pateromichelakis et al., 2013; Rumney, 2013).

Coordinated beamforming (CB) enhances the target user signal strength while mitigates the ICI from the neighboring cells. Unlike the above CS method (using PMI) the eNB considers either the joint leakage suppression (JLS) or zero-forcing beamforming (ZFBF) to transmit the signal based on the CSI feedback. The ZFBF method forces the interference to zero from an eNB for a user who is served by other eNB. Whereas, the JLS method maximizes the signal-to-leakage-plus-noise ratio (SLNR) of the user served by the attached eNB. CB provides more flexibility than CS but requires more feedback overhead, complexity, CSI accuracy and coordination (Hosein, 2008; D. Lee et al., 2012).

2.2.1.2 Joint Transmission

JT CoMP transmits data to a particular cell-edge user from multiple eNBs simultaneously as described in Figure 2.7. Generally, the cell-edge user experiences more interference from adjacent eNBs in HetNets and small cell networks. Therefore, JT can be an effective technique to improve the overall network performance especially the cell-edge user throughput (Q. Li, Hu, Qian, & Wu, 2012). JT considers that each eNB is connected with other adjacent eNBs by a fast X2 interface and the coordinated eNB set centrally or individually decide the RA. JT transmits signals to the user either Coherently

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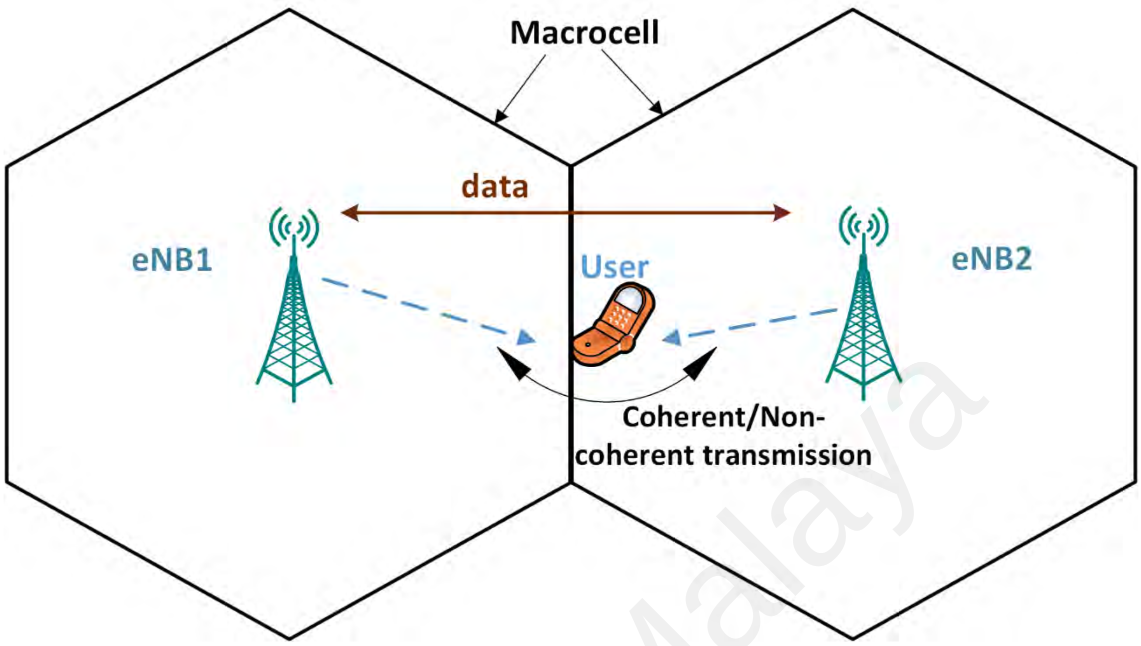

Figure 2.7: Joint transmission

(CJT) or Non-Coherently (NCJT) (Irmer et al., 2011). CJT process ensures that the phase and amplitude of the transmitted signal can be combined in the receiver coherently at symbol level. Each user needs to send the CSI report (consists of CQI, RI and sub-band PMI) to each coordinated eNB (Sun & Yang, 2015). A centralized eNB can act as a Master node to control the other coordinated eNBs (slave node) and the eNB set combinedly perform the PMI-to-RA depending on suggested PMI by the user. However, a fast and reliable X2 interface is required to exchange the control data and user data and to synchronize the eNBs to serve a user by coordinated eNB set (Ali & Synthia, 2015).

NCJT technique implements Cyclic Delay Diversity (CDD) or Single Frequency Network (SFN) method which enhance the transmit power and improve the diversity gain in the user end (Tanbourgi, Singh, Andrews, & Jondral, 2014). NCJT provides high received signal strength which can upgrade the reception quality for the cell-edge user as

NCJT does not adjust the phase or the amplitude of the transmitted signal. Thus, the received signal in NCJT technique are not combined coherently at the receiver. The precoding for single-cell is considered for each eNB individually and the coordinated eNBs exchange only the wideband RI and CQI information in the CSI feedback. (Sun & Yang, 2015).

2.2.1.3 Dynamic Point Selection

DPS is also known as Transmission Point Selection (TPS) or Dynamic Cell Selection (DCS). In DPS, user receives data from single eNB at a time, although the user data is available at multiple eNBs in a coordinated set. The transmitting eNB can be switched to other eNB in the coordinated set for a particular user at a subframe level based on the channel condition and availability of the resource as shown in Figure 2.8. User can choose the suitable eNB at each subframe by using the conventional cell-specific reference signal (CRS) as the PMI method is not implemented in DPS (Chunye, Peter, & Zhang, 2012). When serving eNB is transmitting the other eNBs in the coordinating set remain off for that particular user to avoid further interference (Agrawal et al., 2014). Resources of eNBs can be wasted by keep waiting the other users since multiple eNBs are involved in serving a user but one eNB can transmit the signal at a time. The CSI information from the user should be highly accurate to select the convenient eNB and high backhaul delay can degrade the performance.

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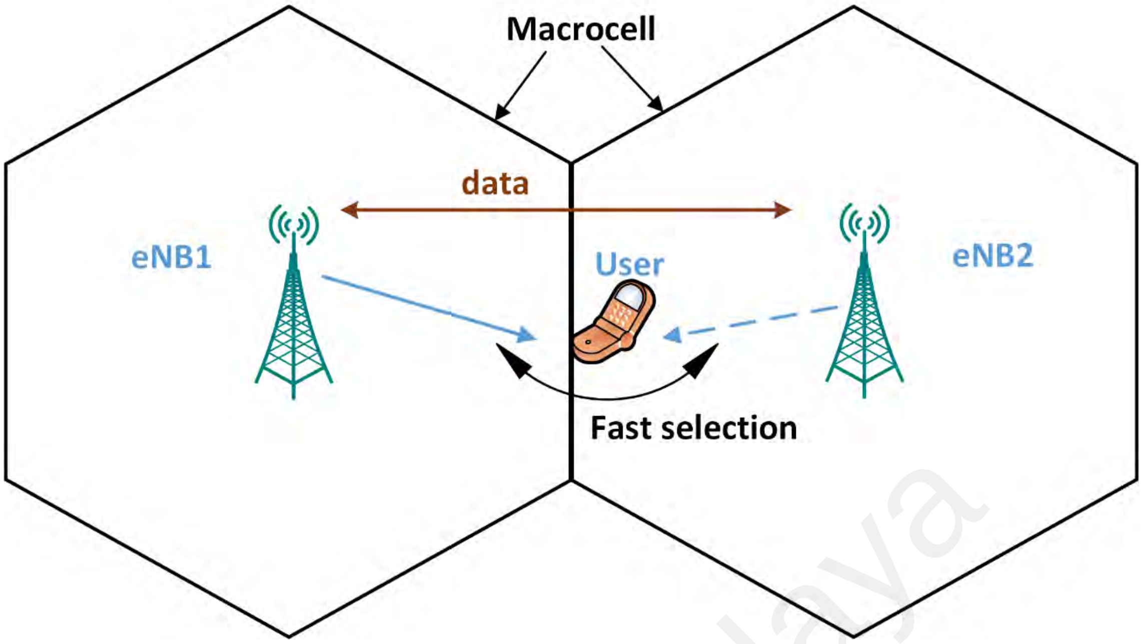

Figure 2.8: Dynamic point selection

2.2.2 CoMP Scheduling approach

The radio resource allocation (RA) process in terms of time, frequency and power in mobile network is noted as scheduling. The overall performance of a network significantly depends on the efficiency of a scheduler. There are two types of CoMP scheduling approach based on the method of coordinating the eNBs. The brief description of these two approaches is given below.

2.2.2.1 Centralized Scheduling

One of the cooperating eNBs in centralized scheduling (usually the attached eNB) acts as a master node and other nodes in the eNB set serves as slave. Master (or central) node performs the scheduling process based on the CSI/CQI received from the user and exchanges the user and scheduling information with other nodes by X2 interface as shown in Figure 2.9 (Brueck, Zhao, Giese, & Amin, 2010). A strict time synchronization among the eNBs is required for seamless services. Moreover, a low latency, well designed, reliable and a high capacity X2 interface among the eNBs are also needed to deploy this scheduling approach.

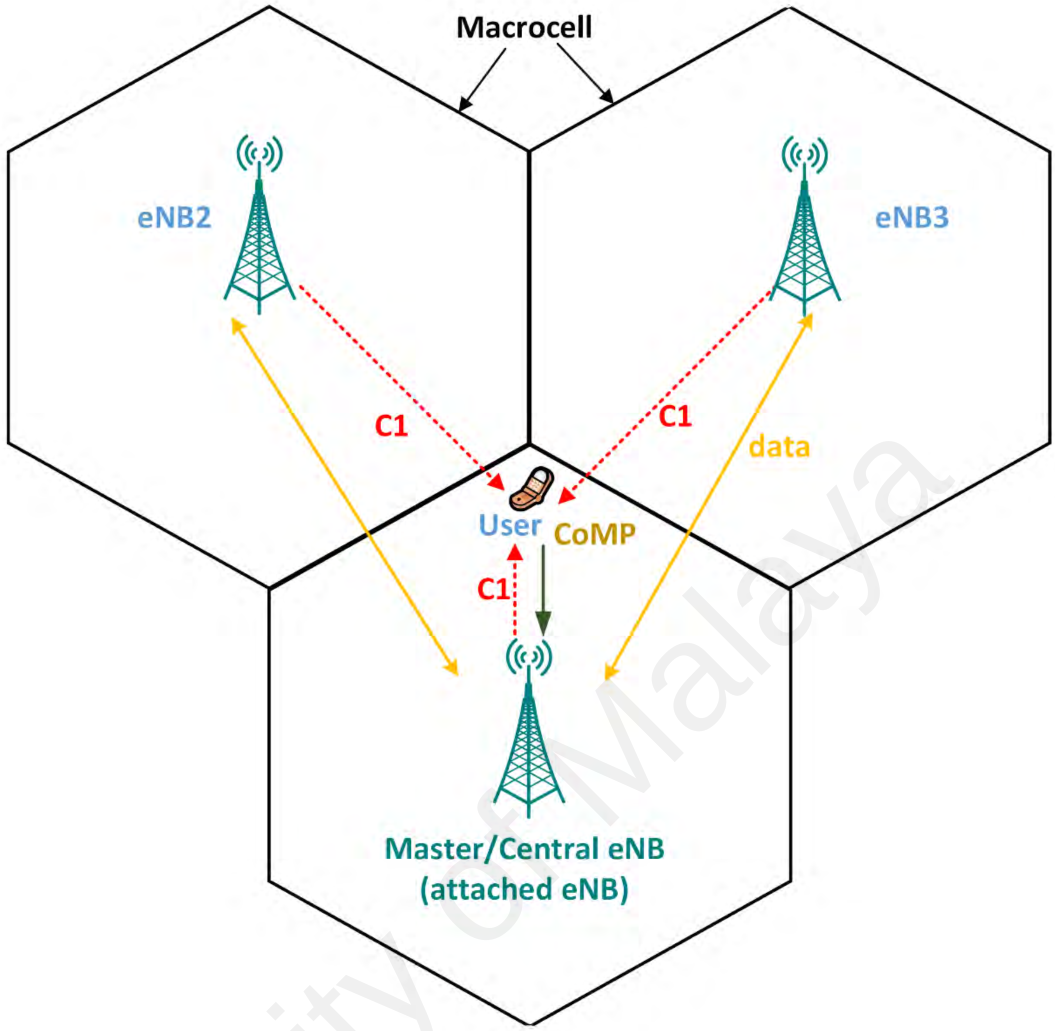

Figure 2.9: Centralized CoMP scheduling

2.2.2.2 Distributed Scheduling

All eNBs of the coordinated set are connected by fully meshed network in the distributed scheduling to exchange the CSI information and user data through the X2 interface. Each eNB in the set performs the scheduling process independently in this scheduling approach according to the CSI feedback from their cooperating eNBs. In general, less amount of backhaul data needs to be exchanged in this approach as each eNB can do the scheduling individually. Therefore, this scheduling approach is more applicable for HetNet where the X2 interface is not capable of handling large amount of data. However, since the femtocells can appear randomly in the HetNet, it would be a challenge to perform the HetNet CoMP scheduling (Pateromichelakis et al., 2013).

2.2.3 CoMP Scheduling Algorithms

Resource allocation is a major aspect in CoMP system due to its significant impact on the overall performance improvement. Therefore, previous researchers propose different algorithms based on various mathematical models for CoMP.

Querying Table based on Proportional Fairness (QTPF) algorithm is proposed to schedule the RB in CoMP (Z. Li et al., 2016). This algorithm divides the available RBs into CoMP RB and non-CoMP RB. The cell center users are scheduled by the conventional PF scheme whereas the cell edge users are scheduled by the priority-based PF to allocate CoMP RBs and pairs the users with the cooperative set. In (Chung, Chang, & Teng, 2014) a green radio resource allocation (GRRA) scheme is used for CoMP transmission based on modulation order, required transmission power and number of coordinated transmission nodes to support multimedia traffic. This scheme assumes predetermined CoMP transmission types and considers different queue for different types of traffic. Both of the above-proposed methods do not clearly define the selection process of cooperative eNB set.

CA is used in with CoMP to allocate the RB for the cell edge user by calculating SINR for each CC of neighboring eNBs. The method in (Ginting, Fahmi, & Kurniawan, 2015) selects the least interference neighboring eNB and checks the capacity of that eNB before it has been assigned to the user. The authors in (Xiaoyong, Dengkun, & Xiaojun, 2009) assign the RB without considering the eNB selection. However, neither of these schemes describe the criteria and procedures of CC selection. The availability of CoMP and CA in

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a heterogeneous network is analyzed in (Jia, Deng, Chen, Aghvami, & Nallanathan, 2017). A genetic algorithm is implemented to solve the max-min optimization problem regarding RA.

Block-level RA based on SINR and selected MCS with low complexity is proposed in (J. Yu & Yin, 2016), where user selection and power allocation is separated. The method assumes that the power allocation is given when the RB scheduler is performing and the scheduled user is fixed for each RB when the power allocation is performing. Joint beamforming and power control algorithm (JBPCA) based on auction theory is proposed in (F. Zhao, Miao, & Chen, 2016). JBPCA algorithm divides the user into authorized and unauthorized user and assumes that authorized users are allocated with idle RBs which can be shared with unauthorized users by implementing spectrum auction scheme to increase the system performance.

PF scheduling algorithm based on beamforming and joint transmission is used to schedule the user in (W. Yu, Kwon, & Shin, 2013), where the scheme selects the user according to PF criteria and assumes that the power allocation and beamforming are fixed. After performing the user selection, the power allocation and beamforming has been updated. Thus, this per-beam basis downlink scheduling does not make interference in the network. PF scheduling based on successive convex approximation (SCA) algorithm with a combination of MIMO and power allocation for CoMP-CB operation is used in (Mosleh, Liu, & Zhang, 2016). Closed -form expression is implemented for special cases and for different SNR scenarios.

Cloud radio access network (CRAN) technology uses in LTE-A for CoMP transmission to reduce the backhaul communication between eNBs as well as to improve network efficiency by implementing load balancing (Checko et al., 2015). Heterogeneous CRAN (H-CRAN) is implemented in different scenarios of CoMP without having any connection between the remote radio head (RRH) and high-power node (HPN) in (Peng, Li, Jiang, Li, & Wang, 2014). eNB transmits user data and control data to the user separately to reduce the traffic in backhaul connection. However, this method is more expensive and more complex than other methods. A semi-dynamic clustering method uses in (H. Zhang et al., 2015), which is based on Affinity propagation algorithm. This proposed method uses online and offline stages by considering reference signal receiving power (RSRP) and sounding reference signal (SRS) to select the cooperative set of eNBs. The queue-aware RA based on partially observed Markov process decision (POMDP) and stochastic gradient algorithm with CRAN is used for a Hybrid CoMP (H-CoMP) system in (J. Li, Peng, Cheng, Yu, & Wang, 2014). An online learning algorithm is used in this scheme by calculating pre-queue post-decision value function to reduce the complexity.

Energy efficient (EE) schedulers are used in previous research works to allocate power efficiently as well as to improve the throughput of the user. Noncooperative power game (PG) method with pricing for MIMO-based CoMP transmission is proposed in (S. Fu, Wen, Wu, & Wu, 2015). The proposed EE scheduler in (Huq, Mumtaz, Rodriguez, & Aguiar, 2014) considers the ratio of transmit energy for each bit and assigns the RBs to the user which needs least energy per bit. Charnes-Cooper and cubic inequity transformation scheme are used to transform the EE RRM problem into concave optimization problem in (Chand, Mahapatra, & Prakash, 2016) and (Huq et al., 2015) respectively, where the first one is solved through the water filling (WF) algorithm and the latter is solved by dual decomposition with estimated gradient scheme.

Efficient Feedback technique (Määttänen et al., 2012) and transmission scheme with limited backhaul data (J. Zhao, Quek, & Lei, 2013) are used to reduce the load in backhaul connection. An integer non-linear centralized CoMP scheduling method is discussed in

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(Ramos-Cantor, Belschner, Hegde, & Pesavento, 2017). In this approach, serving eNB is selected based on the received power. Moreover, it also considers the cell range expansion method in case of Het Net. different traffic condition (Yapeng Wang, Yang, & Yang, 2015). A BF CoMP approach is studied in (Hunukumbure & Vadgama, 2013). The interference nulling information is exchanged among the coordinated eNBs. Signals are transmitted to a user if pre-coder of that user matches with this interference nulling vector. A Control Architecture based on RB separation for CoMP and non-CoMP user is proposed in (Okamawari, Zhang, Nagate, Hayashi, & Fujii, 2011) where the decision of allocating RBs to the user is taken jointly by cooperative nodes. Different scheduling functions and design architectures are discussed in a number of previous studies. Cumulative distribution function-based scheduling method (Park, Choi, & Love, 2014) selects the cooperative set and the user simultaneously for the two-tier network. Newton method with log-barrier penalty function (Abdelaal, Elsayed, & Ismail, 2015) considers the Signal-to-Leakage-plus-Noise-Ratio (SLNR) to overcome the complexity issue. An integrated transmission scheme consists of centralized and distributed algorithms based on RSRP has been used in (S. Fu, Wu, Wen, Ho, & Feng, 2014) to choose the cell-edge user and the cooperative eNBs. A user-specific modified RR is used for CoMP resource allocation (Zhou, Chen, Tan, Chen, & Zhang, 2011a). RR method separately allocates the RBs from cooperative eNBs to different cluster of the user on the basis of 'first come first serve' method rather than the channel condition. The summary of previous studies shows in Table 2.3.

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Table 2.3: Summary of CoMP Scheduling algorithm

CoMP Method	Technique used	Characteristics	Reference
DPS	QTPF	• Cell-center user and cell-edge user are scheduled by a different algorithm.	(Z. Li et al., 2016)
CB, JT	GRRA	• Implement different queue for different types of data in predefined CoMP transmission types	(Chung et al., 2014)
JT	CA	• Deploy different CCs of different cooperative eNBs to users based on SINR. • No efficient CC selection	(Ginting et al., 2015; Jia et al., 2017; Xiaoyong et al., 2009)
JT	SINR/RSRP and selected MCS	• The scheduler allocates RBs depends on the signal strength on the user side.	(S. Fu et al., 2014; J. Yu & Yin, 2016)
CB	JBPCA	• Uses auction theory to choose a user from two predefined user groups.	(F. Zhao et al., 2016)

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Table 2.3: Continued

CB, JT	PF scheduler	• Considers the previous successful transmission rate and instantaneous rate to select the user by assuming that the power allocation and beamforming are fixed. • The combination of MIMO and power allocation is used.	(Mosleh et al., 2016; W. Yu et al., 2013)
CB, JT	CRAN/H-CRAN	• Baseband unit (BBU) pool is used to provide cooperative services of RRH and HPN for the user. • Energy and cost efficiency of network operation • Increase network capacity by load balancing.	(Checko et al., 2015; J. Li et al., 2014; Peng et al., 2014; Q. Wang et al., 2009; H. Zhang et al., 2015)
MU-MIMO, JT	EE Scheduler	• PG, Charnes-Cooper, cubic inequity transformation and WF scheme are used for efficient power control as well as higher throughput.	(Chand et al., 2016; S. Fu et al., 2015; Huq et al., 2015; Huq et al., 2014)

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Table 2.3: Continued

JT, DPS	Efficient control data	• Efficient use of control data between eNBs can reduce the response time to the user and increase the system efficiency.	(Määttänen et al., 2012; Okamawari et al., 2011; J. Zhao et al., 2013)
JT	Different scheduling functions	• Cumulative distribution and Newton method with log-barrier penalty function can handle the complexity issue.	(Abdelaal et al., 2015; Park et al., 2014)
JT	Centralized Scheduler	• A centralized node manages the resource allocation process considering the maximum total received power.	(Ramos-Cantor et al., 2017)
BF	Match interference nulling vector	• Compare the interference nulling vector with the pre-coder of the user to allocate RBs.	(Hunukumbure & Vadgama, 2013)
JT	RR	• The user-specific modified RR method allocates RBs to a different cluster of the user without considering the channel condition.	(Zhou et al., 2011a)

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2.3 Carrier Aggregation

To reach out with the future demands and to implement the IMT-Advanced requirements, LTE-A introduced some new technologies along with the enhancement of previous technologies. In Rel-10, LTE-A proposed CA for supporting wider bandwidth up to 100 MHz (Shen, Papasakellariou, Montojo, Gerstenberger, & Xu, 2012). This technology is also known as channel aggregation, which uses multiple (maximum five) CCs of different frequencies joined together to form a higher overall transmission bandwidth and is used to provide an improved throughput as required for LTE-A system as depicted in Figure 2.10. Each CC may appear as LTE carrier to the legacy users while LTE-A users are able to transmit and receive on several CCs simultaneously. The bandwidth of each CC can be either 1.4, 3, 5, 10, 15 or 20 MHz (Cox, 2012; Iwamura, Etemad, Fong, Nory, & Love, 2010).

CA is designed to be backward compatible which means that legacy Rel-8 and Rel-9 users can co-exist with LTE-A users on the context of the total bandwidth. Moreover, CA supports the frequencies previously occupied by other systems, such as UMTS and GSM for possible CC aggregation. Therefore, the scheduler can allocate resources on any one of the available CCs with a different bandwidth (maximum 20 MHz) to Rel-8 and Rel-9 users. CA will allow the operator to provide additional capacity without causing any unfavorable impact on the legacy LTE (Rel-8 and Rel-9) users (Dahlman et al., 2013; Lin, Andrews, & Ghosh, 2013).

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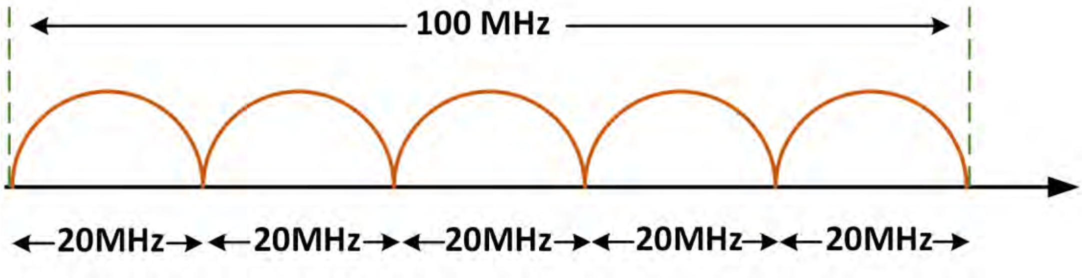

Figure 2.10: Structure of Carrier Aggregation

2.3.1 Structure of CA

Carrier Aggregation allows mobile network operators to combine a number of separate LTE carriers as depicted in Figure 2.11. This enables them to increase the peak user data rates and overall capacity of their networks and to exploit fragmented spectrum allocations. In principle, Carrier Aggregation can be applied to either the FDD or TDD variants of LTE and it can be used to combine carriers whether or not they are contiguous or even in the different frequency band. Ultimately the aim is for Carrier Aggregation to combine up to five separate LTE carriers, each of up to 20MHz. Release 12 will include CA of FDD and TDD frequency bands, as well as support for aggregating two UL CCs and three DL CCs. Note that even though certain CA combinations are specified in later releases, these are release independent and can be supported from previous release equipment due to backward-compatible signaling. 3GPP Rel-13 offers aggregation of four DL CCs and support for CA configurations for UL inter-band and intra-band non-contiguous CA (*LTE Carrier Aggregation Technology Development and Deployment Worldwide,*, October 2014).

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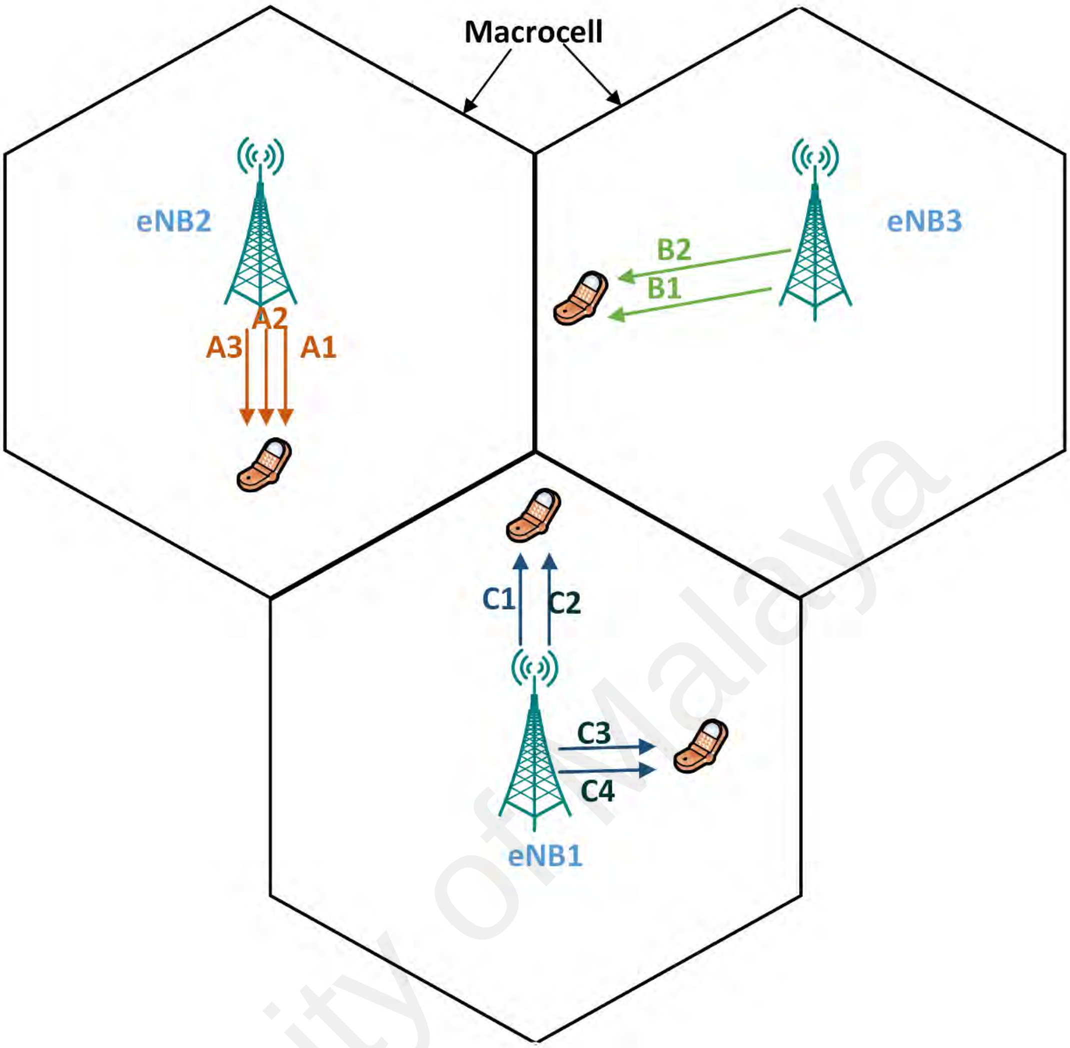

Figure 2.11: Downlink Carrier Aggregation

Multiple CC assignment to a user introduces some new challenges related to the functionalities of RRM. Therefore, a new set of modifications and functionalities in the RRM and link layer are required (Pedersen et al., 2011). Figure 2.12 shows the RRM framework of multiple CCs aggregated in LTE-A system (Yuanye Wang, Pedersen, Sørensen, & Mogensen, 2010). eNB performs the admission control to accept or reject the incoming user. When a user first connects, only one CC is assigned which is call primary CC (PCC) corresponding to a primary serving cell (PCell). Thereafter, one or multiple additional secondary CCs (SCCs) for secondary serving cell (SCell) can be allocated depending on the QoS requirement and cell load (Iwamura et al., 2010). The

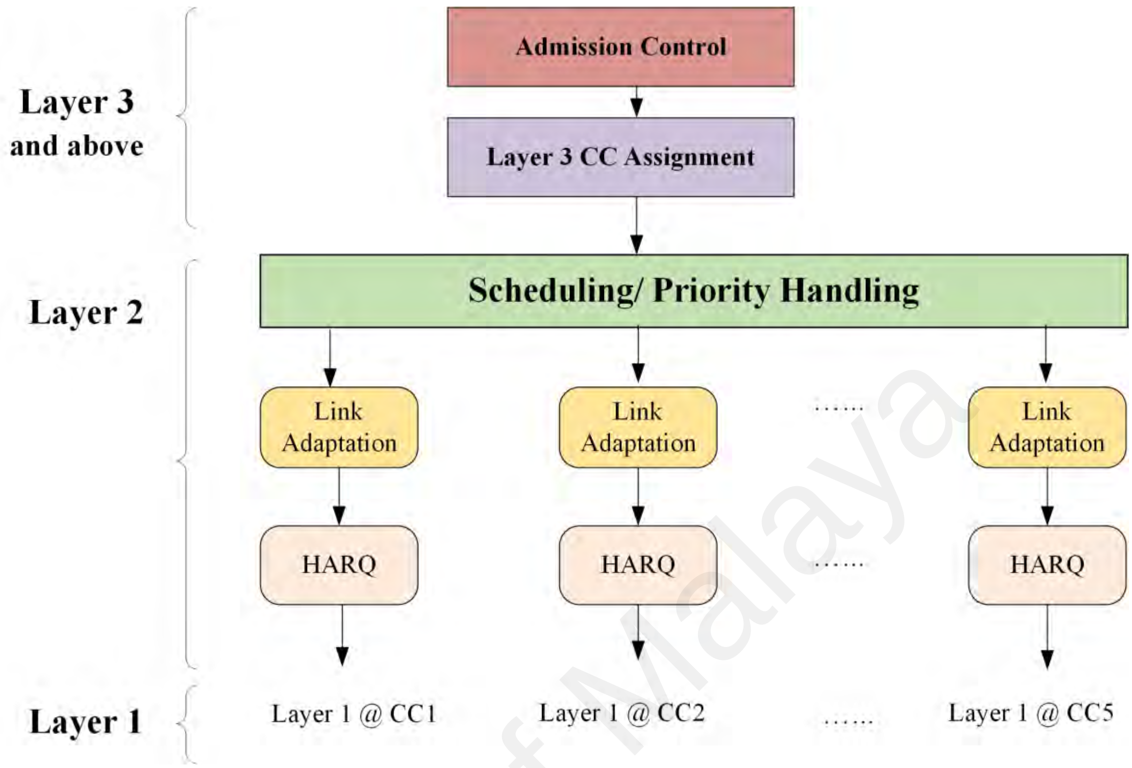

Figure 2.12: RRM framework with carrier aggregation

configuration of PCC/SCC is user specific and different user can have the same CC as both PCC and SCC as shown in Figure 2.13. The PCC is considered as the backbone of the user and is responsible for basic functionalities. Whereas, the SCCs transmit PDSCH (physical DL shared channel), PDCCH (physical DL control channel) and dedicated signals. A CC can transmit scheduling information of other CCs along with its own scheduling information since LTE-A supports cross-carrier scheduling for load balancing and interference management. The eNB can change the PCC due to the movement of a user and load balancing. The SCCs can also be changed dynamically based on carrier load, amount of buffered data and QoS requirement. Furthermore, each CC performs its own HARQ process to correct the error (Tran, Shin, & Shin, 2012).

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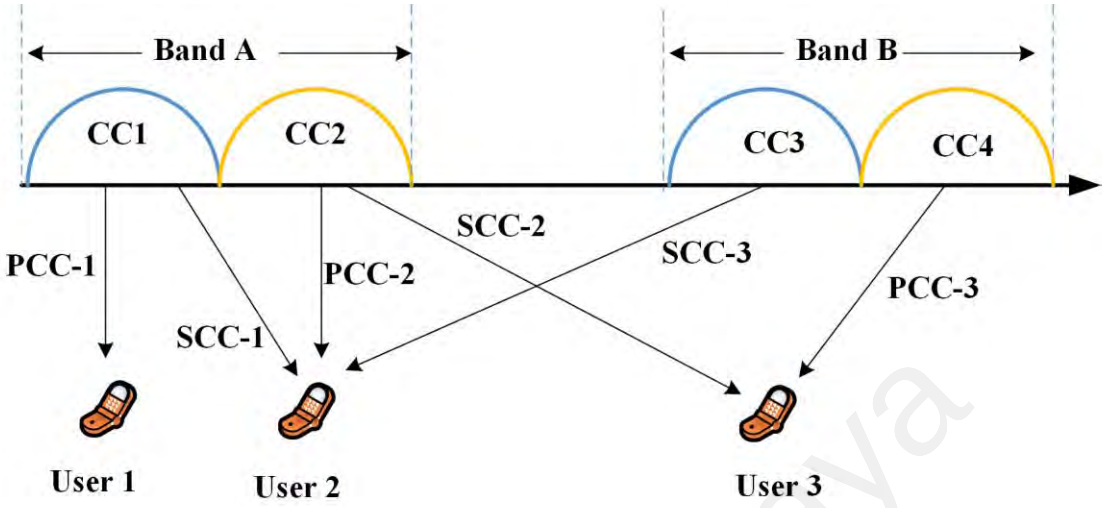

Figure 2.13: CC Configuration for different user

2.3.2 Types of CA

There are three different types of CA based on the way the CCs are arranged in the frequency bands- Intra-band contiguous, Intra-band non-contiguous and Inter-band ("Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (Release 11)," December 2012). The Intra-band contiguous CA configuration refers to contiguous carriers aggregated in the same operating band. The Intra-band non-contiguous CA configuration refers to non-contiguous carriers aggregated in the same operating band. The Inter-band CA configuration refers to aggregation of component carriers in different operating bands, where the carriers aggregated in each band can be contiguous or non-contiguous (Yuan, Zhang, Wang, & Yang, 2010). Figure 2.14 shows the different types of CA.

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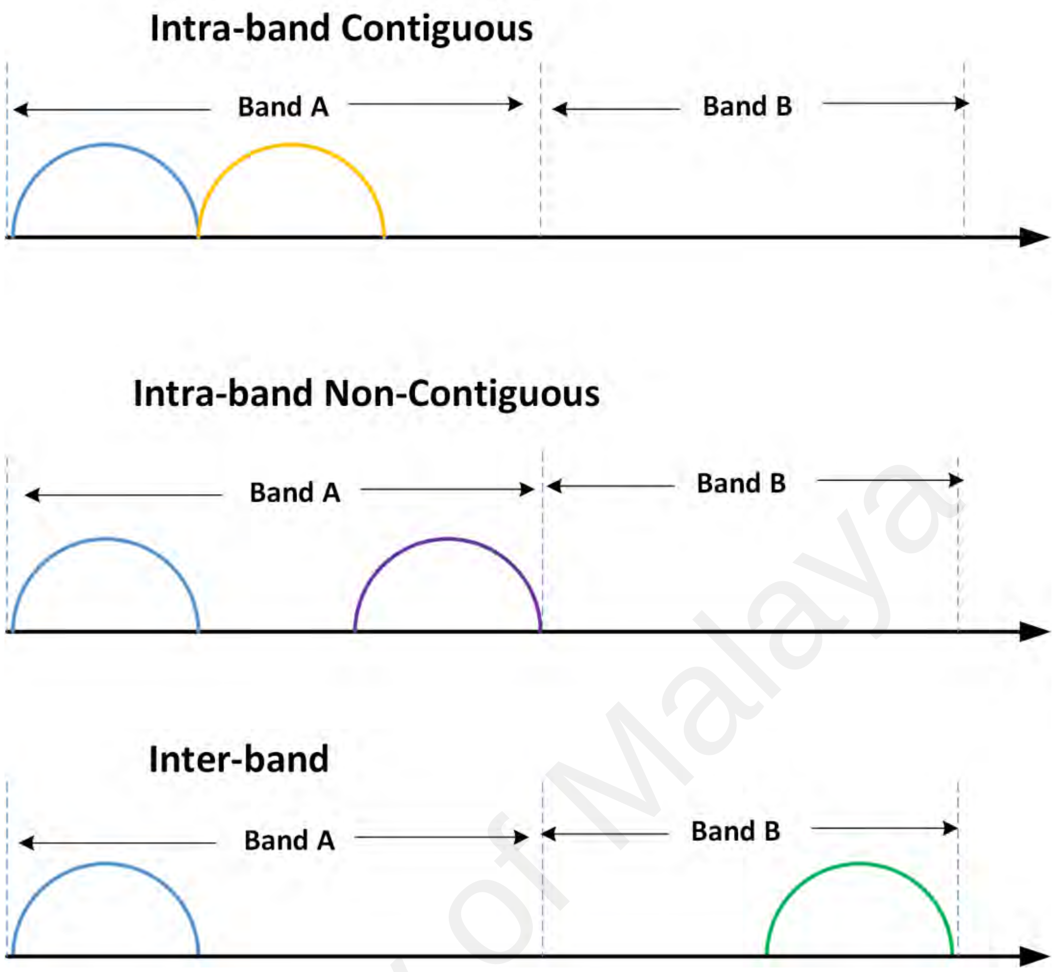

Figure 2.14: Different types of Carrier Aggregation

- Intra-band contiguous is the simplest CA deployment, which aggregates multiple adjacent CCs in the same operating band. It requires less power and lower costs than the other two types. It can be implemented without making much change to the LTE physical layer structure. Moreover, it is possible to use a single transceiver to utilize the continuous CCs for an LTE-A user. It is a less likely scenario in the lower frequency band due to the unaviability of contiguous frequency. However, higher frequency bands such as 3.5GHz or 6 GHz can be possible to implement this type of CA (H. Lee, Vahid, & Moessner, 2014).

- Intra-band non-contiguous CA combines multiple non-adjacent CCs in the same operating band. The multicarrier component is no longer considered as a single signal and therefore, it requires more transceivers which adds more complexity and cost (Miki, Iwamura, Kishiyama, Anil, & Ishii, 2010).

- Inter-band CA aggregates multiple CCs in separate operating bands. These CCs in different bands can be contiguous or non-contiguous. More advanced multiple transceivers are required, which increases the complexity, cost, and power requirement (Yuan et al., 2010).

2.3.3 CA Benefits and Performance

CA is an efficient technique to combine together fragmented spectrum and provides a wider bandwidth. However, CA has several other benefits:

- **Higher speeds**: The available resource increases by aggregating multiple carriers which provides higher data rate across the coverage area of the cell.
- **Capacity gain**: CA increases the trunking gains by scheduling dynamically across the entire spectrum which improves the cell capacity, network efficiency, and user experience.
- **Optimum utilization of resources**: The backward compatibility of CA technique helps the mobile operators to combine multiple CCs from across the spectrum and thus can manage the resources more efficiently.
- **CA in unlicensed scenarios provides new spectrum resources for the operators:** There is always a scarcity of the licensed spectrum due to explosion of the user and services. Moreover, it can be expensive for the operators when new spectrums are available. CA facilitates the operators to utilize the unlicensed spectrum which can reduce the network operation cost.

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2.3.4 CC Selection Method

Downlink radio resource management has a major impact on the overall performance of the mobile network. Therefore, a wide range of study has been conducted by researchers on various aspects of resource management. A good number of researchers have used PF and modified algorithms for packet scheduling with different approaches of CC selection. Joint scheduling also has been proposed to enhance the QoS.

The Circular Selection (CS) scheme is used in (L. Zhang, Liu, Huang, & Wang, 2010) where CCs have been assigned circularly to the users. The authors proposed CC coupling method to balance the load. This method first determines whether the particular CC is idle or busy. If any CC is idle, the load from the other CC will be transferred to the idle one until the CC turns into the busy state. This coupling occurs in every TTI. Round Robin packet scheduling algorithm is chosen for allocating the RB. Compared to other schemes, the authors claim that their method provided higher throughput and improved coverage performance due to efficient balance of the load over multiple CCs. However, in the case of different packet size of user, the efficiency can be decreased. Moreover, it significantly increases the power consumption of the users and the signal processing complexity.

In (Meucci, Cabral, Velez, Mihovska, & Prasad, 2009), CCs have been assigned to a lower frequency at first, then users with higher CQI (Channel Quality Indicator) values move to a higher frequency based on the load of all other CCs. The authors consider two frequencies (2 GHz and 5 GHz) for the proposed method. When a user arrives, the scheduler directly allocates the 2 GHz band, then it checks the load in both bands. If the load is lower in 5 GHz than in 2 GHz, the user with the highest CQI value will be assigned to the 5 GHz band. In case of higher network loads, the users with the lowest CQI value will be moved to the 2 GHz band as propagation loss is typically lower than 5 GHz. Load is calculated based on the availability of the resources for the cell and utilized by the users. Although this approach increases the computational complexity and it does not consider the multi-band approach.

In (Songsong, Chunyan, & Caili, 2009), user grouping PF algorithm (UG-PF) is proposed to improve fairness among users. In this model, path-loss with a certain threshold and coverage of each CC is calculated. Then, the users are divided into some specific groups according to the number of available CCs which can be assigned to the users from their location. The cell-edge user groups are also allowed to access the RBs in the CCs of lower frequencies. Moreover, the users with poor CQI value can obtain higher throughput and better fairness among the users by this algorithm compared with the conventional PF algorithm. However, the average cell throughput can go down by allocating a lot of RBs to users with poor CQI. A generalized PF based Cross-CC PF is proposed in (Yuanye Wang, Pedersen, Mogensen, & Sørensen, 2009) to adapt the level of fairness between users with different aggregation capabilities and with different channel conditions. This method selects CC randomly for users and distributes the load across all CCs. It proves that when the CC selection is predetermined for a user, Cross-CC PF is a better scheduler to improve the throughput. The proposed method requires the exchange of data on the previous user throughput for all CCs. Considering that throughput of all CCs makes the scheduling metric of LTE-A users smaller compared with the basic PF. Their results show better fairness to the users and it is also shown that Cross-CC PF boosts the average user throughput and coverage performance without sacrificing the average cell throughput.

Absolute and relative policy is proposed in (Liu et al., 2011) by considering the signal quality of the CC. Their method divided the cell coverage area into two different cells, named PCell with designated primary CC and SCell with secondary CC. When an LTE-

A user arrives, eNB firstly attaches itself with a PCell as the work assumes that PCell has best signal quality. According to the absolute policy, when the signal quality of a CC is higher or lower than a predefined absolute threshold, the CC is added or removed to the user respectively. On the other hand, based on the relative policy, if the signal quality of a CC offsets higher or lower than the corresponding CC of PCell, the CC is added or removed respectively. However, it is a challenge to determine the threshold or offset value.

In (Liao, Chen, & Chen, 2014), the work proposed a greedy method to maximize the throughput with PF packet scheduling algorithm. The method considered link adaptation jointly with CC assignment and RB allocation. After calculating the gain of all possible combinations, CCs have been assigned to users which have the highest gain. With regards to RB allocation, the method checks whether or not the weighted transmission rate of user with maximum gain is higher than currently assigned RB. However, the authors considered that all CCs have an equal number of RB and all users have similar capabilities which are currently unrealistic assumption compared to the real world. The results are compared with the Least Lord (LL) and Random Carrier (RC) methods, and a modified algorithm named SS. Table 1 shows the summary of previous studies regarding carrier aggregation methods with different CC selection approaches and packet schedulers. The packet delay outage ratio (PDOR) based Opportunistic PDOR aware (OPA) method is proposed with AGSS scheme to maximize the capacity and minimize the delay in (Ragaleux, Baey, & Gueguen, 2016). Table 2.4 summarizes the CC selection methods and packer scheduler of previous studies.

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Table 2.4: Summary of CC Selection Methods

CC Selection Method	Packet Scheduler	Characteristics	Reference
Random selection with load balancing	Cross-CC PF	• Select CC randomly for users. • Allows load balancing across CCs over the long-term, but not short-term.	(Y. Wang et al., 2009)
Circular selection	RR	• Select CC randomly without considering any channel condition. • Less complex than others and used as a reference method.	(L. Zhang et al., 2010)
Inter-band carrier switch	PF	• Assign CC at a lower frequency, then according to the load of all CCs, users with higher CQI move to a higher frequency. • It increases the complexity and it does not support the multi-band approach.	(Meucci et al., 2009)

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Table 2.4: Continued

Lowest path loss	User grouping PF (UG-PF)	• Assign a CC to the user with lowest path loss. • Support user grouping based on the number of CCs that the users can be assigned. • Consider cell-edge user by introducing a weighting factor.	(Songsong et al., 2009)
Absolute and Relative policy	PF	• Add or remove a CC depending on the signal quality of a CC is higher/lower to a threshold/offset value. • It is difficult to determine the threshold/offset value of a CC.	(Liu et al., 2011)
Largest Gain	PF	• Calculate largest gain to assign CC with MCS. • Check whether the weighted transmission rate of maximum gain with user *i* is higher than the currently assigned RB.	(Liao et al., 2014)
Uses PDOR scheme	OPA	• Combines OPA and AGSS methods by using PDOR.	(Ragaleux et al., 2016)

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Table 2.4: Continued

RSRP based	MLWDF	• User is allocated the CCs with highest RSRP.	(Tian, Gao, Zhu, & Chen, 2011)
Geometry (G-) factor	Cross-CC PF	• Selects CCs from different non-contiguous band based on G-factor of the CCs.	(H. Wang, Rosa, & Pedersen, 2011)
HOL delay	Queue side greedy (QSG)	• RB scheduling based on backlog and selects the CC depending on HOL delay	(Cheng, Gupta, & Mohapatra, 2013)
Least load	PF	• Selects CC with lowest traffic loads. • Ensures better performance than other methods, but does not provide good delay performance.	(Yuanye Wang et al., 2010)

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2.4 LTE-A Packet Scheduling Structure

Scheduling is the process in which eNB decides which UEs should be given resources to send or receive data. In LTE, scheduling is done per subframe level (i.e. each 1 ms TTI). Sitting just above the Physical layer, the MAC Scheduler assigns RBs to the user and is responsible for deciding on how uplink and downlink channels are used by the eNB and the users of a cell as depicted in Figure 2.15. It is clear from the Figure that the MAC scheduler receives various information from the upper layers and makes the scheduling decision. It also enforces the necessary QoS for user connections ("Long Term Evolution Protocol Overview," October, 2008).

In order to take its RA decisions, the MAC Scheduler receives information such as:

- QoS data from the PCRF: minimum guaranteed bandwidth, maximum allowed bandwidth, packet loss rates, relative priority of users, etc.
- messages from the UEs regarding the radio channel quality, the strength or weakness of the signal, etc.
- measurements from the radio receiver regarding radio channel quality, noise and interference, etc.
- buffer status from the upper layers about how much data is queued up waiting for transmission

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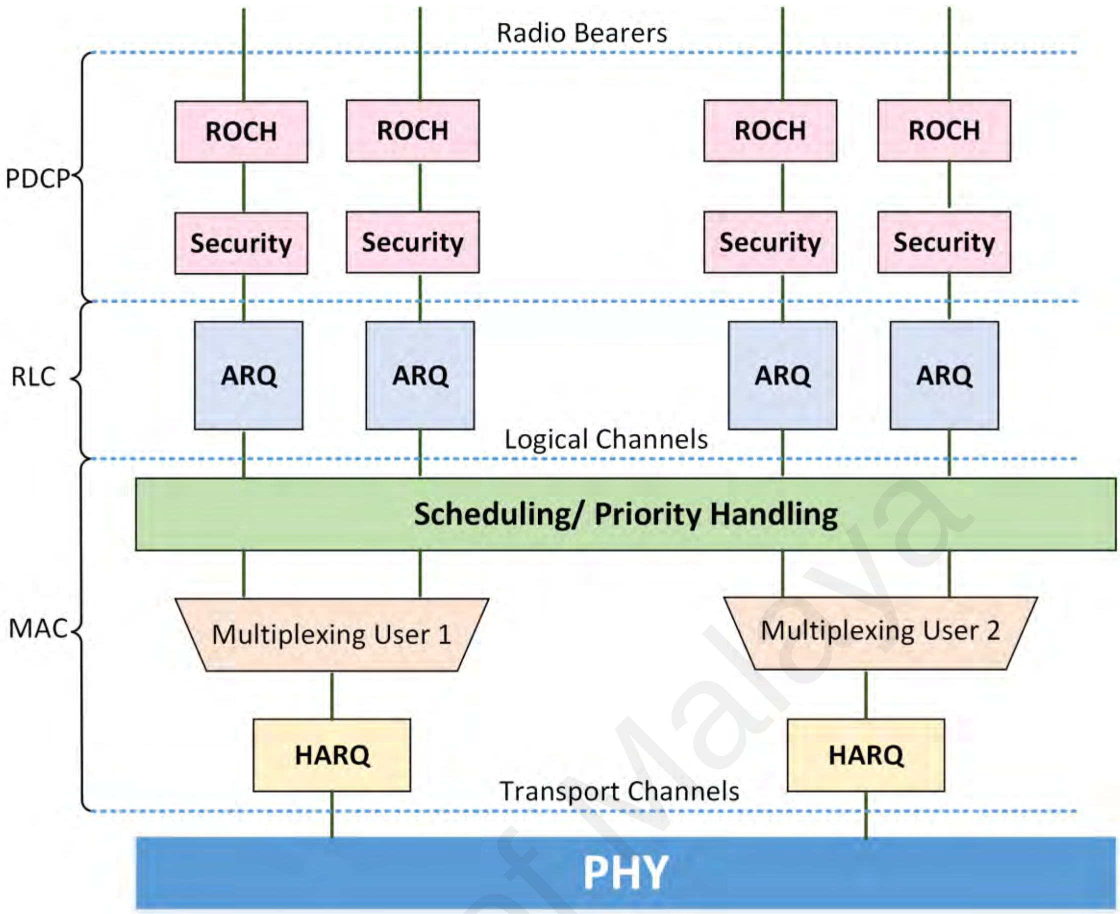

Figure 2.15: Downlink packet scheduling structure

Different performance indicators have been used in evaluating performance of packet schedulers of various research works. The main three are summarized as below.

- **QoS provision to different services**: A QoS framework is a fundamental component of the next generation broadband network for satisfactory service delivery of evolving Internet applications to the end users, and managing the network resources. Today's popular mobile Internet applications, such as voice, gaming, streaming, and social networking services, have diverse traffic characteristics and, consequently, demand different QoS requirements. The data traffic associated with these services must be delivered to the end users at specific data rates and/or within specific delay, packet loss and delay variation bounds.

These requirements can collectively be termed as QoS. A rather flexible QoS framework is highly desirable to be future-proof to deliver the incumbent as well as emerging mobile Internet applications.

- **System spectral efficiency**: System spectral efficiency is typically measured in bit/s/Hz (bit per second per Hz), bit/s/Hz/cell (bit per second per Hz per cell) or bit/s/Hz/site (bit per second per Hz per site). It is a measure of the quantity of users or services that can be simultaneously supported by limited radio frequency bandwidth in a defined geographic area. It may, for example, be defined as the maximum throughput, summed over all users in the system, divided by the channel bandwidth.
- **Fairness among users**: Fairness measures or metrics are used in network management to determine whether users or applications are receiving a fair share of system resources. The fairness index of the user is calculated and compared by Jain's fairness index (Jain, Chiu, & Hawe, 1984). The fairness ranges from $1/Q$ to 1 where Q is the number of user. Higher the value approaching to 1 is considered as better fairness.

In this thesis, the most commonly used performance metrics are adopted to validate the effectiveness of the proposed scheduling method. They include average user throughput, average cell throughput, Cell-edge throughput, Spectral efficiency and fairness index.

The packet scheduling algorithms can be divided into two major groups namely- QoS unaware and QoS aware. The brief descriptions of these types are given subsequently.

2.4.1 QoS Unaware Packet Scheduling Algorithm

QoS unaware algorithms are based on the assumption of time-invariant and error-free transmission media. These algorithms do not consider any kind of channel condition to allocate the RBs. While their direct application in LTE is not realistic, they are typically jointly used with channel-aware approaches to improve system performance. Some of the widely used QoS unaware schedulers are described below.

2.4.1.1 First in First Out (FIFO)

The simplest case of channel unaware allocation policy serves users according to the order of resource requests, exactly like a First in First Out (FIFO) queue. We can translate this behavior in LTE expressing the metric of the *i*-th user on the *j*-th RB as

$$m_{i,j}^{FIFO} = t - T_{i,j} \tag{2.1}$$

where t is the current time and $T_{i,j}$ is the time instant when the request was issued by the *i*-th user on the *j*-th RB. This technique is very simple but both inefficient and unfair.

2.4.1.2 Round Robin (RR)

It performs fair sharing of RBs among users (Capozzi et al., 2013). Round Robin (RR) metric is similar to the one defined for FIFO with the difference that, in this case, T_i refers to the last time when the user was served. In this context, the concept of fairness is related to the amount of time in which the channel is occupied by users. Of course, this approach is not fair in terms of user throughput, that, in wireless systems, does not depend only on the amount of occupied resources, but also on the experienced channel conditions. Furthermore, the allocation of the same amount of time to users with very different application-layer bitrates is not efficient.

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2.4.1.3 Proportional Fairness (PF)

The PF algorithm takes both fairness among users and system spectral efficiency into consideration and allocates the radio resource to users based on the ratio of their achievable instantaneous throughput and their time-averaged throughput (Choi & Bahk, 2007). It allocates a fair share of the radio resource to all users and maintains good system spectral efficiency at the same time, by considering the trade-off between user fairness and system spectral efficiency. The PF scheduling metric $m_{i,j}^{PF}$ is given in equation 2.2

$$m_{i,j}^{PF} = \frac{r_{i,j}(t)}{\bar{r}_i \ (t-1)} \tag{2.2}$$

Here, $r_{i,j}(t)$ is instantaneous throughput of user i, RB j and $\bar{r}_i \ (t-1)$ represents previous average throughput.

2.4.1.4 Maximum Throughput

The strategy known as Maximum Throughput (MT) aims at maximizing the overall throughput by assigning each RB to the user that can achieve the maximum throughput in the current TTI (Capozzi et al., 2013). The scheduling metric can be simply expressed as

$$m_{i,j}^{FIFO} = d_i^j(t) \tag{2.3}$$

MT is obviously able to maximize cell throughput, but, on the other hand, it performs unfair resource sharing since users with poor channel conditions (e.g., cell-edge users) will only get a low percentage of the available resources (or in extreme case, they may suffer of starvation). A practical scheduler should be intermediate between MT, that maximizes the cell throughput, and BET, that guarantees fair throughput distribution

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among users, in order to exploit fast variations in channel conditions as much as possible while still satisfying some degrees of fairness.

2.4.2 QoS Aware Packet Scheduling Algorithm

LTE-A network aims to support diverse application with variety of QoS requirements, apart from system spectral efficiency and user fairness, the crucial point is to meet users' QoS requirements in a multi-service mixed traffic environment. For example, real-time services like audio phone and video conference require end-to-end performance guarantees because a reliable and timely transmission is needed. On the other hand, non-real-time services can tolerate delays to a certain limit but require long-term minimum throughput guarantees. The QoS unaware packet scheduling algorithms (section 2.5.1) cannot achieve the set targets by International Telecommunication Union Recommendations (ITU-R) as they are only designed to improve fairness, spectral efficiency or a trade-off between them. Therefore, QoS aware packet scheduler is more efficient to provide the services which has strict QoS requirement. The following sections presents some of the state-of-the-art on QoS aware packet scheduling algorithms (Singh, 2013).

2.4.2.1 Modified Largest Weighted Delay First (MLWDF)

The MLWDF algorithm ensures ideal throughput to the system and maintains better fairness to all users (Stolyar & Ramanan, 2001). This scheduler largely depends on QoS and packet delay. The throughput optimal MLWDF algorithm has less complexity among all other scheduling algorithms and it considers the real-time traffic. The primary goals of this scheduler are to provide better QoS, to enhance the spectral efficiency and to provide good fairness to the user (Andrews et al., 2001).

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MLWDF is a throughput-optimal scheduling algorithm that considers HOL packet delay, the probability of packet loss and delay threshold along with instantaneous and previous throughput of the user (Ameigeiras, Wigard, & Mogensen, 2004). The scheme is defined by the following equation.

$$m_{i,j}^{MLWDF} = \alpha_i . D_{HOL,i} . \psi_{i,j} \tag{2.4}$$

where,

$$\alpha_i = \frac{-\log \delta_i}{\tau_i} \tag{2.5}$$

$$\psi_{i,j} = \frac{r_{i,j}(t)}{\bar{r}_i(t-1)} \tag{2.6}$$

Here, $D_{HOL,i}$ denotes HOL packet delay, which is the waiting time between the packet arrival time and the time it is transmitted successfully. δ_i represents the probability of packet loss and τ_i is the value of delay threshold. The delay threshold τ_i for user i is based on user applications. $\psi_{i,j}$ is the throughput ratio same as the PF metric $m_{i,j}^{PF}$.

2.4.2.2 Exponential Proportional Fairness (EXP/PF)

The exponential/proportional fair (EXP/PF) algorithm was developed to support multimedia applications in an adaptive modulation and coding and time division multiplexing (AMC/TDM) system (Rhee, Holtzman, & Kim, 2003). A user in AMC/TDM system can either belong to a RT service or a NRT service. Therefore, the EXP/PF equation to be used for a user depends on the user's service type (Rhee, Holtzman, & Kim, 2004). The metric $m_{i,j}^{\mathrm{EXP/PF}}$ is computed for each user for RT and NRT services. The following equation is for RT services (Basukala et al., 2009).

$$m_{i,j}^{EXP/PF} = exp\left(\frac{\alpha_i . D_{HOL,i} - x}{1+\sqrt{x}}\right) . m_{i,j}^{PF} \tag{2.9}$$

where,

$$x = \frac{1}{N_{RT}} . \sum_{i=1}^{N_{RT}} D_{HOL,i} \tag{2.10}$$

Here $m_{i,j}^{PF}$ is the throughput ration as PF algorithm, N_{RT} is the number of RT packets, α_i is the variable as in equation 2.5.

For the NRT services, the scheduling metric can be written as follows

$$m_{i,j}^{EXP/PF} = \frac{w(t)}{M(t)} . m_{i,j}^{PF} \tag{2.11}$$

where,

$w(t) = \{ w(t-1) \quad -\rho \ldots\ldots\ldots\ldots. \; (D_{HOL})_{max} > \tau_i$

$\{ w(t-1) \quad +\rho/\acute{\upsilon} \ldots\ldots\ldots. \; (D_{HOL})_{max} < \tau_i$

Here $M(t)$ is the average number of RT packets waiting at eNB buffer at time t, ρ and $\acute{\upsilon}$ are constants, $(D_{HOL})_{max}$ is the maximum HOL delay.

In the EXP/PF algorithm, RT users are prioritized over NRT users when their HOL packet delays are approaching the delay deadline. If HOL delays of all users are about the same, the exponential term in (2.9) is close to 1 and EXP/PF behaves like PF. If one of the user's delays becomes large, the exponential term in (2.9) will override the left term in (2.9), which reflects channel states, and dominate the selection of a user.

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2.4.2.3 Logarithmic Rule (LOG Rule)

LOG Rule is a channel-aware QoS-aware algorithm and it considers the HOL delay of the user and spectral efficiency. The aim of this algorithm is to guarantee the delay budget which is the key component of QoS requirement. The scheduler metric increases logarithmically when the HOL delay increases (Sadiq, Baek, & De Veciana, 2011). The LOG Rule metric can be expressed as follows

$$m_{i,j}^{LOG\text{-}Rule} = N_i . log\left(\Pi + \Lambda_i . D_{HOL,i}\right) . \Gamma_{i,j} \tag{2.7}$$

where, Λ_i =5/.099 τ_i, N_i = 1/$E(\Gamma_{i,j})$, Π = 1.1 and $\Gamma_{i,j}$ represents spectral efficiency of user *i,* RB *j* (Capozzi et al., 2013).

2.4.2.4 Exponential Rule (EXP/Rule)

EXP Rule can be considered as modified form of the above-mentioned EXP/PF (section 2.5.2.2). It is also a channel-aware QoS-aware algorithm which considers HOL delay, queue status for real-time packets, probability of packet loss, delay threshold, and spectral efficiency (Sadiq, Madan, & Sampath, 2009). The EXP Rule scheduling metric can be calculated as follows.

$$m_{i,j}^{EXP\text{-}Rule} = N_i . exp\left(\frac{\Lambda_i . D_{HOL,i}}{\Pi + \sqrt{\left(\frac{1}{N_{RT}}\right)\sum_i D_{HOL,i}}}\right) . \Gamma_{i,j} \tag{2.8}$$

where,

Λ_i ϵ (5/.099 τ_i, 10/.099 τ_i),

N_i = 1/($\Gamma_{i,j}$), Π = 1

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This algorithm is considered as more robust solution as it takes into account the queue condition along with the channel condition. The scheduling metric increases exponentially as the delay parameters and the queue length increase. This growth is comparatively higher than the LOG Rule metric (Shakkottai & Stolyar, 2002).

2.4.3 Problem Findings and Summary

LTE-A introduces CoMP technique to improve the performance specially the cell-edge user. However, poor received signal, interference from adjacent cells in the cell-edge area, narrow bandwidth, and inefficient eNB coordination scheme can reduce the efficiency of using the CoMP. Although earlier studies propose different algorithms for CoMP to enhance the performance, the cell-edge users have lower throughput compared to the LTE-A standard (Ginting et al., 2015; Z. Li et al., 2016). Previous research works related to downlink radio resource allocation with CA have not considered the delay factor, queue length, and the error probability (Mosleh et al., 2016; W. Yu et al., 2013; Zhou, Chen, Tan, Chen, & Zhang, 2011b). Inefficient CC selection method causes low throughput despite having wider bandwidth (S. Songsong, 2009; Y. Wang et al., 2009; Xiaoyong et al., 2009).

MLWDF algorithm ensures ideal throughput to the system and to maintains better fairness to all users than other algorithms. This scheduler largely depends on QoS and packet delay. The throughput optimal MLWDF algorithm has less complexity among all other scheduling algorithms and it considers the real-time traffic. The primary goals of this scheduler are to ensure required QoS, and to enhance the spectral. Other scheduling algorithms such as EXP/PF, EXP/Rule, and LOG/Rule are comparatively more complex to implement (Basukala et al., 2009; Sadiq et al., 2009).

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It is clear from the studies that individual technology (i.e. CoMP or CA) cannot significantly improve the overall performance. Moreover, poor eNB coordination scheme, inefficient packet scheduler and CC selection method also cause poor performance. This thesis can address these issues by the proposed method to improve the throughput and overall system performance. In summary,

- There is no method in the literature that combines the CoMP and CA techniques for LTE-A homogeneous network with an efficient CC selection method. Moreover, no CoMP scheduling algorithm in the literature considers the delay parameters and packet drop probability. Narrow bandwidth of CoMP user also causes low throughput.
- Efficient eNB coordination scheme by considering queue length, HOL delay and channel gain has not been thoroughly studied and analyzed.
- CC selection method does not satisfy the requirement of the user. Interference and low SINR are not considered. Calculating gain by considering queue length and delay parameters for CC selection has not been deeply explored.
- Implementation of MLWDF algorithm in LTE-A packet scheduling has not been properly investigated.

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CHAPTER 3: RESOURCE SCHEDULING FOR COMP AND CA

3.1 Network Scenario

This work implements CoMP and CA in a homogeneous scenario with inter-cell coherent JT CoMP method to improve the throughput of the cell-edge user as well as to boost the overall system performance. The users who are located at the edge of the cell are considered as cell-edge users and other users in the cell are considered as cell-center users. In this scenario, each macrocell has one eNB without any other RRH or relay node in the cell in avoiding the complexity of the network. The attached eNB (Master/center eNB) of a user is connected with six other adjacent neighboring eNBs to make a cooperative set as shown in Fig 3.1. This cooperative set requires a reliable backhaul connection as the eNBs are placed geographically away from other adjacent eNBs. The distance between the eNBs in this work for different scenarios such as Urban, suburban and rural is same. An X2 interface with low latency and high capacity is used to share the information among the cooperative eNBs in this network scenario.

The proposed method in this work implements centralized coherent JT transmission scheme where the cell-edge user receives multiple coherent signals from different eNBs with different frequencies (to perform CA) at the same time. The cooperative eNB set exchanges the CSI, scheduling, and user information to serve the cell-edge user simultaneously. However, a maximum three eNBs can attach to a cell-edge user whereas a cell-center user is allowed to connect only one eNB at a given time. Furthermore, a maximum 4 CCs can be assigned to all users.

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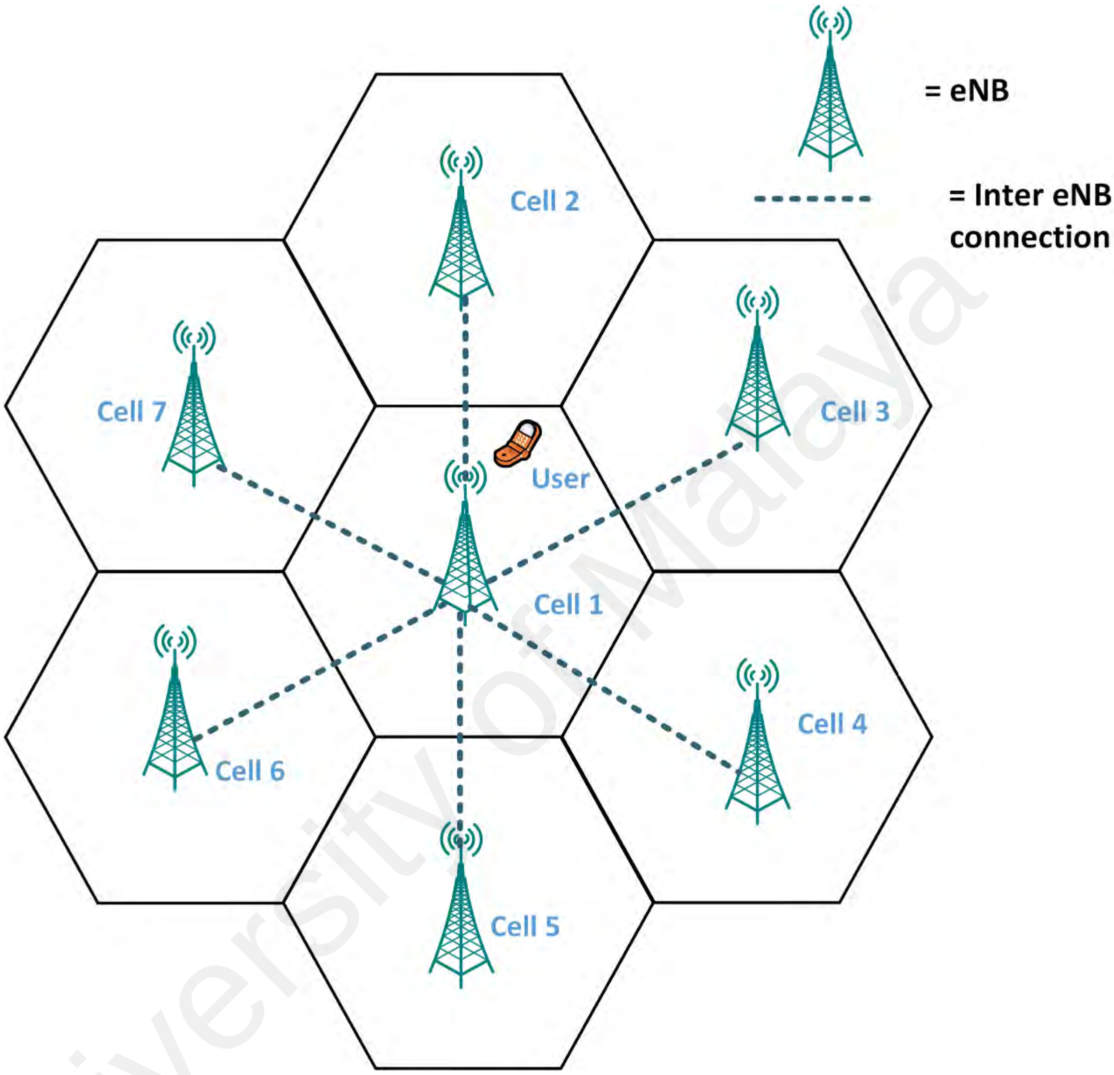

Figure 3.1: Cooperative eNB set in homogeneous CoMP deployment for Cell 1 user

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3.2 Channel model

The channel in mobile communication is the link between transmitter and receiver. The nature of the radio signal changes when it transmits from the transmission point to receiving point due to the distance between these two points, real-life environment, and transmitting scenario (such as indoor-to-outdoor, outdoor-to-indoor) (Andersen, Rappaport, & Yoshida, 1995). The model that calculates the received signal is known as the channel model. In general, pathloss, shadow fading (also known as slow fading), and multipath (also known as fast fading) are the main three elements of the channel model (Rappaport, 1996).

3.2.1 Pathloss

Pathloss is a type of attenuation due to reflection, diffraction, and refraction while the signal traveling a distance in the open air. An efficient pathloss model can vary depending on the carrier frequency, distance, different environments (such as femtocell, microcell, macrocell) and propagation type (such as indoor-to-outdoor, outdoor-to-indoor). The pathloss model is formed by the slow change of user position and signal power. COST231 pathloss model can be deployed both in urban and suburban scenarios (Damosso, 1999). This model is the combination of Walfisch-Bertoni and Ikegami models (Correia, 2009; Ikegami, Takeuchi, & Yoshida, 1991; Walfisch & Bertoni, 1988). This model considers the heights of transmitter, receiver, and buildings, width of the streets and roads. Therefore, the COST231 model can give more accurate estimation in the urban and suburban area as there are many buildings between the eNBs and the users. The COST231 pathloss model can be defined as

$$PL_i = \begin{cases} PL_O + L_{rts} + L_{ms} & \text{for } L_{rts} + L_{ms} > 0 \\ PL_O & \text{for } L_{rts} + L_{ms} \leq 0 \end{cases} \tag{3.1}$$

Where,

PL_O= Free space pathloss

L_{rts}= Roof-top to street diffraction

L_{ms}= Multi-screen loss

Free space pathloss can be estimated as

$$PL_O=32.4+20Log(\bar{R})+20Log(f) \tag{3.2}$$

Here $\bar{R}$ is the distance between eNB in kilometers and the user, f is the carrier frequency. Roof-top to street diffraction L_{rts} is defined by Ikegami model and approved by the ITU-R in their recommendation (Ikegami et al., 1991; ITU-R, 2015). L_{rts} can be calculated by following expression.

$$L_{rts}=-8.2-10\,Log(St)+10\,Log(f)+20Log\left(H_{roof}-H_{user}\right)+L_{cf} \tag{3.3}$$

Here St is street width, H_{roof} is height of the building and H_{user} is the height of the user in meters L_{cf} is correction factor.

L_{ms} in equation 3.1 can be calculated as

$$L_{ms}=L_b+54+18\,Log(\bar{R})+k_f Log(f)-9Log(b) \tag{3.4}$$

where,

$$L_b=-18\,log\,(1+(\Delta H_b) \tag{3.5}$$

$$k_f=-4+0.7(\frac{f}{925}-1) \tag{3.6}$$

Here ΔH_b is the height difference of the eNB and the buildings in meters.

According to 3GPP the pathloss for the rural area can be formulated as follows (*LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios, 3GPP TR 136.942 V9.0.1 Release 9*, 2010).

$$PL_i = 95.5 + 34.1\, Log(\bar{R}) \tag{3.7}$$

3.2.2 Shadow Fading

Most of the time there are some obstacles (such as trees, buildings) between the eNBs and the user in real-life scenarios. These objects cause the shadow fading which is also called slow fading. According to 3GPP, the correlation of shadow fading can be defined as (*Physical layer aspects for evolved Universal Terrestrial Radio Access (UTRA), 3GPP TR 25.814 V7.1.0*, September 2006):

$$\text{Shadowing correlation} = \begin{cases} 1.0 & \text{between sectors} \\ 0.5 & \text{between cell} \end{cases} \tag{3.8}$$

$$\text{Shadow fading } \varsigma_i = 10^{\chi^i/10} \tag{3.9}$$

$$\chi^i = a\acute{k} + b\acute{k}_i \text{ and } a^2 + b^2 = 1 \tag{3.10}$$

where, χ^i is lognormal Gaussian distribution of user *i*, $\acute{k}$ and $\acute{k}_i$ both represent Gaussian random variables with standard deviation 8 dB and an expectation 0. The correlation is 100% when $a^2 = b^2 = 0$ *and* it will be 50% when $a^2 = b^2 = 0.5$.

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3.2.3 Multipath Fading

The radio signal is reflected or diffracted in the medium before arriving at the receiving user. Thus, multiple signals arrive at the receiving end by multiple paths. That causes the multipath problem due to the different phase and arrival time of the received multiple signals. Rayleigh distribution is generally used to model the multipath fading. The multipath fading with path loss PL_i, zero mean and standard deviation $\underline{k}$ can be formulated as follows (Sklar, 1997).

$$PL_{Multi} = \frac{PL_i}{\underline{k}} e^{-\frac{(PL_i)^2}{2\underline{k}^2}} \tag{3.11}$$

Figure 3.2 shows the channel model considered in this thesis work.

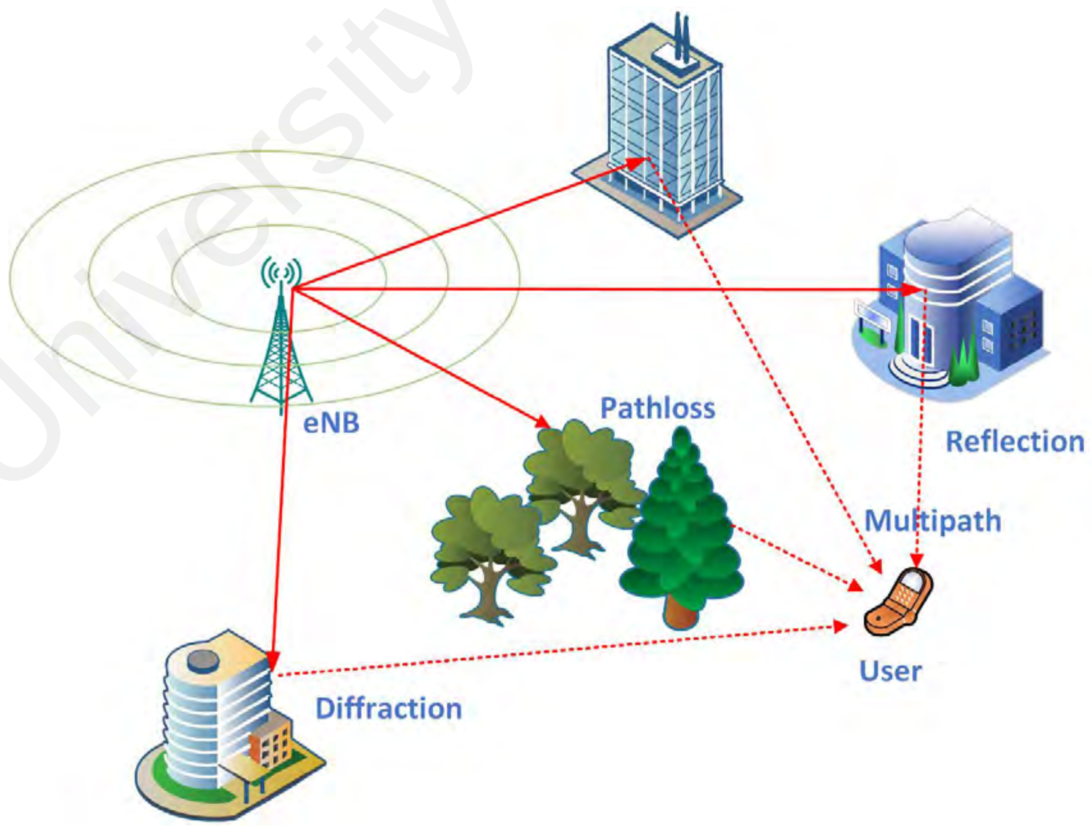

Figure 3.2: Channel Model

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3.3 CoMP Settings

The proposed scheduling algorithm in this thesis considers the Inter-Cell CoMP deployment in a homogeneous network where the attached eNB of a particular cell-edge user and the adjacent neighboring eNBs serve combinedly to that user. However, a maximum of three eNBs can serve a cell-edge user at a time in this proposed method. JT technique with centralized CoMP approach has been deployed for this cooperative service. The cell-edge user can able to connect with multiple eNBs depends on the coverage area and the available resources. The users who are in the center area of the cell (cell-center user) are not considered for CoMP services thus cannot get services from more than one eNB at a time.

3.3.1 Centralized CoMP

The attached eNB of each cell-edge user in the proposed method is considered as a Master eNB and all other cooperative neighboring eNBs are considered as slave eNBs for that particular user. The master eNB shares the resource status information of the user with the cooperative slave eNBs. Based on the received information and available resource the slave eNBs make the RA decision and send it to the Master eNB. Then the Master eNB calculates the possible gain based on these RA decisions by considering all other constraints and the user requirement. If the RA decisions can improve the user's current performance, the cooperative eNB set combinedly allocate the resources to the cell-edge user.

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3.3.2 JT CoMP

The proposed method deploys the JT CoMP by transmitting the coherent signals to the cell-edge user from multiple cooperative eNBs at a time to enhance the received signal quality. The phase and amplitude of the transmitted signals can be combined in the receiving cell-edge user. The set of frequencies from a cooperative eNB and the attached eNB are same according to JT CoMP method. By applying CA technique in the proposed method, the cell-edge user can be connected with multiple frequencies from multiple eNBs at the same time. However, the proposed method in this thesis allocates maximum two adjacent cooperative eNBs through two frequency sets to a cell-edge user.

3.3.3 Status and Information Exchange Between eNBs

The attached (Master) eNB of a cell-edge CoMP user exchanges the load information and resource status with its neighboring eNBs as described in Figure 3.3 (*Wireless technology evolution towards 5G: 3gpp release 13 to release 15 and beyond*, February, 2017). The resource status update includes RSRP and other CSI information such as RI and Channel Quality Index (CQI) with the associated user ID. The neighboring eNB considers this information for making the RA decision and sends the decision to the attached eNB. If this RA from the neighboring eNB along with other constraints and parameters can improve the gain of the user, the cooperative eNBs allocate the resources to the user. This work assumes that all eNBs are connected with a fast and reliable X2 backhaul connection.

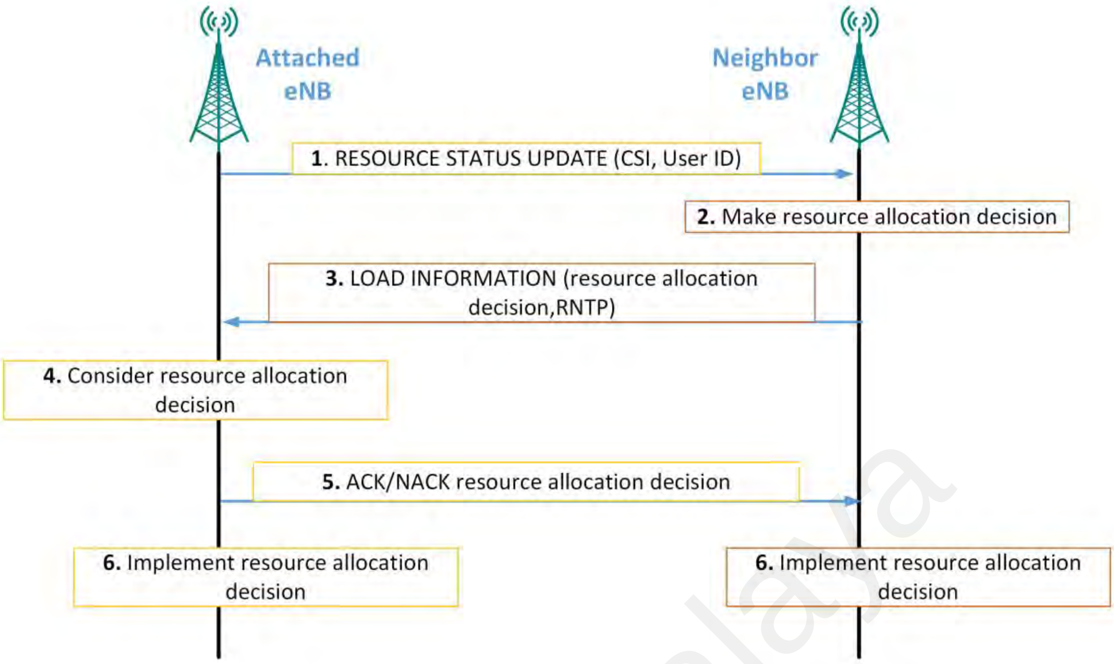

Figure 3.3: Status and information exchange between eNBs

3.4 CC Selection

CA technique is applied to both cell-center and cell-edge user in the proposed method. CC selection for a user in each scheduling cycle is an important step of RA as it can significantly improve the overall system performance. This thesis considers the noncontiguous inter-band CA approach to increase the bandwidth of the user. Master eNB for a cell-edge user considers its own available CCs and the available CCs of the cooperative slave eNBs along with other several constraints to assign a CC to a user. On the other hand, attached eNB for the cell-center user considers only of its own available CCs to allocate it to the user. The proposed method also considers that a maximum 4 CCs of 10 MHz each can be assigned to a user at a given time.

3.4.1 Queue Length

Every CC from each eNB has its own queue to manage the data packets so that a CC can serve the different user. The longer the queue, the longer the waiting time for a user to be served from that CC. Therefore, the queue length of each CC has a vital impact on the overall system performance. The proposed method estimates the queue length of each available CC from each eNB and implements in a way that the CCs with shorter queue length has the higher possibility to be assigned to the user. This approach can reduce the waiting time for the user and it can distribute the traffic load across the network.

3.4.2 Maximum Gain

The proposed method estimates all possible gain of available resources (i.e. eNBs, CCs) for all users to assign CCs with less interference and less noise so that the user can achieve better throughput. The gain can be calculated by the difference between weighted transmission rate and the current transmission rate of a user. The maximum gain is calculated by considering the queue length of each CC in this proposed method. If the maximum gain is higher than the threshold value (positive gain), the proposed method assigns that CC to the user. Therefore, higher the gain for a CC, higher the possibility of that CC to be assigned to a user. The proposed overall resource allocation procedure in this thesis work is briefly described in the following Figure 3.4.

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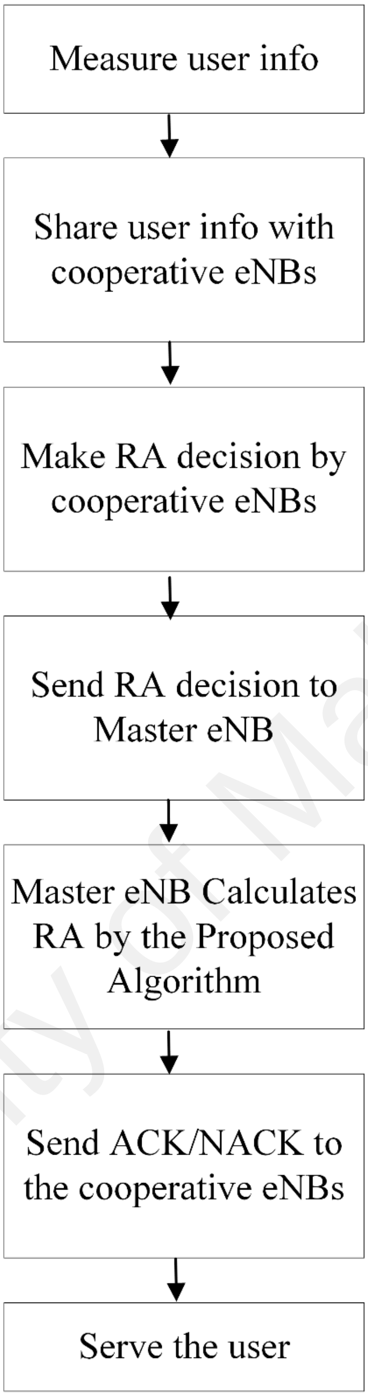

Figure 3.4: Proposed overall resource allocation procedure

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3.5 Problem Formulation

This thesis considers that maximum three eNBs can jointly transmit to a particular cell-edge user as shown in Figure 3.5 whereas the cell-center users are connected with one eNB. Furthermore, all users can receive a maximum four CCs from eNBs to strengthen the desired signal and to improve the receiving bandwidth. The eNB of the cell where the user is originally located is called the 'attached eNB' (Master eNB for the cell-edge user) for that user which coordinates with all other adjacent eNBs to transmit the coherent signal. Centralized CoMP approach is implemented where all eNBs are connected with their adjacent eNBs by fast backhaul connection.

3.5.1 Estimate the Weighted Transmission Rate

Let e, i, j, k, l be the eNB, user, CC, RB and MCS index, respectively where $e \epsilon B = \{1, \ldots, B\}$, $i \epsilon Q = \{1, \ldots, Q\}$, $j \epsilon R = \{1, \ldots, R\}$, $k \epsilon S = \{1, \ldots, S\}$ and $l \epsilon T = \{1, \ldots, T\}$. The symbols used in this thesis are shown in the preface section.

The received signal $Y_{e,i,j,k}$ of user i, CC j and RB k for eNB e can be written by the following equation (3.12) (Määttänen et al., 2012; H. Zhang et al., 2015).

$$Y_{e,i,j,k} = \underbrace{\sqrt{P_{e,i,j,k} G_{e,i,j,k}} H_{e,i,j,k} X_{e,i,j,k}}_{Desired} + \underbrace{\sum_{c \neq e} \sqrt{P_{c,i,j,k} G_{c,i,j,k}} H_{c,i,j,k} X_{c,i,j,k}}_{Interference} + \sigma^2 \tag{3.12}$$

where $P_{e,i,j,k}$ is the transmit power, $G_{e,i,j,k}$ is the large-scale gain and $H_{e,i,j,k}$ is the complex channel gain of user i, CC j and RB k for eNB e. The term $X_{e,i,j,k}$ denotes the transmit signal from eNB e to user i of CC j and RB k. This thesis assumes that $E\{| X_{e,i,j,k} |^2\} = 1$. The $P_{c,i,j,k}$, $G_{c,i,j,k}$, $H_{c,i,j,k}$ and $X_{c,i,j,k}$ are the transmit power, large-scale gain, complex channel gain and transmit signal of the other adjacent cells, respectively. The first term

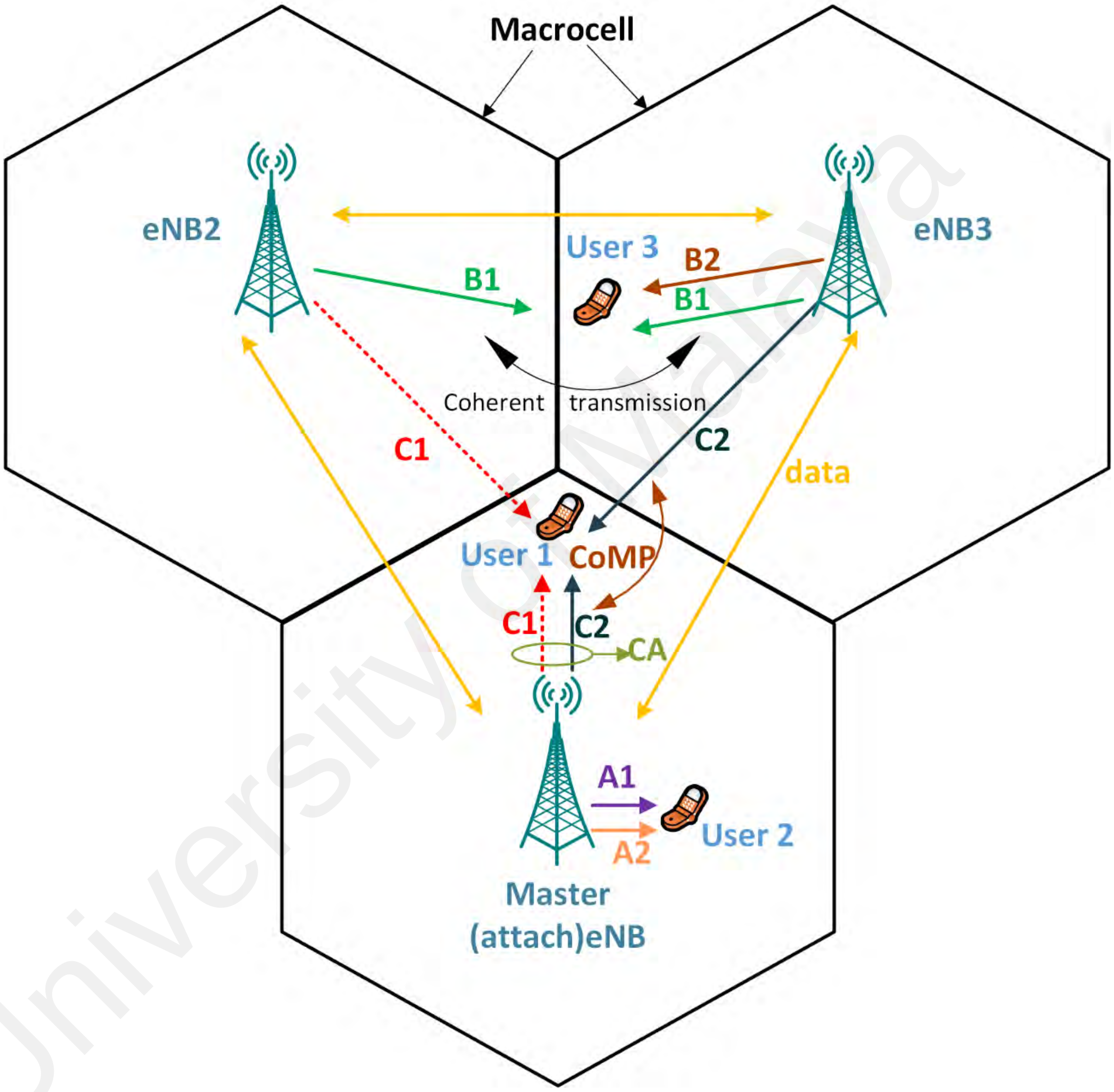

Figure 3.5: Proposed network scenario of CoMP with CA

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in equation (3.12) is the desired signal for user i, the second term is the interference from the other cells and σ^2 represents the additive noise. Let L be the set of attached and adjacent eNBs of user i where $L \subset B$. Therefore, the SINR $\gamma_{e,i,j,k}$ of user i, CC j and RB k for eNB e can be obtained by the following equation (3.13) (Jia et al., 2017).

$$\gamma_{e,i,j,k} = \frac{P_{e,i,j,k} G_{e,i,j,k} |H_{e,i,j,k}|^2}{\sum_{f=1, f \neq e}^{L} P_{f,i,j,k} G_{f,i,j,k} |H_{f,i,j,k}|^2 + \sigma^2} \tag{3.13}$$

The Shannon-Hartley theorem is considered to calculate the throughput of the user by using the SINR $\gamma_{e,i,j,k}$ and bandwidth (BW) of the channel (W. C. Lee, 1990; Shannon & Weaver, 1949). The instantaneous throughput r_i of user i can be written as

$$r_i = BW.\ log_2 (1 + \gamma_{e,i,j,k}) \tag{3.14}$$

The weighted transmission rate $Z_{e,i,j,k,l}$ of user i, CC j, RB k, and MCS index l for eNB e can be calculated by using the instantaneous throughput defined in the previous equation (3.14).

$$Z_{e,i,j,k,l} = \frac{r_i(t)}{\overline{r_i}(t-1)} \tag{3.15}$$

where r_i (t) is the instantaneous throughput of user i at transmission time interval (TTI) t and $\overline{r_i}$(t-1) is the previous average throughput. For simplicity, the TTI t is not included in the rest of the thesis.

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3.5.2 Formulate the Scheduling Function

The MLWDF scheduling algorithm is implemented for downlink radio resource management. This throughput optimal algorithm uses the probability of packet loss, maximum delay and HOL packet delay along with previous and instantaneous throughput of the user for keeping all the queues stable (Stolyar & Ramanan, 2001). Referring to MLWDF algorithm, the resource scheduling through CoMP and CA is formulated by solving the following function:

$$\sum_{e=1}^{B}\sum_{i=1}^{Q}\sum_{j=1}^{R}\sum_{k=1}^{S}\sum_{l=1}^{T}\varphi_{e,i,j,k,l}.Z_{e,i,j,k,l}.\alpha_i.D_{e,i,j} \tag{3.16}$$

subjected to the following constraints

$$\sum_{i=1}^{Q}\varphi_{e,i,j,k,l}\leq 1 \qquad \text{for } e \in B, j \in R, k \in S, l \in T \tag{3.17}$$

$$\sum_{l=1}^{T}\varphi_{e,i,j,k,l}\leq 1 \qquad \text{for } e \in B, i \in Q, j \in R, k \in S \tag{3.18}$$

$$\sum_{j=1}^{R}\varphi_{e,i,j,k,l}\leq m \qquad \text{for } e \in B, i \in Q, k \in S, l \in T \tag{3.19}$$

$$\sum_{e=1}^{B}\varphi_{e,i,j,k,l}\leq n \qquad \text{for } i \in Q, j \in R, k \in S, l \in T \tag{3.20}$$

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$$D_{e,i,j} \leq \tau_i \qquad \text{for } e \in B,\ i \in Q,\ j \in R \qquad (3.21)$$

$$\varphi_{e,i,j,k,l} \in \{0,1\} \qquad (3.22)$$

where, $\varphi_{e,i,j,k,l}$ is the variable to express whether or not CC j, RB k and MCS l of eNB e is assigned to user i which is expressed in equation (3.22), $D_{e,i,j}$ is the HOL delay of user i, CC j and eNB e. The function value of all users is calculated by the equation (3.16) based on all available CCs, RBs and MCS index of eNBs. The higher the value of a user, the higher the chance to get RBs. Thus, the greater the ratio of throughputs and HOL delay and lower the threshold delay, the higher the possibility of user i being allocated the RBs. The condition in (3.17) ensures that one RB of a CC cannot be assigned to more than one user. The condition in (3.18) states that each user is allowed to use only one MCS index with assigned CC and RB. The condition in (3.19) limits the user not to be allocated more than m number of CC. The condition in (3.20) restricts the user not to be attached with more than n number of eNBs. The condition in (3.21) states that HOL delay of a CC for an eNB must be less than the delay threshold.

The variable α_i in equation (3.16) allows the scheduler to distribute the packet delay. When increasing the value of α_i for user i and keeping unchanged of the values for other users, reduces the packet delay of user i at the expense of increasing the queuing time for other users. This technique balances the probability of exceeding the threshold value τ_i which assures to serve the maximum possible number of users. The variable α_i can be defined in the following equation (3.23).

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$$\alpha_i = \frac{-\log \delta_i}{\tau_i} \tag{3.23}$$

Here, δ_i is the probability of packet loss and τ_i represents the delay threshold value for user i according to the application. The threshold values of different applications are shown in Table 3.1. HOL delay of user i needs to be kept below the threshold value τ_i. The maximum probability of exceeding the threshold value should be equal to or less than the value of δ_i. Therefore, the QoS requirement of user i is given by

$$Pr\{D_{e,i,j} > \tau_i\} \leq \delta_i \tag{3.24}$$

The delay threshold values with priority levels for different applications are shown in Table 3.1 ("General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access," December 2011). Lower the priority value, higher the priority of the data packet if the queue is congested. The conversational voice has the highest priority in the list below. Data packets of lowest priority application in a congested queue would be discarded first. According to 3GPP standard, some of the services provides a guaranteed bit rate (GBR) and some of the services are non-guaranteed bit rate (Non-GBR). This thesis considers the Conversational Voice, Conversational Video and HTTP types of data in the simulation process.

Table 3.1: Value of delay threshold for different applications

Application	Priority	Delay Threshold (ms)	Resource Type
Real-time Gaming	3	50	GBR
Conversational Voice	2	100	GBR
Conversational Video	4	150	GBR
Non-Conversational Video (Buffered Streaming)	5	300	GBR
Live Streaming Video	7	100	Non-GBR
HTTP, FTP	8	300	Non-GBR

Errors occur in large scale at the receiving end due to the various noise and interference affects the real-life wireless environment. A correlated error model is needed to calculate the performance accurately. Therefore, this thesis estimates the probability of packet loss δ_i by the Markov chain model with a closed-form expression (K. K. Lee & Chanson, 2002). This model considers the packet delay instead of modeling the packet queue due to the advantage that if the packet delay exceeds the value of τ_i it can be dropped. There are two states in the above Markov chain model namely success state with low error probability and failure state with high error probability. The success state is considered as a usable system in this thesis when packets can be transmitted successfully. The simplified equation to calculate δ_i for the low error probability scenario is given in (3.25).

$$\delta_i = \varepsilon_i \left(1 - W_i\right)^{\tau_i} \tag{3.25}$$

Here ε_i represents the error probability and W_i denotes the probability from failure state to success state of user i. The ε_i assumed to be a small value and W_i should be larger than

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ε_i in success state for making the system usable. The δ_i largely depends on the τ_i and the queue length. The model demonstrates that δ_i can be assessed accurately by using constant values of ε_i and W_i while varying the τ_i values (K. K. Lee & Chanson, 2002). Therefore, this thesis assumes that $\varepsilon_i \approx 0.01$, $W_i \approx 0.1$ and τ_i varies depends on the user applications (as described in Table 3.1) for success state. The δ_i declines drastically when (1- W_i) decreases, especially when the τ_i is large with a constant value of ε_i. On the contrary, if the τ_i is not large enough, the δ_i increases when the errors are expected to occur.

The ε_i is large and W_i is relatively smaller than ε_i in failure state with high error probability. Therefore, the δ_i in the failure state can be formulated as

$$\delta_i \approx 1 \approx \varepsilon_i \tag{3.26}$$

which shows that the value of α_i from the equation (3.23) will be very low. Thus, the user will have a very low chance to get any RB. Due to the enormous error in this state, no packets can be transmitted successfully and this can make the system unusable. Section 3.5.3 describes the full derivation of the above two-state model.

Considering the logarithm, equation (3.25) and finally equation (3.23) can be written as follows

$$log(\delta_i) = \tau_i log(1\text{-}W_i) + log(\varepsilon_i) \tag{3.27}$$

$$\alpha_i = \frac{-\{\tau_i log(1\text{-}W_i) + log(\varepsilon_i)\}}{\tau_i} \tag{3.28}$$

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3.5.3 Derivation of The Two-State Model

This thesis proposes a method based on the Greedy model to provide a solution to the resource scheduling problem in (3.16) with low computational complexity while satisfying the conditions in (3.17) - (3.22). Markov chain model is considered in calculating the probability of packet loss in this thesis.

The Markov chain model has been used by previous researchers (Anchora, Canzian, Badia, & Zorzi, 2010; Nasralla, Hewage, & Martini, 2014) in LTE system to model the correlated errors in different ways. The Markov model has two states- success and failure as shown in Figure 3.6. In success state, the transmitter can send a packet successfully whereas packet transmission can be failed in a failure state. The probability of packet loss can be calculated by considering the error probability, probability of transforming from one state to another state, packet arrival rate and maximum delay (K. K. Lee & Chanson, 2002).

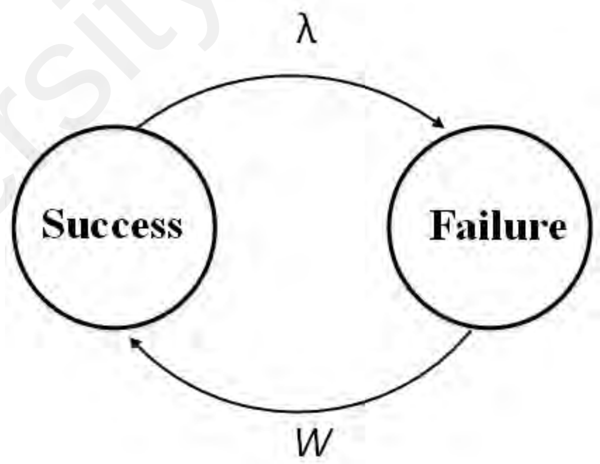

Figure 3.6: Two-state Markov chain model

For simplicity, notation of user i will not include in the following derivation. The probability of packet loss δ can be written as

$$\delta = \frac{\pi_{\tau,1}}{\beta} \tag{3.29}$$

Here $\pi_{\tau,1}$ is the steady-state probability of (τ, 1) state where packets can be dropped for the extensive delay and β is the arrival rate. $\pi_{\tau,1}$ can be expressed as follows.

$$\pi_{\tau,1} = \frac{1}{C_{sum}} \tag{3.30}$$

By using approximate value and defining the range of parameter values, the simplified expression of C_{sum} which is called the sum of coefficient can be written as follows (K. K. Lee & Chanson, 2002).

$$C_{sum} \approx \frac{Wx^{\tau}}{\lambda\beta} + \frac{W(1-x^{\tau})}{v(1-x)} + \frac{1}{\beta} \tag{3.31}$$

$$C_{sum} \approx \frac{x^{\tau}W^{2}(\beta-1)+\lambda(\lambda\beta-W+2\beta W)}{\lambda\beta(\lambda\beta-W+\beta W)} \tag{3.32}$$

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Here λ is the probability from success state to the failure state, $\nu \approx 1-\beta$ will be a small value when λ and β are small. So, from equation (3.29), (3.30), and (3.32) can be written as

$$\delta = \frac{\pi_{\tau,1}}{\beta} \approx \frac{\lambda(\lambda\beta - W + \beta W)}{x^{\tau} W^{2}(\beta-1) + \lambda(\lambda\beta - W + 2\beta W)} \tag{3.33}$$

Success state: The error probability ε in success state with small error probability scenario is small to make the system usable. Since $\varepsilon = \lambda/(\lambda+W)$, W is relatively large compare to λ. Thus λ/W is small and $x \approx 1/(1-W)$. Therefore, δ can be written as follows.

$$\delta \approx \frac{\lambda(\lambda/_{W}\beta - 1 + \beta)}{x^{\tau} W(\beta-1) + \lambda/_{W}(\lambda\beta - W + 2\beta W)} \tag{3.34}$$

$$\delta \approx \frac{\lambda(\beta-1)}{x^{\tau} W(\beta-1)} \tag{3.35}$$

$$\delta \approx \frac{\lambda(1-W)^{\tau}}{W} \tag{3.36}$$

Since $\varepsilon \approx \lambda/W$, finally we, have

$$\delta = \varepsilon(1-W)^{\tau} \tag{3.37}$$

Failure state: In the failure state, ε is relatively large which can make the system unusable for undue error. Since $\varepsilon = \lambda/(\lambda+W)$ is large, W is relatively small, thus $\lambda \gg W$. Therefore, we can write

$$\varepsilon = \lambda/_{(\lambda+W)} \approx \lambda/_{\lambda} = 1 \tag{3.38}$$

The terms βW, $x^{\tau} W^{2}(\beta-1)$ and $2\beta W$ from the above equation (3.33) can be neglected as W is relatively small. We can calculate the δ for the failure state with large error probability scenario as follows.

$$\delta \approx \frac{\lambda(\lambda\beta - W + \beta W)}{x^{\tau} W^{2}(\beta-1) + \lambda(\lambda\beta - W + 2\beta W)} \approx 1 \approx \varepsilon \tag{3.39}$$

This work calculates the probability of packet loss by using the Markov model to estimate the variable α_i and eventually gets the weighted transmission rate of the user from equation (3.16). Higher packet loss probability with shorter maximum delay makes higher α_i value and higher weighted transmission rate value. Therefore, there will be a higher chance for that user to get the RB from the scheduler. Moreover, the Markov model is comparatively less complex and the parameters of this method match with the parameter of the MLWDF scheduling algorithm which is used in this thesis. Thus, a Markov model is the suitable approach to implement the proposed method.

3.6 Proposed Model

The proposed method maximizes the user throughput, enhances the spectral efficiency and the fairness by implementing CoMP with CA technique. This method considers several constraints such as number of cooperative eNBs, HOL delay and maximum number of CCs that can be assigned to a user while maintaining the low computational complexity. The weighted transmission rate is calculated for all users. Then all possible gains of user i are estimated before assigning the CC j of eNB e. This proposed method defines the gain as the difference between weighted transmission rate $Z_{e,i,j,k,l}$ according to available resources and the current transmission rate of the user. If the $Z_{e,i,j,k,l}$ is higher than the current rate, user can transfer more data and thus can achieve higher gain. If the maximum gain is a positive value CC j of eNB e with MCS index l is assigned to user i. If the weighted transmission rate for maximum gain with the variable α_i and HOL delay for each RB is better than currently assigned one, RB k is allocated to user i. The step-by-step procedure of the proposed method is given below.

3.6.1 Step-By-Step Procedure

Step 1: Let Ω (e, j, k) be the current transmission rate with currently being allocated eNB e, CC j and RB k of the user. This proposed method assumes that initially RBs of all CCs are not assigned to any user. Thus Ω (e, j, k) is set to zero at the initial stage. The weighted transmission rate $Z_{e,i,j,k,l}$ of eNB e, user i, CC j, RB k and MCS l is estimated by the instantaneous rate and previous average rate as in equation (3.15). eNB e is considers as currently attached eNB V for cell-center user and as a set of adjacent cooperative eNBs L including the currently assigned one for cell-edge user.

Step 2: Let g (e, i, j, l) be the gain of user i for allocating CC j of eNB e with MCS l. The gain can be calculated by the following equation (3.40).

$$g(e,i,j,k)=\sum_{k=1}^{S} max(0,Z_{e,i,j,k,l} - \Omega(e,j,k)) \qquad (3.40)$$

If the current rate Ω (e, j, k) is better than the weighted rate $Z_{e,i,j,k,l}$, then there will be no gain. After calculating the queue length $\xi_{e,j}$ of CC j for eNB e and all possible gains, assignment (e', i', j', l') with the maximum gain can be calculated by the equation (3.41).

$$(e',i',j',l')=argmax_{e\in B,i\in Q,j\in R,l\in T}\, g(e,i,j,l)/\,\xi_{e,j} \qquad (3.41)$$

If the $g\ (e', i', j', l')$ is higher than zero, CC j' of eNB e' with MCS l' will be allocated to user i'. Otherwise, it will enter into the next loop.

Step 3: After that, HOL delay $D_{e',i',j'}$ for user i' and CC j' of eNB e' is calculated by considering the queueing time. Then, the variable $\alpha_{i'}$ of user i' is assessed by the above equation (3.23). This variable considers several parameters such as delay threshold and the probability of packet loss.

Step 4: The weighted transmission rate $\omega\ (e', i', j', k, l')$ of user i' with the variable $\alpha_{i'}$ and delay $D_{e',i',j'}$ is calculated for each RB k and CC j' of eNB e'. If the $\omega\ (e', i', j', k, l')$ is better than the current transmission rate $\Omega\ (e, j, k)$, then RB k of CC j' for eNB e' is allocated to user i' and $\Omega\ (e, j, k)$ is set to $\omega\ (e', i', j', k, l')$.

Step 5: Assigned CC j' of eNB e' is removed from the available list of CCs for user i' to avoid the assignment of CC j' to the same user for same eNB e'. Moreover, it assures that maximum m number CCs are assigned to user i'.

Step 6: Repeat *Step 2-5* until it satisfies any one of the following conditions: (i) no further gain is achieved after assigning a new CC. (ii) reaches any one of the terminating constraints (3.17) – (3.21) mentioned above (iii) all users have been allocated with the required RBs and CCs.

The proposed downlink scheduling algorithm using CoMP and CA methods is given in Figure 3.7.

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Algorithm 1: Proposed method

1: $\Omega(e, j, k) = 0$ for all eNB e, CC j and RB k
2: **if** user i is cell edge user
3: Calculate $Z_{e,i,j,k,l}$ for all $e \in L$, $i \in Q$, $j \in R$, $k \in S$, $l \in T$
4: **else**
5: Calculate $Z_{e,i,j,k,l}$ for $e \in V$, $i \in Q$, $j \in R$, $k \in S$, $l \in T$
6: **end if**
7: **repeat**
8: Calculate gain $g(e, i, j, l)$ for each e, i, j and l
9: Calculate Queue length $\xi_{e,j}$ for each CC j of eNB e
10: $(e', i', j', l') = \text{argmax}_{e \in B, i \in Q, j \in R, l \in T}\ g(e, i, j, l) / \xi_{e,j}$
11: **if** $g(e', i', j', l') \leq 0$
12: go to line 26;
13: **else**
14: Assign CC j' of eNB e' to user i' with MCS l'
15: Calculate HOL Delay $D_{e', i', j'}$ of user i' for CC j' eNB e'
16: Calculate the variable $\alpha_{i'}$ of user i'
17: **for** each $k \in S$ do
18: $\omega(e', i', j', k, l') = Z_{e',i',j',k,l'} * \alpha_{i'} * D_{e', i', j'}$
19: **if** $\omega(e', i', j', k, l') > \Omega(e', j', k)$ then
20: Assign RB k of CC j' for eNB e' to user i'
21: $\Omega(e', j', k) = \omega(e', i', j', k, l')$
22: **end if**
23: **end for**
24: Remove CC j' of eNB e' associated with user i'
25: **end if**
26: until reach any terminating condition

Figure 3.7: Scheduling algorithm of the proposed method

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3.6.2 Computational Complexity

There are two iterations in the proposed method. First iteration estimates weighted transmission rate for each user with computational complexity of $O(uqrst)$ in line 2-6. Here u is the number of eNBs which depends on type of the user and the cluster size of a network. Main iteration and assignment of eNB, CC, RB and MCS index are depicted in lines 7-26. This main iteration calculates the following in each loop: (i) all possible gain for allocating a CC from an eNB by considering queue length, HOL delay and the variable $\alpha_{i'}$ (lines 8 - 16) and (ii) RBs allocation with $O(uqrt)$ and $O(s)$ computational complexity (lines 17 -23), respectively.

The total number of iterations of the proposed method will be ($q \times m \times n$), where m is the highest number of CCs can be assigned and n is maximum number of eNB can be attached to a user. Note that this thesis considers at a maximum 4 CCs can be assigned to a user. If the maximum gain is not higher than zero after calculating all possible gain for all available CCs of all neighboring eNBs, the scheduler will remove the user i from the queue. Furthermore, the algorithm assigned the CC with maximum gain to the user and this CC will not be considered for the same user from same eNB by removing it from the available list (line 24). Therefore, the proposed method can avoid to re-calculate the gains of unassigned CCs of the first iteration for the second and following iterations as the gains will be same. Thus, the total computational complexity can be written as $O(uqrst + qnst(m-1)) = O(qst\ (ur + n(m-1)))$. The flow chart of the proposed scheduling method is shown in Figure 3.8.

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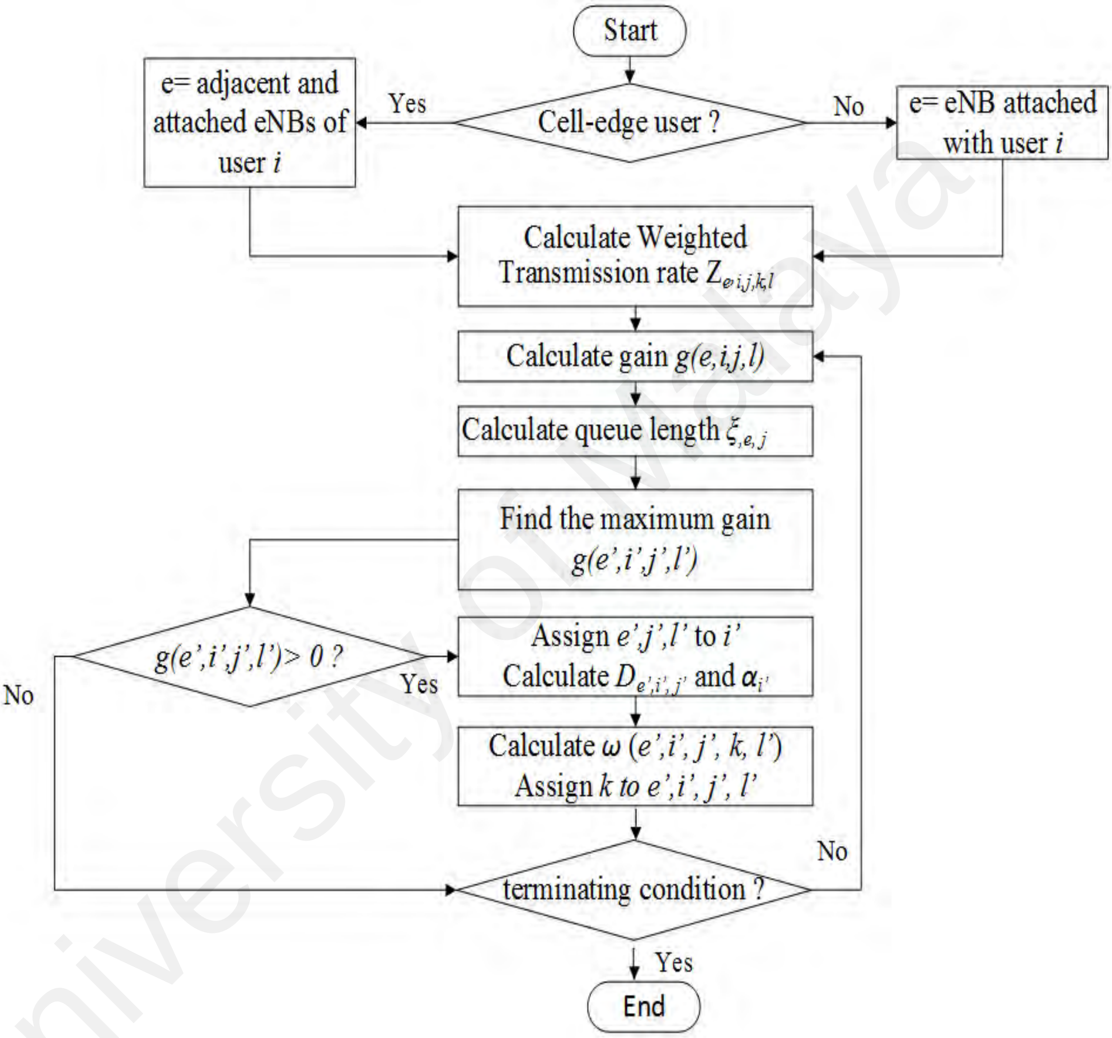

Figure 3.8: Flowchart of the proposed method

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CHAPTER 4: SIMULATION RESULTS AND DISCUSSION

4.1 General Simulation Settings

Vienna LTE-A system level simulator based on MATLAB is used to implement the proposed method (Rupp, Schwarz, & Taranetz, 2016; Taranetz et al., 2015; "Vienna LTE-A simulators, Institute of Telecommunications, Vienna University of Technology, Austria," 2016). The performance of the proposed method is evaluated by performing a number of simulations and it is compared with QTPF (Z. Li et al., 2016) and joint transmission RR (JT-RR) (Zhou et al., 2011a) methods. The hexagonal cell is considered where users are scattered and evenly distributed all over the cell area. The number of user deployment in each cell varies from 10 to 60. The users are moving in an average speed of 5 kmph. Four CCs of 10 MHz bandwidth from two different bands are used. The Closed Loop Spatial Multiplexing (CLSM) with four transmitters and one receiver for downlink transmission is implemented. The eNB power transmission is 46 dBm and the available MCS index is according to the 3GPP standard ("Requirements for Further Advancements for Evolved Universal Terrestrial Radio Access (E-UTRA) (LTE-Advanced)," September 2012). The performance is evaluated by mixed types of data which contains Video, HTTP, and VoIP. Each type of data has its own delay budget ("General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access," December 2011). 1000 TTI is the duration of the simulation process. The list of general simulation parameters is given in Table 4.1.

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Table 4.1: General Simulation Parameters with corresponding values

Parameters	Values
Total bandwidth	40 MHz (4x10 MHz)
User Deployment	Random all over the cell area
Total number of eNB	21
Number of user per eNB	10,20,30,40,50,60
CoMP transmission method	Joint transmission
Scheduling algorithm	Proposed method, QTPF, JT-RR
MCS index	29 available MCSs as in 3GPP
eNB power transmission	46 dBm
Thermal noise density of the user	-174 dBm
Simulation time	1000 TTI
Traffic Model	Mixed (HTTP, VoIP, Video)

4.2 Performance Metrics

This work evaluates the performance of the proposed method by considering several performance metrics. The main five metrics are Average User Throughput, Average Cell Throughput, Cell-Edge User Throughput, Fairness Index and Spectral Efficiency. RBs per TTI per user, SINR and Spectral efficiency mapping, SINR and throughput mapping parameters are also taken into consideration to estimate the performance. The brief description of the main five performance metrics is given below.

4.2.1 Average User Throughput

This work considers two types of users in the cell- active and inactive mode. The average throughput of all active users in a cell area is the average user throughput. The ratio of total number of transmitted bits of active user and the total transmission time is defined as average user throughput. The calculation of average user throughput does not consider the inactive users.

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4.2.2 Average Cell Throughput

The average cell throughput is measured by the average aggregated throughput of all inactive and active users of a cell. Therefore, the aggregated average user throughput and the cell throughput are not same as the simulation does not consider the inactive user to calculate the average user throughput. The average cell throughput can be affected by (a) when there is fewer user in the cell, more user will have a higher number of RBs with higher channel quality which can increase the cell throughput (b) in case of higher number of user, less user will have fewer RBs with good channel quality which causes lower cell throughput.

4.2.3 Cell-Edge User Throughput

The users are equally distributed in the cell area. If the distance between the attached eNB and the user exceeds the threshold value, the user is considered as cell-edge user. This type of user are located in the edge of the cell. Therefore, the throughputs of these users are not same as the cell-center users due to low SINR and high attenuation. This thesis estimates the cell-edge user throughput separately to analyze the system performance more accurately.

4.2.4 Fairness Index

The fairness index of the user is calculated by Jain's fairness index (Jain et al., 1984), which can be described by the following equation,

$$F = \left(\sum_{i=1}^{Q} \eta_i\right)^2 \Big/ Q \sum_{i=1}^{Q} \eta_i^2 \tag{4.1}$$

where, F is the fairness index, η_i denotes the average throughput of user i and Q is the number of user. The fairness ranges from $1/Q$ to 1. The fairness will be maximum when

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all users in the cell are attached with similar number of RBs. The above equation (4.1) shows that higher the average throughput of user, higher the chance to achieve better fairness. This index depicts how the available RBs are distributed among users. Higher index means user are receiving good number of RBs and low index means that RBs are not distributed efficiently.

4.2.5 Spectral Efficiency

The spectral efficiency of the system shows how efficiently the MAC layer protocol utilizes the frequency spectrum. Spectral efficiency is measured by the ratio of the total successfully transmitted bits of all users and the total channel bandwidth for a specific time. The unit of spectral efficiency is bit/s/Hz (Miao, Zander, Sung, & Slimane, 2016). Higher spectral efficiency shows that the scheduling algorithm can distribute the RBs in such an efficient way that users receive their required RBs. Lower spectral efficiency means that the waste of RBs is higher due to inefficient distribution during scheduling process.

4.3 Traffic Model

Three types of data are used in the simulation process of this thesis namely VoIP, (Voice over Internet Protocol), Video and HTTP (Hyper Text Transfer Protocol). The data type of VoIP is considered as guaranteed bit rate (GBR), whereas Video and HTTP are considered as non-guaranteed bit rate (Non-GBR) for all user. In order to provide QoS guaranteed VoIP performance, an RTP (Real-time Transport Protocol) AMR (Adaptive Multi-Rate) 12.2 codec with a 12.2 kbps bitrate is used (3GPP, 2007). Videos are encoded by an H.264/AVC (Advanced Video Coding) encoder with a constant bitrate of 242 kbps, while this thesis considers the bitrate of 250 kbps for HTTP packets (Singh, 2013).

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4.4 Performance Analysis of Different Scenarios

The performance of the proposed method has been evaluated by simulating it in various plots such as different network loads, geographical areas, frequencies, user speeds, and technologies. Each type of plot has its own simulation settings. Therefore, different simulation plots give different results for the proposed method.

The first simulation plot is different scenarios with different types of traffic model. Three types of scenarios have been deployed in this plot namely Scenario 1, Scenario 2 and Scenario 3 with equal RT and NRT traffic, More RT traffic than NRT and More NRT traffic than RT, respectively. Mixed types of data (HTTP, VoIP, Video) traffic have been utilized in these scenarios to analyze the performance in various network load situations. Scenario 1 contains 50% HTTP, 25% VoIP and 25% Video type data of total network load for equal RT and NRT traffic scenario as this thesis considers HTTP as NRT and VoIP and Video are RT data. Scenario 2 contains 30% HTTP, 50% VoIP, 20% Video and Scenario 3 contains 70% HTTP, 10% VoIP, 20% Video.

The operating frequency bands used in this simulation plot are 2100 MHz and 2300 MHz with 40 MHz of total channel bandwidth which contains 4 CCs of 10 MHz each. The geographical area is urban macro and users are distributed equally through the cell area with 5 kmph (walking) speed. Proposed method, QTPF, and JT-RR scheduling algorithms are implemented to analyze the performance.

The pathloss model used in this simulation plot is COST231 (Correia, 2009; Damosso, 1999). COST231 pathloss model is more suitable for urban and suburban deployment scenarios (Ikegami et al., 1991; Walfisch & Bertoni, 1988). The general simulation parameters for different scenarios is given in Table 4.2.

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Table 4.2: Simulation Parameters for Different Scenarios

Parameters	Values
Operating frequency band	2100 MHz and 2300 MHz
Total bandwidth	40 MHz (4x10 MHz)
Deployment Scenario	Urban macro
User Speed	5 kmph
Scheduling algorithm	Proposed method, QTPF, JT-RR
Pathloss model	COST231
Simulation time	1000 TTI
Traffic Model	Scenario 1: Mixed (50% HTTP, 25% VoIP, 25% Video)
	Scenario 2: Mixed (30% HTTP, 50% VoIP, 20% Video)
	Scenario 3: Mixed (70% HTTP, 10% VoIP, 20% Video)

4.4.1 Scenario 1: Equal traffic load of RT and NRT data

Scenario 1 implements the proposed method and compares the obtained results with QTPF and JT-RR algorithms. The simulation process considers 50% HTTP, 25% VoIP and 25% Video data of overall network load. Main figures from obtained results are included in the following sections (and subsections) and the remaining additional figures are added in Chapter 5, Appendix B.

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Figure 4.1, Figure 4.2 and Figure 4.3 show the cell-edge user throughput, average user throughput and average cell throughput, respectively. The proposed method outperforms other algorithms in all these throughput comparisons. Figure 4.1 shows that the proposed method achieves higher cell-edge throughput than QTPF and JT-RR. The reasons for this higher throughput are (a) The proposed method considers different delay parameters and queue length of each CC. Therefore, the cell-edge user with longer waiting time can get priority from the scheduler and receives a comparatively higher number of RBs. However, the other algorithms do not consider the delay parameters and distributes RBs by rotation basis (JT-RR) or just considers the throughputs (QTPF). (b) The proposed method transmits multiple signals from different eNBs with multiple CCs to the cell-edge users which strengthen the received signals and increase the bandwidth. Thus, the throughput is higher than other methods.

Figure 4.2 shows that throughput of all algorithms is decreasing when the number of users is increasing and the throughputs are quite similar for fewer (10 or 20) users as there are more available RBs. However, the proposed method performs much better for higher number of user due to effective CC selection method, considering delay parameters and error probability. Moreover, higher cell-edge user throughput also helps to achieve higher average user throughput than other methods. Figure 4.3 shows that the average cell throughput is fluctuating within a small margin and eventually decreasing for higher number of user due to the fewer available RBs. The aggregated user throughput and the cell throughput are not same as the average user throughput calculation does not consider the inactive users in the cell. Therefore, the average cell throughput increases in some cases and decreases in others.

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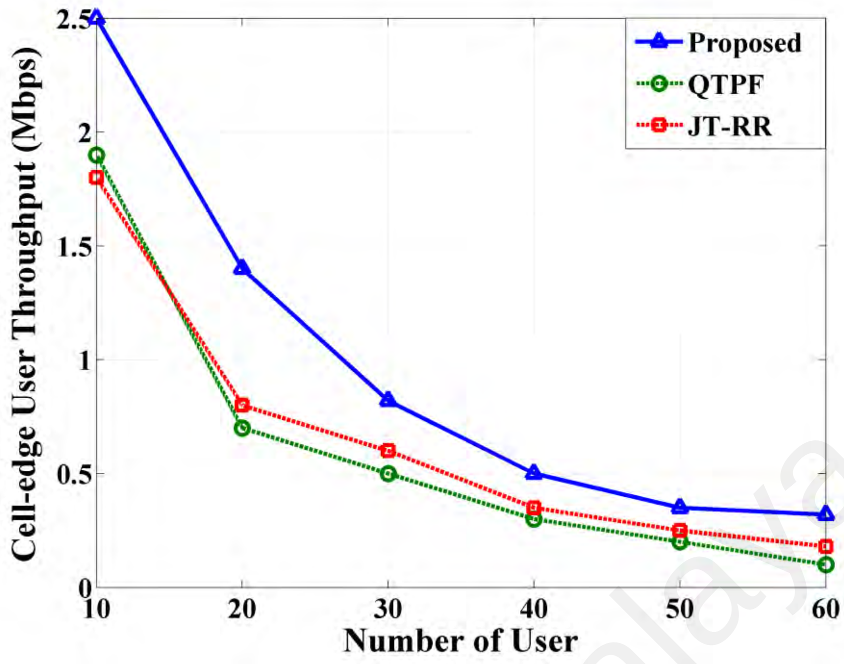

Figure 4.1: Cell-edge user throughput for Scenario 1 user

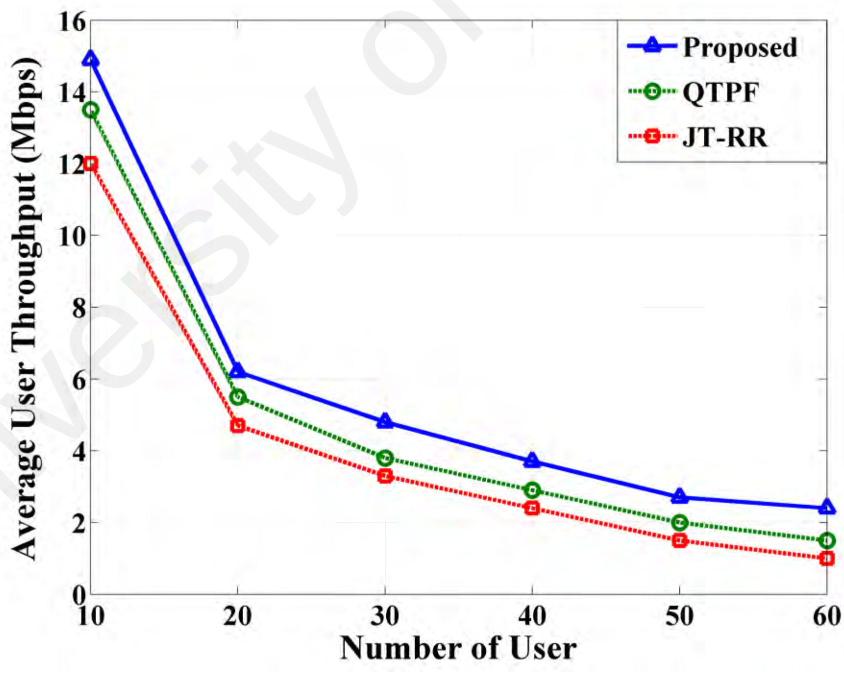

Figure 4.2: Average user throughput for Scenario 1 user

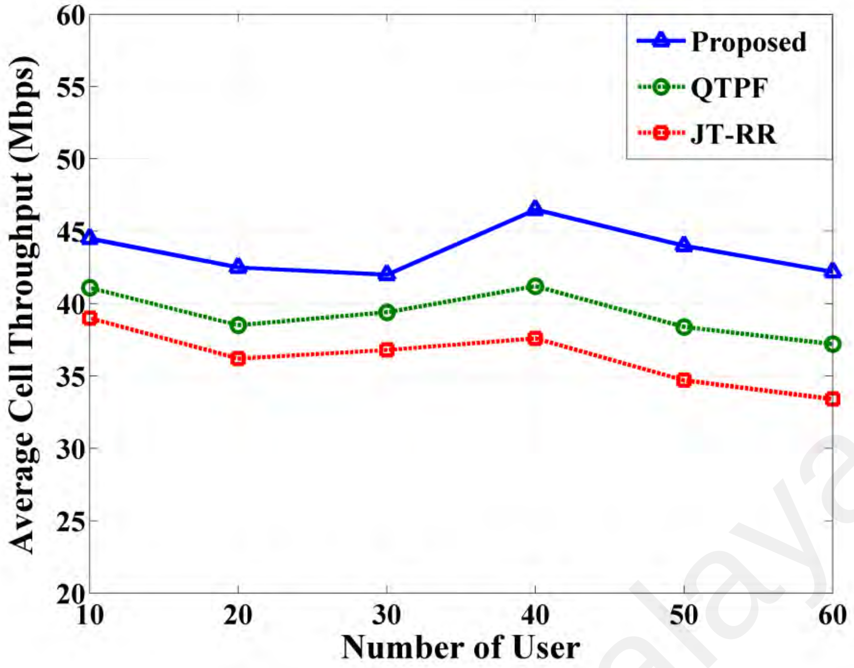

Figure 4.3: Average cell throughput for Scenario 1 user

Figure 4.4 depicts the spectral efficiency of different algorithms for different number of users. In this scenario, as there is equal amount of NRT and RT data, data packets get equal priority from the scheduler. Therefore, the spectral efficiency is not decreasing rapidly for higher number of users like other scenarios due to less amount of packet loss and higher throughput. Figure 4.5 shows the fairness index for different user in this scenario. The proposed method distributes more fairly to the user than other algorithm as it gives priority to the user with high delay and high error rate. Whereas, QTPF and JT-RR do not consider the queue condition or delay parameters. Figure 4.6 shows the comparison of RBs per TTI per user. Higher the RBs allocation per user, higher the chance to have better throughput. The proposed method allocates marginally higher RBs to the user than other algorithms. The improvement of the proposed method for this scenario regarding all parameters is given in Table 4.3. The above table shows that the proposed method outperforms the other algorithms in all aspects.

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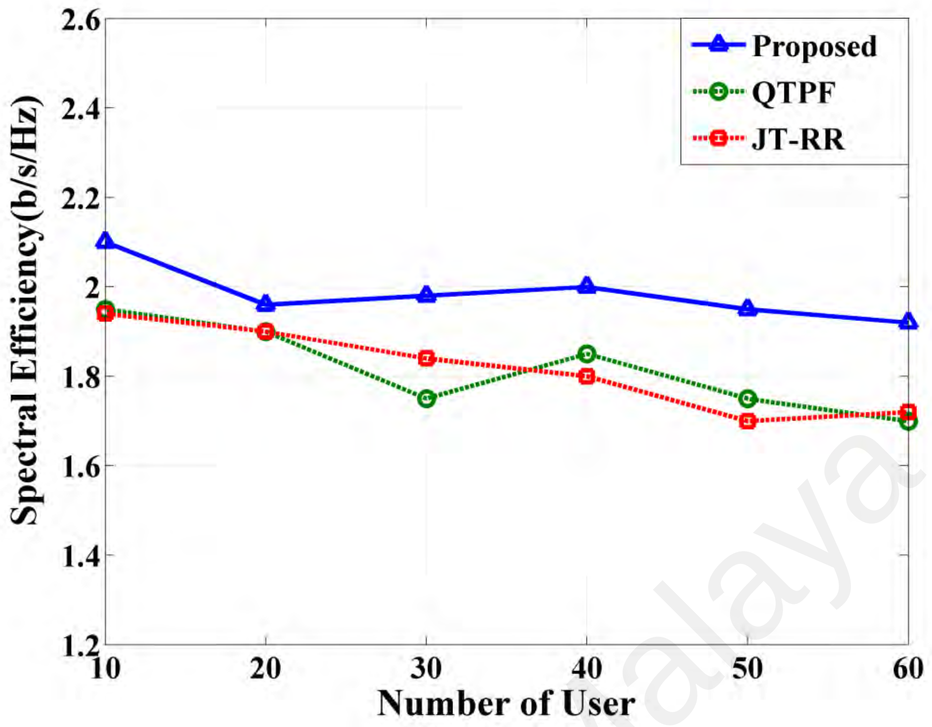

Figure 4.4: Spectral Efficiency for Scenario 1 user

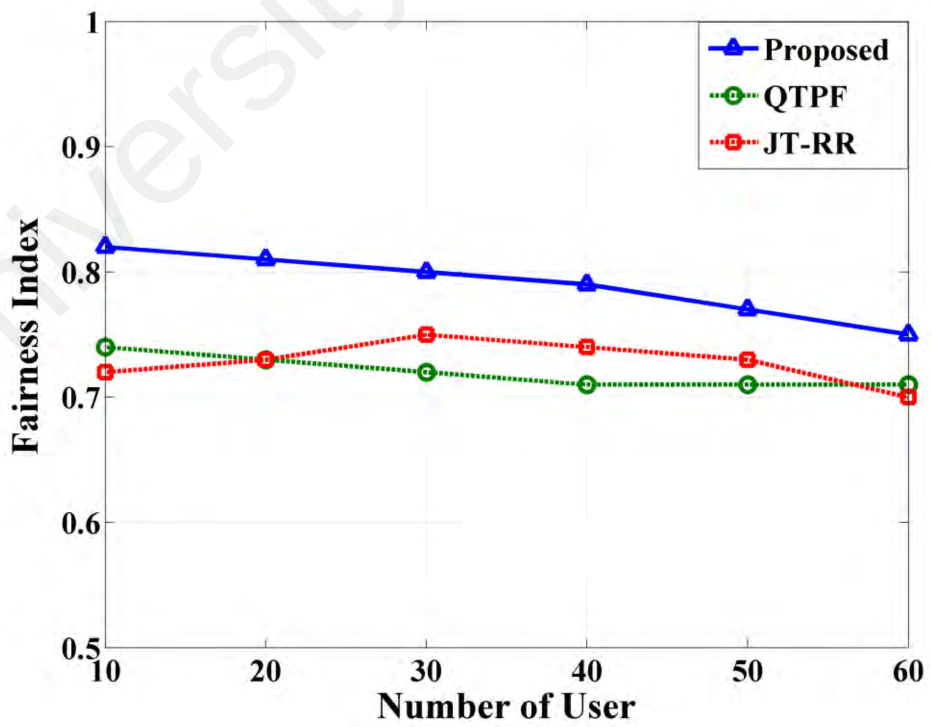

Figure 4.5: Fairness Index for Scenario 1 user

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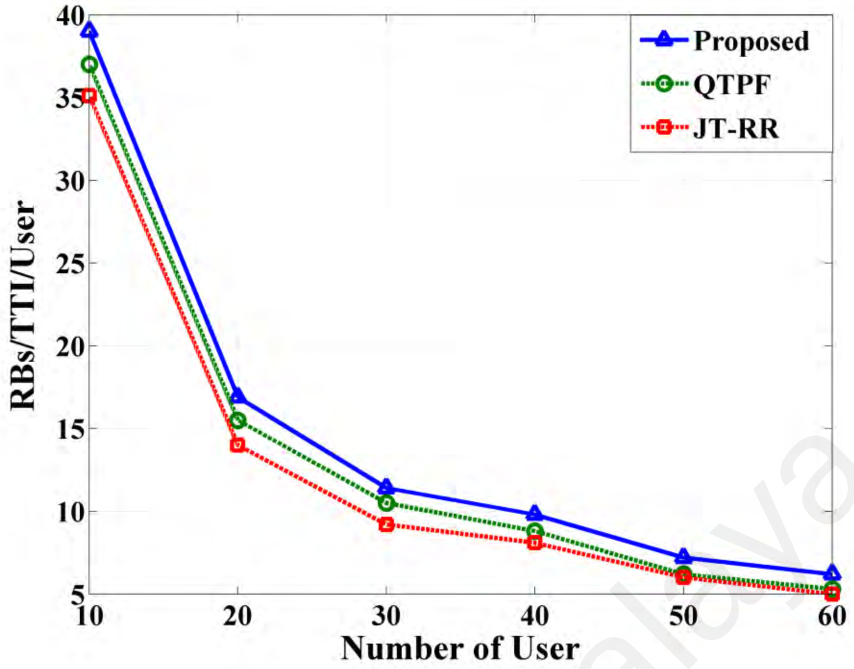

Figure 4.6: RBs per TTI per user for Scenario 1 user

Table 4.3: Improvement of the Proposed method for Scenario 1

Parameters/ Algorithms	QTPF (%)	JT-RR (%)
Cell-edge Throughput	44.1	33.3
Average Throughput	21.1	35.5
Average Cell Throughput	9.9	16.8
Spectral Efficiency	8.5	8.4
Fairness Index	8.8	7.6
Allocate RBs/TTI/User	10.0	16.6

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4.4.2 Scenario 2: More RT traffic than NRT

The simulation process in this Scenario 2 considers 30% HTTP, 50% VoIP and 20% Video data of overall network load. Figure 4.7 shows that the cell-edge user throughput for Scenario 2 user is comparatively higher than other algorithms. The reasons for this better performance are: (a) The proposed method transmits the multiple coherent signals from multiple cooperative eNBs with CA technique to cell-edge user which enhances the throughput. (b) The proposed method also considers the probability of packet loss, error rate and the probability from failure state to success state. Thus, the cell-edge users with high attenuation and high error rate get higher priority and achieve higher throughput. On the other hand, QTPF and JT-RR methods do not use any of the above parameters which leads to a high error rate and low throughput.

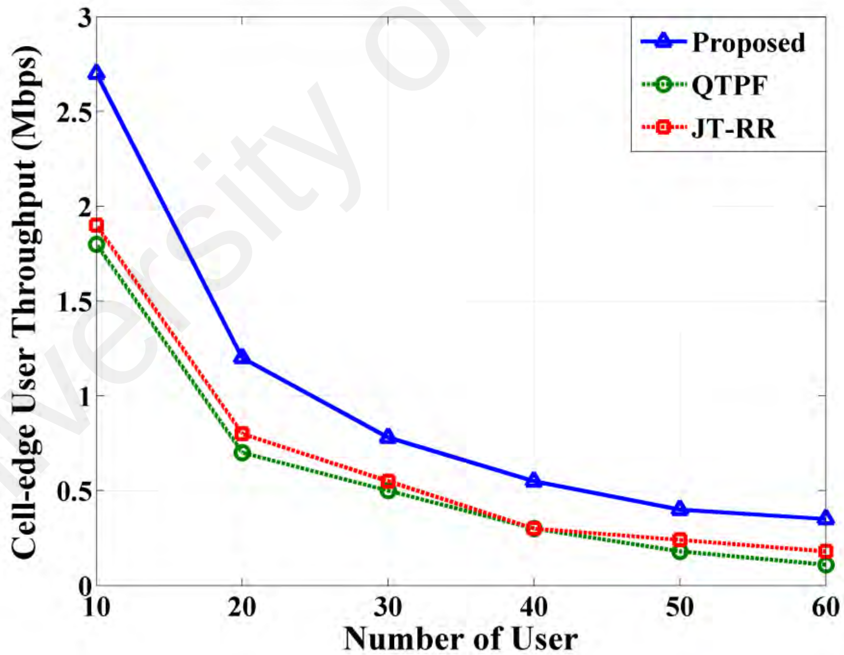

Figure 4.7: Cell-edge user throughput for Scenario 2 user

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Figure 4.8, Figure 4.9 and Figure 4.10 show the average user throughput, average cell throughput and throughput comparison of the proposed method, respectively. These figures demonstrate that the proposed method is not only effective for the cell-edge user but also effective for other users in the cell. The throughputs in Figure 4.8, Figure 4.9 of the proposed method for this Scenario 2 are comparatively higher than other algorithms as well as higher than Scenario 1 throughputs. The reason is that Scenario 2 has a higher amount of RT data with short maximum delay. Therefore, the proposed method gives priority to RT data which leads to less packet loss and high throughput. Moreover, the proposed method calculates the maximum gain from all available resources to assign a CC which ensures less interference and low error rate. As expected, JT-RR has the lowest throughputs due to not considering the delay parameters and randomize assignment of CCs to the user. Figure 4.10 shows the Empirical Cumulative Distribution Function (ECDF) of the average user throughput for a different number of users. This figure demonstrates that the throughput is decreasing when the number of users is increasing due to the lack of available RBs, more congestions and more noise and interferences.

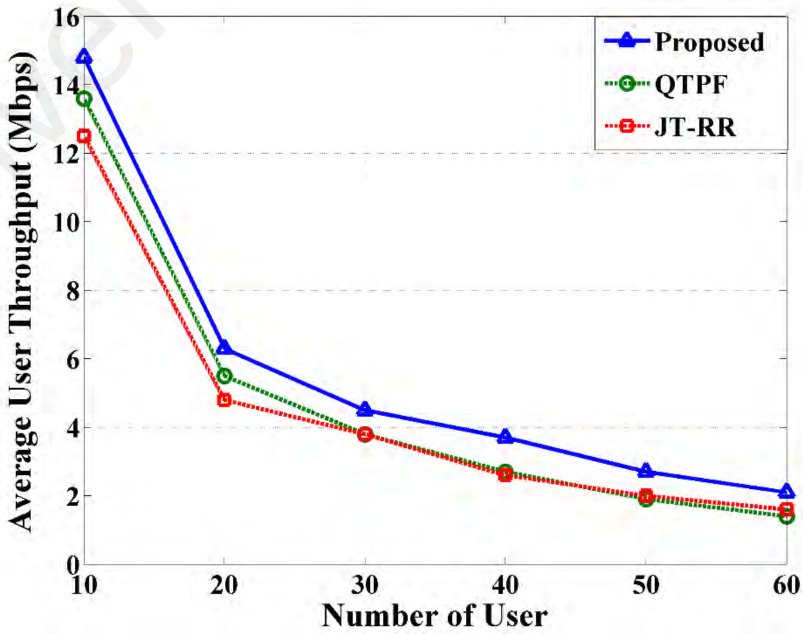

Figure 4.8: Average user throughput for Scenario 2 user

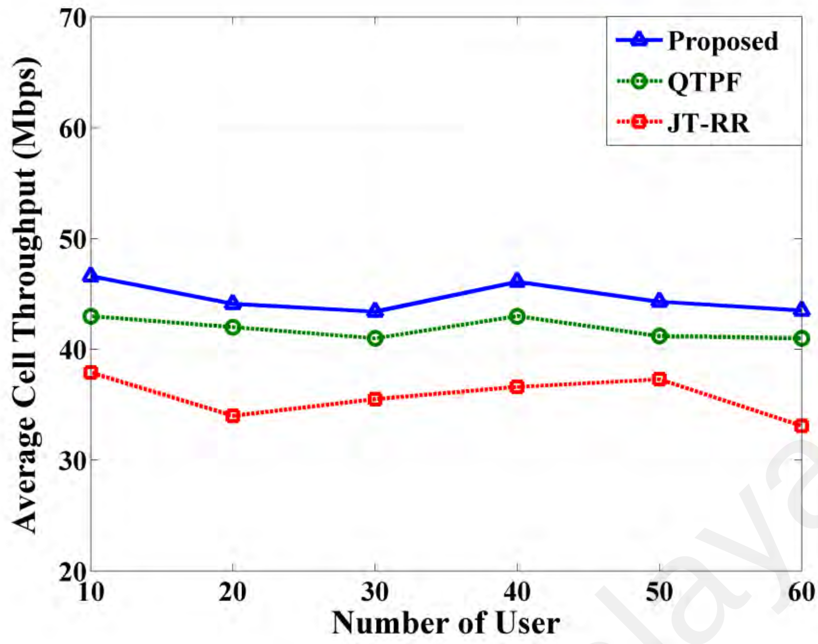

Figure 4.9: Average cell throughput for Scenario 2 user

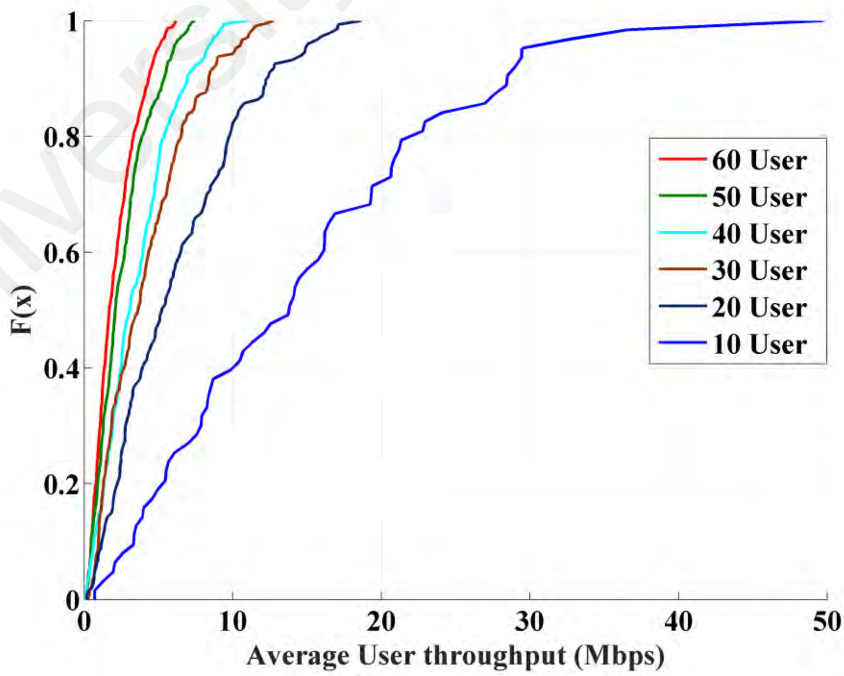

Figure 4.10: Throughput comparison of the proposed method

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Figure 4.11 and Figure 4.12 demonstrate the spectral efficiency comparison of different algorithms and ECDF of the user average spectral efficiency comparison of the proposed method for different users, respectively. As expected, the spectral efficiency improvement of the proposed method in Figure 4.11 for Scenario 2 is higher than the Scenario 1, as the Scenario 2 contains more RT data. Since the RT data packet has a short delay threshold value, it has the higher priority to get RBs from the packet scheduler. According to Table 4.3 and 4.4, it can be said that the overall average improvement of Scenario 2 is 10.85% whereas Scenario 1 improves 8.45%. By transmitting multiple signals to cell-edge and considering the several delay parameters, error parameters, and queue condition, the proposed method can reduce the packet drop rate and error rate which leads to better efficiency. Figure 4.12 shows that the spectral efficiency for the different user are very close to each other and maintains a stable efficiency despite increasing the number of users due to efficient resource allocation procedure of the proposed method.

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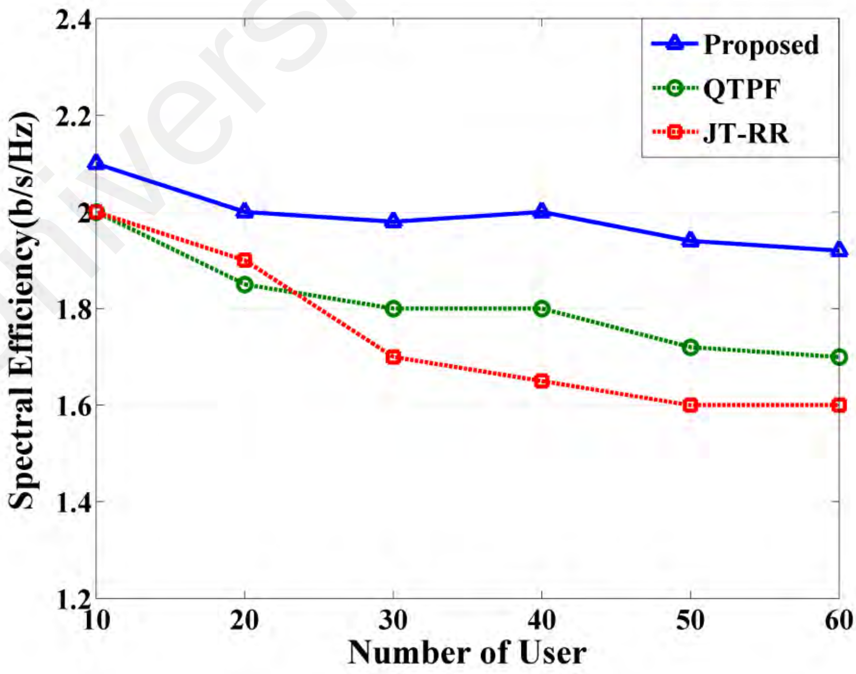

Figure 4.11: Spectral efficiency for Scenario 2 user

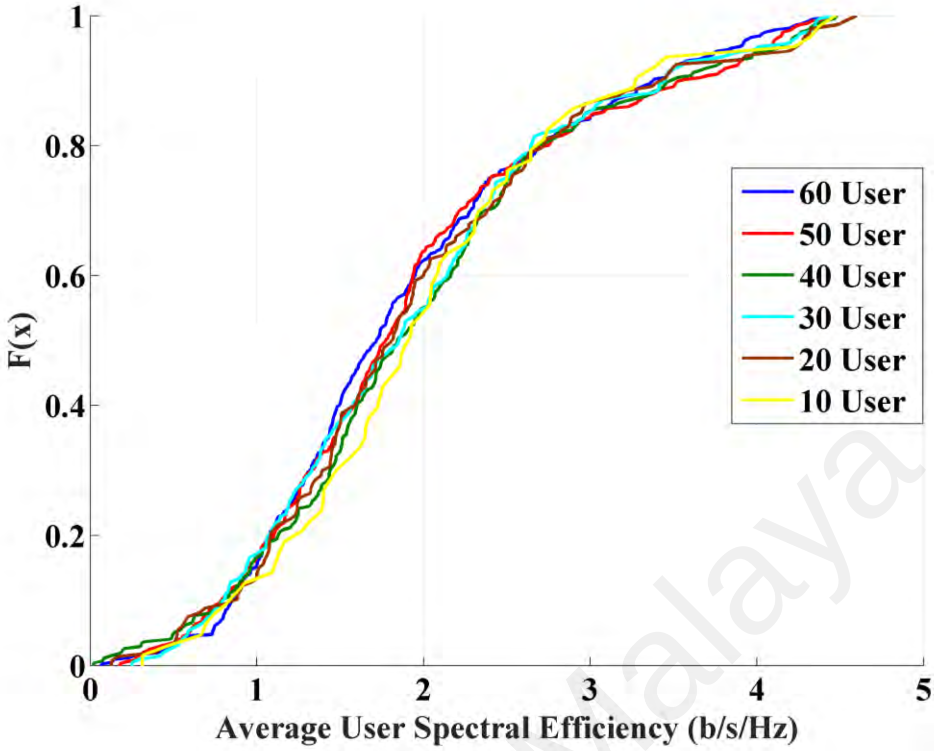

Figure 4.12: Spectral efficiency comparison of the proposed method

Figure 4.13 shows that fairness index of the proposed method is also higher than that of Scenario 1 fairness along with higher improvement rate due to providing higher priority to those users who have longer HOL delay and have shorter maximum delay budget. However, QTPF and JT-RR methods do not prioritize the users with a longer delay. As a result, high packet loss and high error rate cause the performance degradation of these two methods. Figure 4.14 shows that the proposed method can allocate more RBs to the user for its efficient scheduling process which enhances the performance of all users in the cell. Table 4.4 depicts the improvement of the proposed method regarding all performance parameters.

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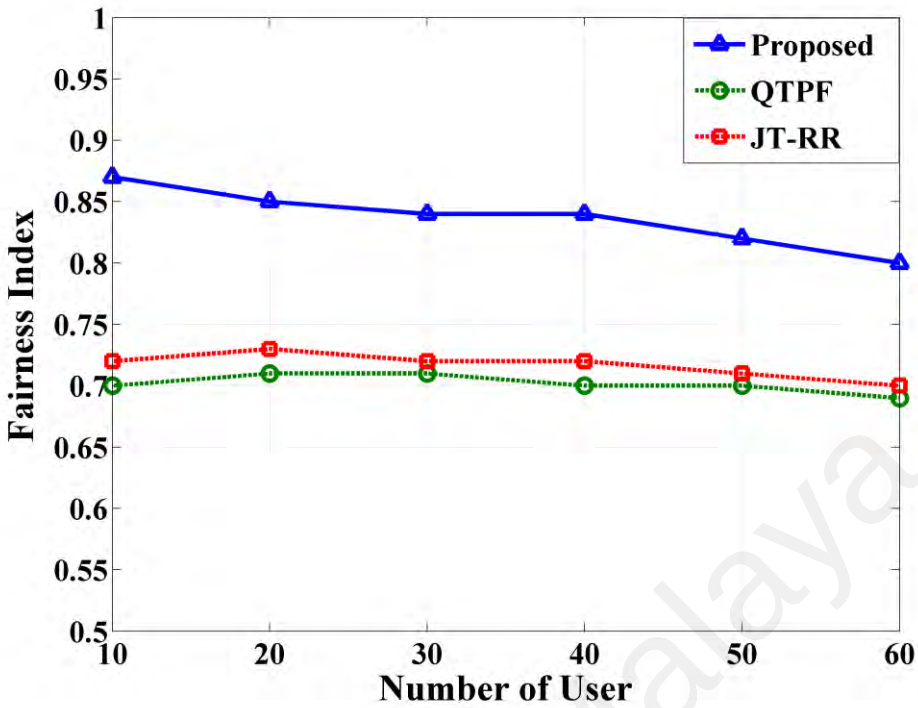

Figure 4.13: Fairness Index for Scenario 2 user

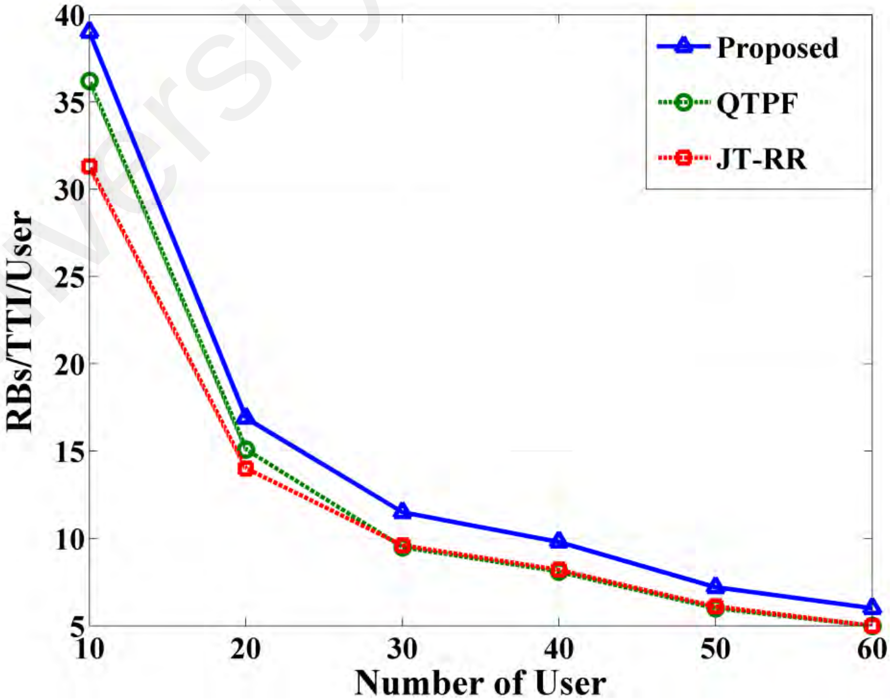

Figure 4.14: RBs per TTI per user for Scenario 2 user

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Table 4.4: Improvement of the Proposed method for Scenario 2

Parameters/ Algorithms	QTPF (%)	JT-RR (%)
Cell-edge Throughput	46.7	37.8
Average Throughput	21.1	22.4
Average Cell Throughput	6.3	20.0
Spectral Efficiency	9.1	12.6
Fairness Index	16.1	14.3
Allocate RBs/TTI/User	14.3	17.0

4.4.3 Scenario 3: More NRT traffic than RT

The simulation process in Scenario 3 contains 70% HTTP, 10% VoIP and 20% Video data of overall network load. Figure 4.15 shows that the cell-edge user throughput of the proposed method is the lowest compared to other scenarios. As this scenario has more NRT data traffic and proposed method gives more priority to the user with shorter maximum delay, the NRT data traffic facing comparatively more delay and more packet loss than other scenarios. However, the proposed method performs better than QTPF and JT-RR due to implement the JT-CoMP with CA to the cell-edge user and for considering the HOL delay, error probability, maximum delay and the throughputs of the user. Average cell throughput in Figure 4.16 and Average user throughput in Figure 5.1 also demonstrates that the proposed method performs better than QTPF and JT-RR methods for deploying efficient CC selection method for all users, having better cell-edge throughput and balancing the queue effectively. Figure 5.2 shows the SINR and throughput mapping for each user (in the case of 40 users) of the proposed method. The figure shows the mapping between the wideband SINR and the throughput. As several points could be overlapping, the figure shows another option which is a binned (over wideband SINR) mean throughput mapping (the red dot).

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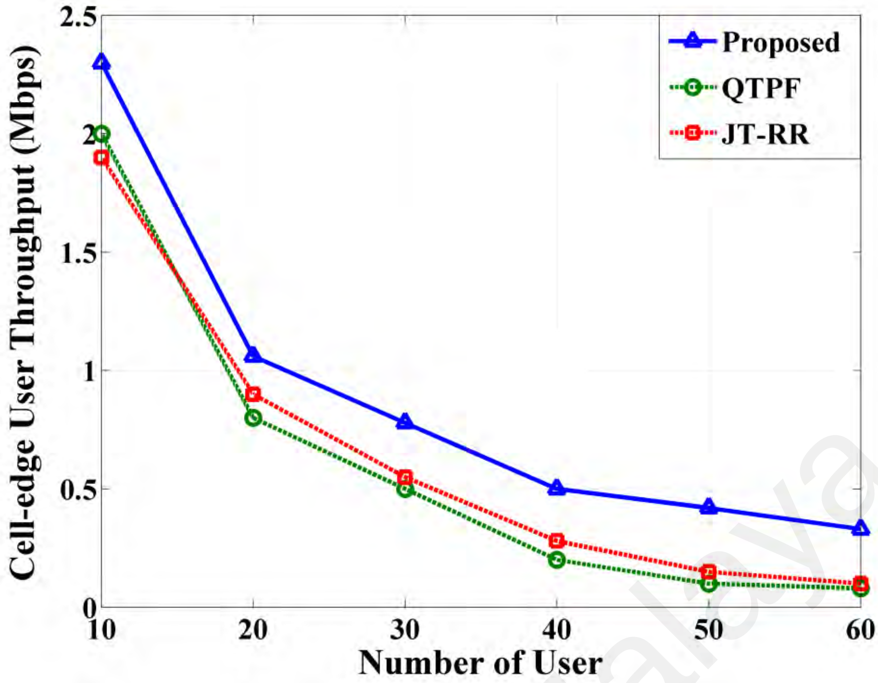

Figure 4.15: Cell-edge user throughput for Scenario 3 user

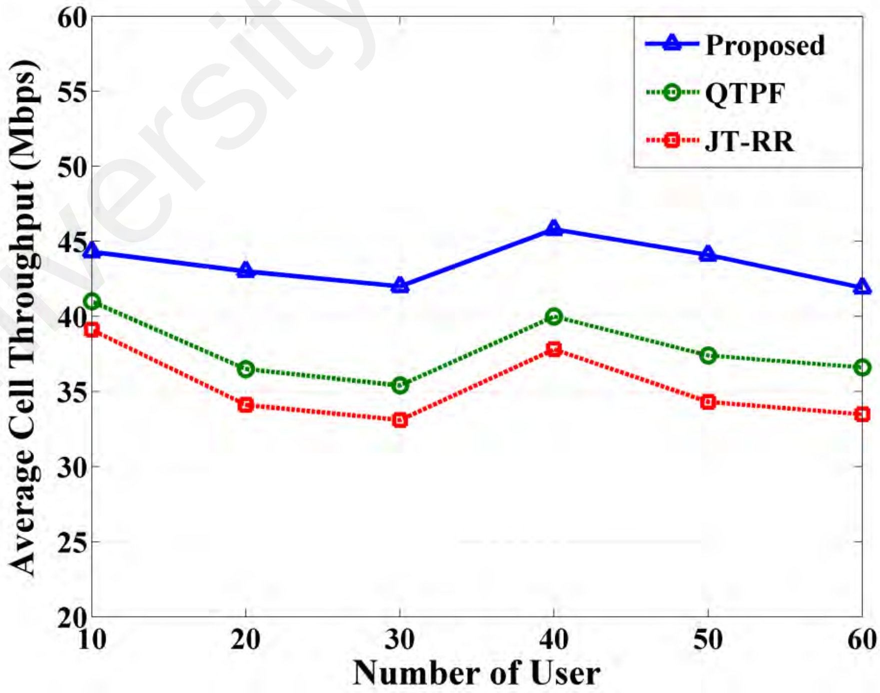

Figure 4.16: Average cell throughput for Scenario 3 user

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Fairness index of the proposed method in Figure 4.17 shows that Scenario 3 has the lowest among all scenarios. As mentioned above that this Scenario 3 has a high amount of NRT and proposed method prioritizes the RT data user, the fairness goes down. However, the fairness of QTPF and JT-RR methods is quite the same as other scenarios due to having the same approach for all types of data. Table 4.5 shows the improvement of proposed method for Scenario 3. As because of considering the inactive users in the cell area for calculating the average cell throughput, the aggregated average user throughput is not the same as the aggregated average cell throughput.

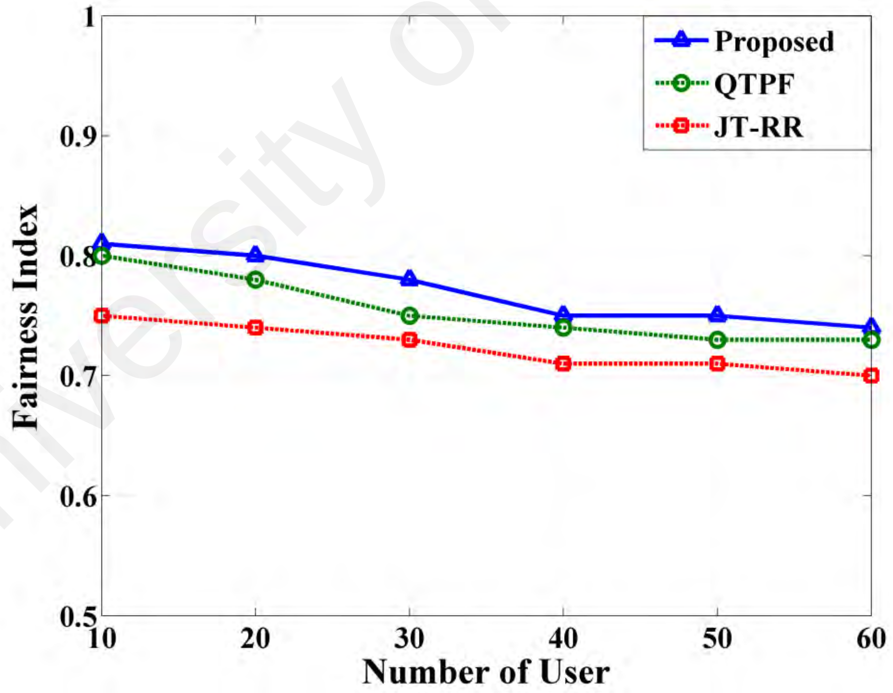

Figure 4.17: Fairness Index for Scenario 3 user

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Table 4.5: Improvement of the Proposed method for Scenario 3

Parameters/ Algorithms	QTPF (%)	JT-RR (%)
Cell-edge User Throughput	47.6	40.0
Average Cell Throughput	13.1	19.0
Average User Throughput	17.8	26.7
Spectral Efficiency	7.4	10.5
Fairness Index	2.2	6.3
Allocate RBs/TTI/User	13.5	17.8

4.5 Performance Evaluation in Different User Speed

This thesis deploys the proposed method in four different user speed levels to analyze the efficiency of the method. Two frequency sets are considered 2100 MHz and 2300 MHz to choose the CCs with the same total of 40 MHz of channel bandwidth as previous simulation plot. Urban macrocell with the COST231 pathloss model is used. Four different user speed levels such as 0 kmph (Static), 5 kmph (walking), 50 kmph (average car speed) and 100 kmph (fast car speed) are considered in this simulation plot. Simulation Parameters are summarized in Table 4.6 below.

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Table 4.6: Simulation Parameters for Different User Speed

Parameters	Values
Operating frequency band	2100 MHz and 2300 MHz
Total bandwidth	40 MHz (4x10 MHz)
Deployment Scenario	Urban macro
User Deployment	Random all over the cell area
Number of user per eNB	10,20,30,40,50,60
User Speed	0 kmph / 5 kmph / 50 kmph / 100 kmph
Scheduling algorithm	Proposed method
Pathloss model	COST231
Simulation time	1000 TTI
Traffic Model	Mixed (HTTP, VoIP, Video)

Figure 4.18, Figure 4.19 and Figure 4.20 show the Cell-edge user throughput, Average user throughput and average cell throughput of the proposed method, respectively, for different user speed. These three figures demonstrate that static user (0 kmph) performs better than other users with higher speed due to less packet loss, lower error rate, and less signal attenuation. As expected, a user with the highest speed (100 kmph) achieves the lowest throughput as the high-speed causes high attenuation, high packet loss and possible failed handover. The throughputs of the proposed methods for all speeds decreases sharply when the number of user increases. The cell-edge user with higher speed suffers comparatively more than the other users due to the distance and poor signal quality.

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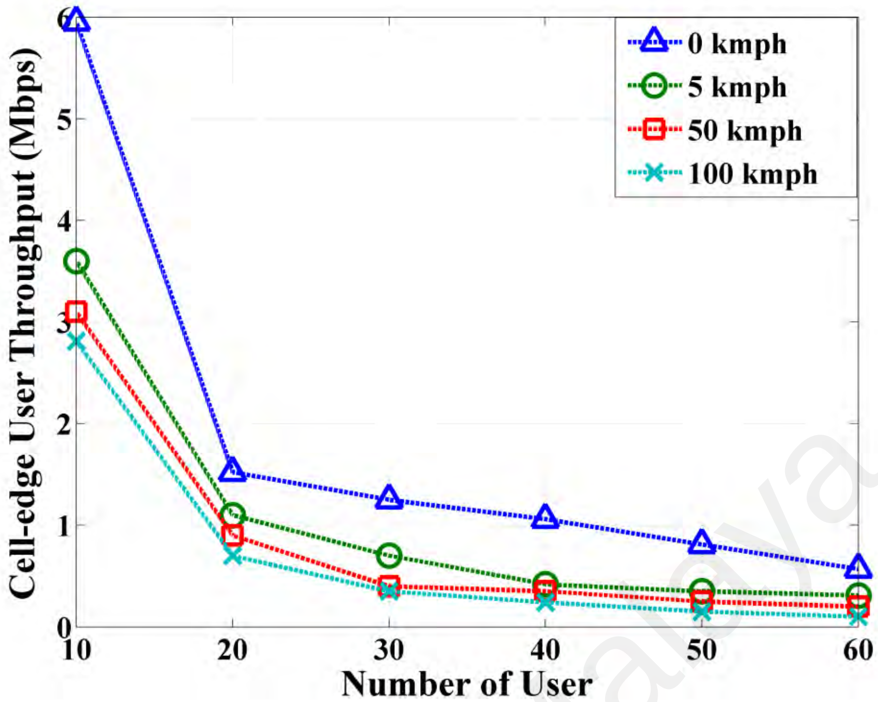

Figure 4.18: Cell-edge user throughput for different user speeds

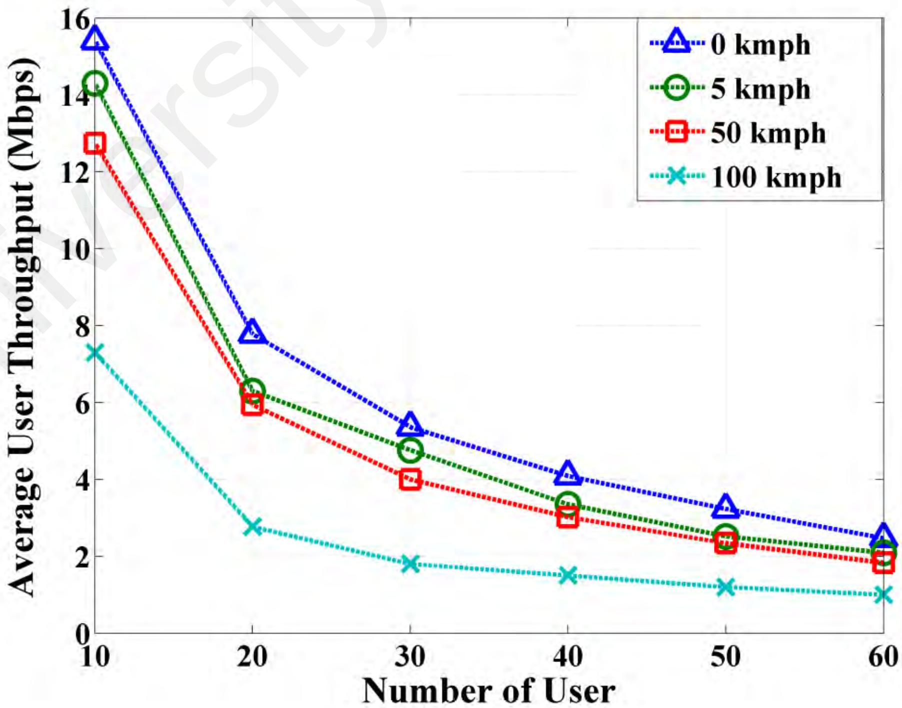

Figure 4.19: Average user throughput for different user speeds

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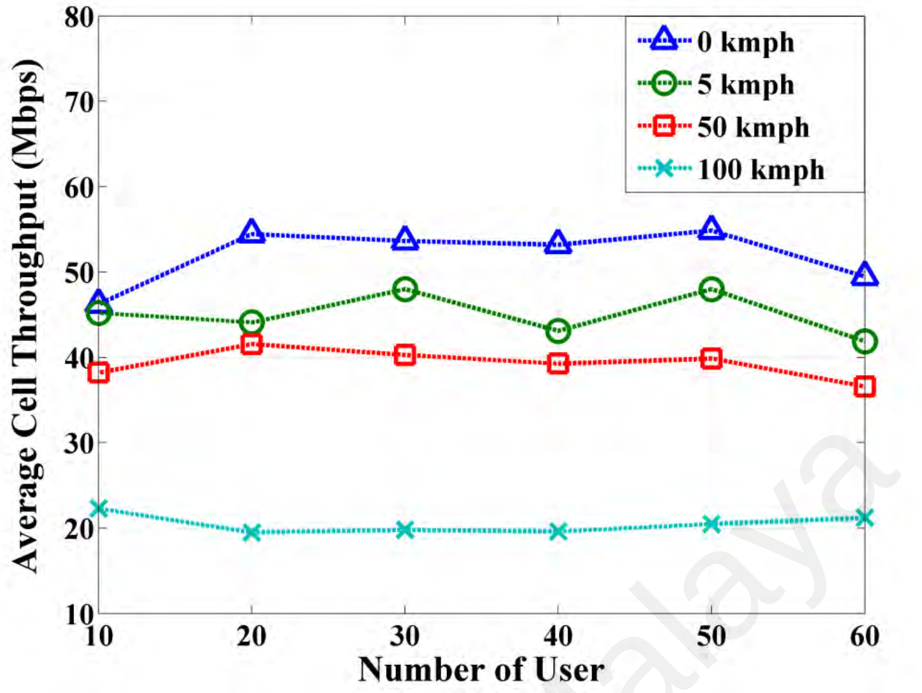

Figure 4.20: Average cell throughput for different user speeds

4.6 Performance Evaluation for Different Frequencies

Different frequency has different attenuation rate and has a different level of interference. Therefore, this thesis implements the proposed method in three different frequency sets to analyze the performance. Among the three sets Set 1 has comparatively lower frequency bands (900 MHz and 1800 MHz) which is commonly used for 2G/3G communication. However, as 2G technology is shutting down in many countries and LTE technology replaces 2G/3G, these frequency bands will widely use in LTE/LTE-A. Mid-range frequency bands (2100 MHz and 2300 MHz) have been selected for Set 2 in this simulation plot to analyze the performance of the proposed method, as these set of frequencies are widely used and have wider available free space. Whereas, to investigate the effect of higher frequency, this thesis chooses comparatively higher frequency bands (2600 MHz and 3500 MHz) for Set 3. Simulation parameters are depicted in following Table 4.7 for this simulation plot.

Figure 4.21, Figure 4.22 and Figure 4.23 show the cell-edge user throughput, average user throughput and average cell throughput of the proposed method, respectively, for three different frequency sets. Set 1 with comparatively lower frequency performs marginally better than the sets with higher frequency due to less attenuation, low data error rate, and less interference. The throughputs of higher frequencies are comparatively lower as these frequencies are affected more by the noise and interference. However, by considering the error rate, possibility of packet loss and delay parameters, the proposed method minimizes the error rate and packet loss and thus the throughput performance of all the sets are very close to each other. Therefore, the frequencies in Set 2 and Set 3 also can be used widely to serve the user by the mobile operators around the world. Moreover, frequencies in these Sets have more duplex spacing which can also solve the limited spectrum issue.

Table 4.7: Simulation Parameters for Different Frequencies

Parameters	Values
Operating frequency band Set 1	900 MHz and 1800 MHz
Operating frequency band Set 2	2100 MHz and 2300 MHz
Operating frequency band Set 3	2600 MHz and 3500 MHz
Total bandwidth	40 MHz (4x10 MHz)
Deployment Scenario	Urban macro
Number of user per eNB	10,20,30,40,50,60
User Speed	5 kmph
Scheduling algorithm	Proposed method
Pathloss model	COST231
Simulation time	1000 TTI
Traffic Model	Mixed (HTTP, VoIP, Video)

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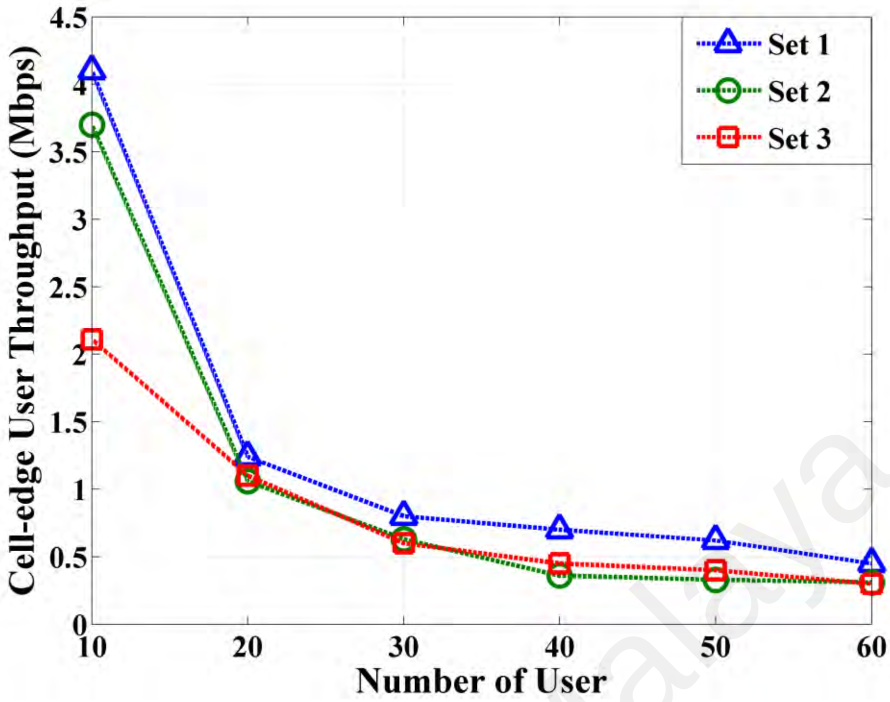

Figure 4.21: Cell-edge user throughput for different frequency sets

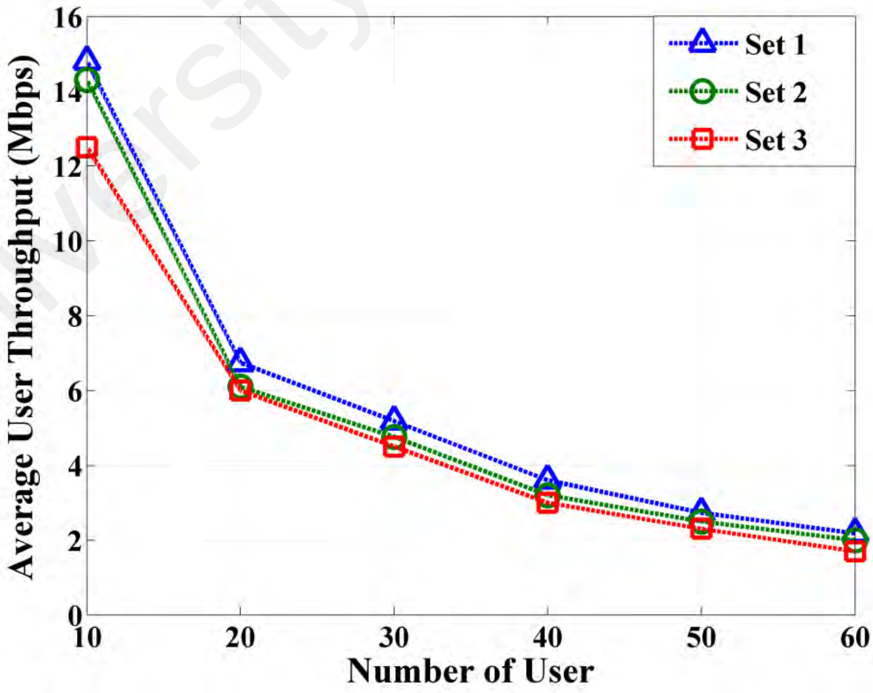

Figure 4.22: Average user throughput for different frequency sets

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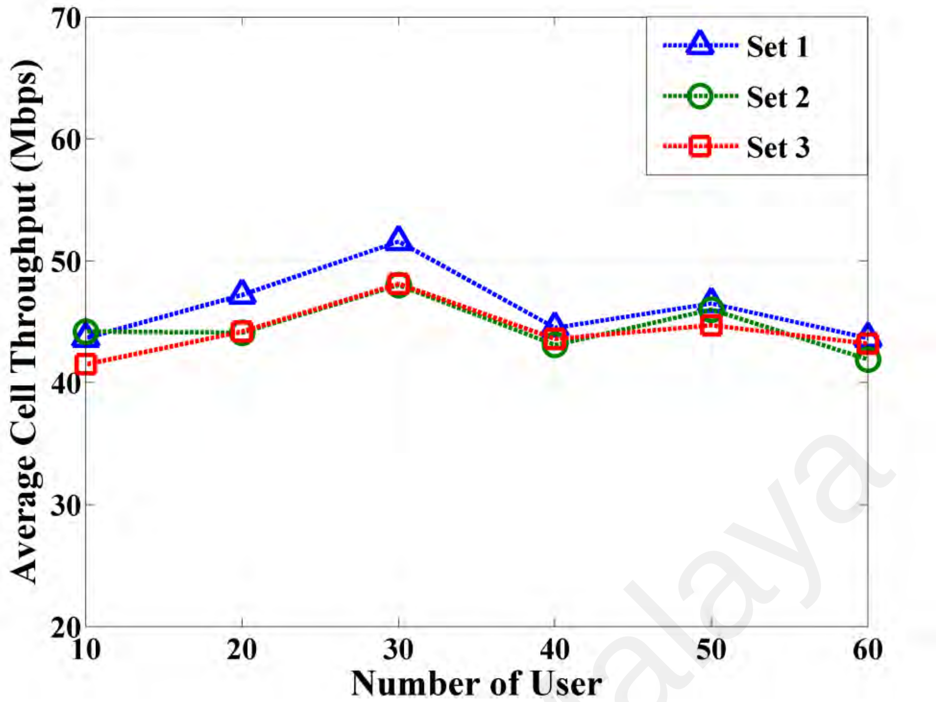

Figure 4.23: Average cell throughput for different frequency sets

4.7 Performance Comparison in Different Geographical Area

Different geographical areas have various types and levels of interference, noise, and attenuation. The overall performances are not the same for all areas. Therefore, this thesis deploys the proposed method in three separate geographical areas such as urban, suburban and rural with QTPF and JT-RR methods. Macrocell with same cell size for all areas is considered for this simulation plot. COST231 pathloss model is used for Urban macro/ Sub-urban macro cell whereas, rural area uses the pathloss model according to 3GPP. Users are equally distributed in the cell area and are moving in 5 kmph speed (walking model). Mixed types of traffic model are deployed with a simulation time of 1000 TTI. The following Table 4.8 shows the simulation parameters for this simulation plot.

Table 4.8: Simulation Parameters for Different Geographical Area

Parameters	Values
Operating frequency band	2100 MHz and 2300 MHz
Total bandwidth	40 MHz (4x10 MHz)
Deployment Scenario	Urban macro/ Sub-urban macro/ Rural
User Deployment	Random all over the cell area
Number of user per eNB	10,20,30,40,50,60
Scheduling algorithm	Proposed method, QTPF, JT-RR
Pathloss model	Rural - According to 3GPP
	Urban macro/ Sub-urban macro - COST231
Simulation time	1000 TTI
Traffic Model	Mixed (HTTP, VoIP, Video)

4.7.1 Rural

The level of interference, noise and attenuation are comparatively less in a rural area due to less number of the user, fewer obstacles and less number of other interfering nodes. As these interferences affect much to the cell-edge user due to the distance from eNBs, the cell-edge user throughput in a rural area is better than other areas. Figure 4.24, Figure 4.25 and Figure 4.26 show the cell-edge user throughput, average user throughput and average cell throughput of different methods, respectively. It is clear from these figures that the proposed method performs better than QTPF and JT-RR methods for deploying the CoMP with CA for cell-edge user and efficient CC selection process. The proposed method also considers delay parameters, probability of packet loss and error probability which reduce the packet loss rate and thus increase the throughput. On the other hand, QTPF prioritizes the user with low previous throughput. Whereas, JT-RR does not consider any of the above parameters and selects the CC randomly and assigns RBs to the user by rotation which causes longer delay and high packet loss.

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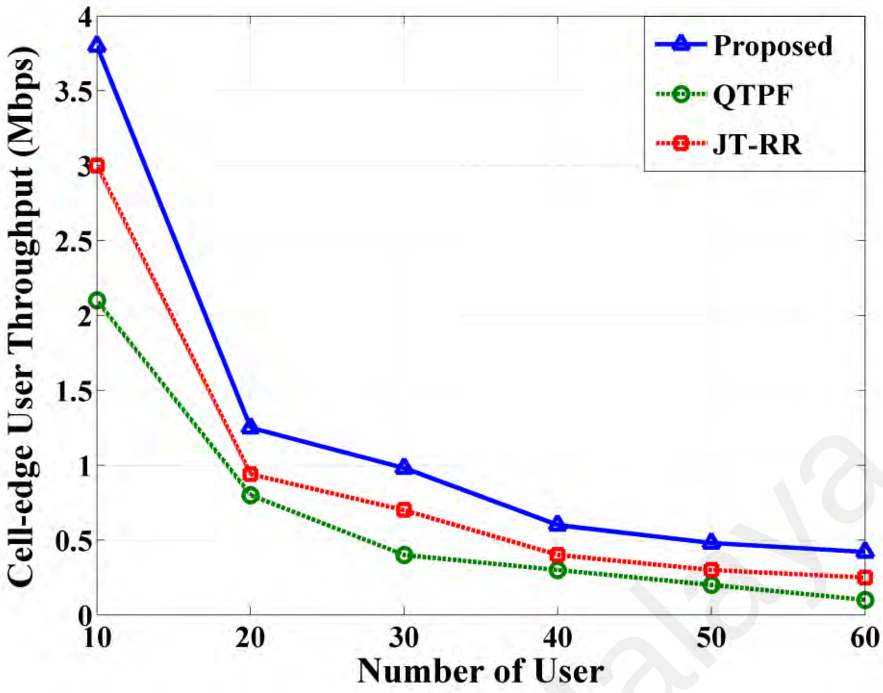

Figure 4.24: Cell-edge user throughput for different Rural user

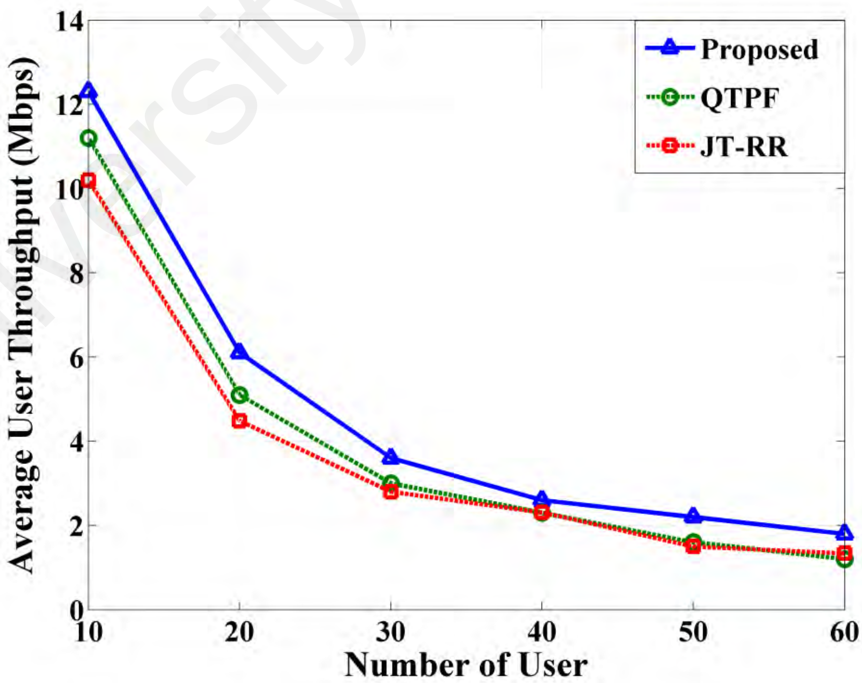

Figure 4.25: Average user throughput for different Rural user

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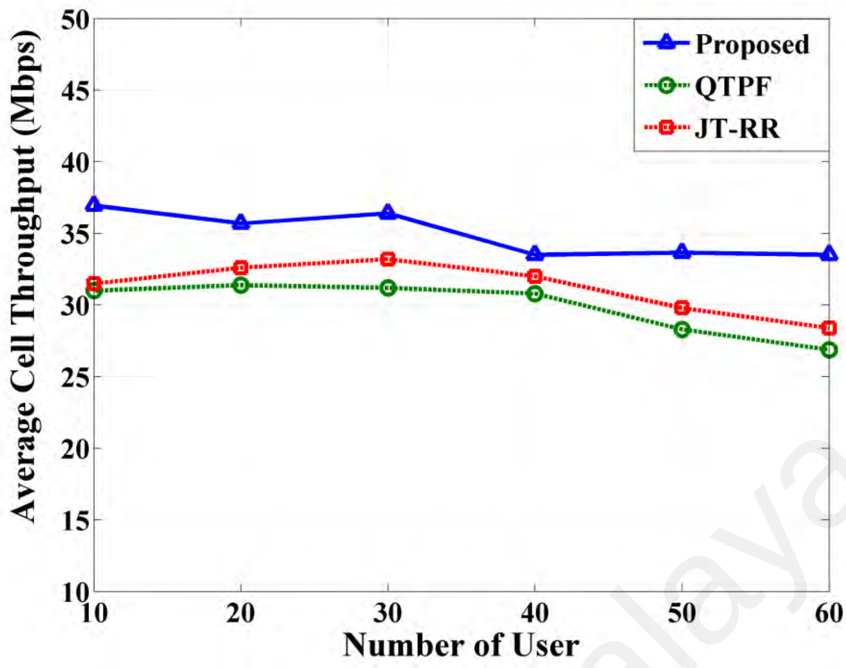

Figure 4.26: Average cell throughput for different Rural user

Spectral efficiency in Figure 4.27 demonstrates that the proposed method can utilize the frequency spectrum more efficiently than the QTPF and JT-RR methods due to low packet loss and high throughputs. The Spectral efficiency of the proposed method remains nearly in similar values when the number of user increases, whereas it is decreasing for other methods due to the inefficient scheduling process. Efficient eNB coordination by the proposed method also has a vital effect to achieve better spectral efficiency than the other methods. Fairness index in Figure 4.28 shows that the proposed method allocates the RBs to the user more fairly than other methods as it prioritizes the user with a longer delay and high probability of packet loss. However, the fairness index of all methods decreases when the number of users increases due to the high congestion of the user. The RBs per TTI per user for this rural area in Figure 4.29 indicates that the RBs allocation rate of all methods is very close to each other, but the end performances are not the same. Because of distributing the available RBs to the user more efficiently, the overall performance of the proposed method is better than the QTPF and JT-RR methods. Table 4.9 depicts the performance improvement of the proposed method.

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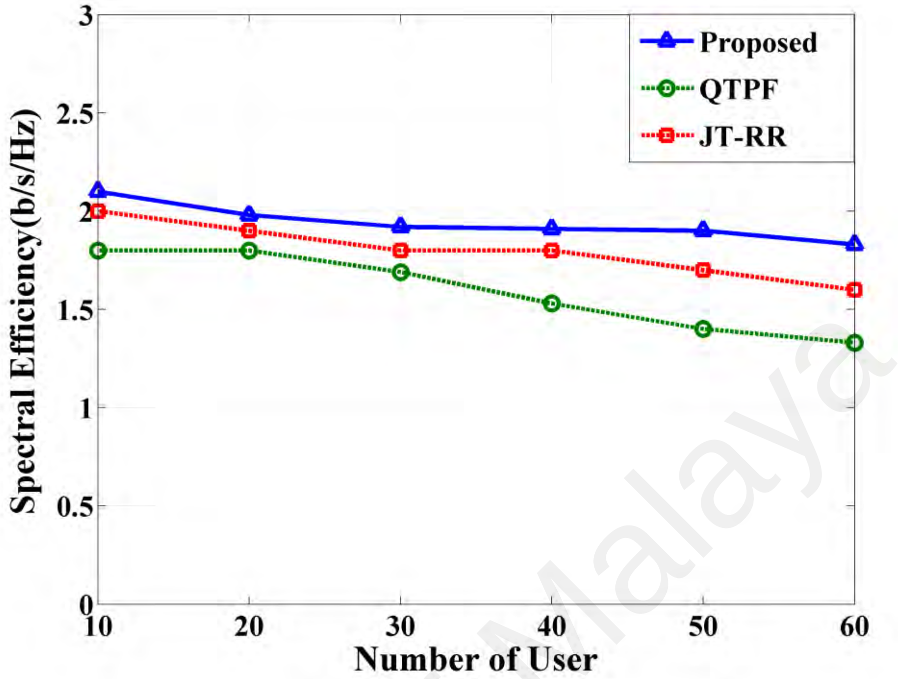

Figure 4.27: Spectral efficiency for the different Rural user

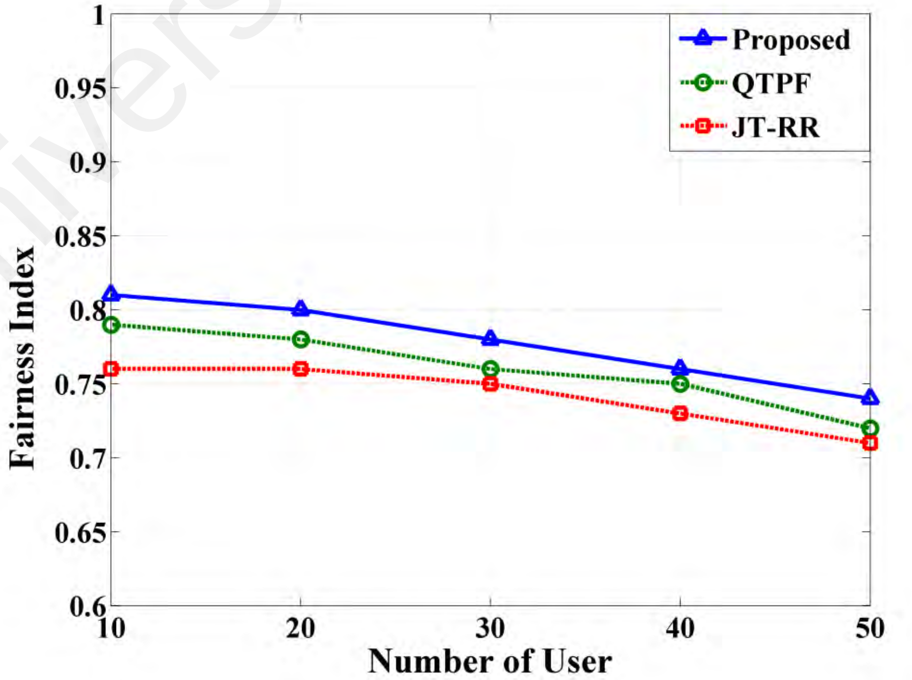

Figure 4.28: Fairness Index for different Rural user

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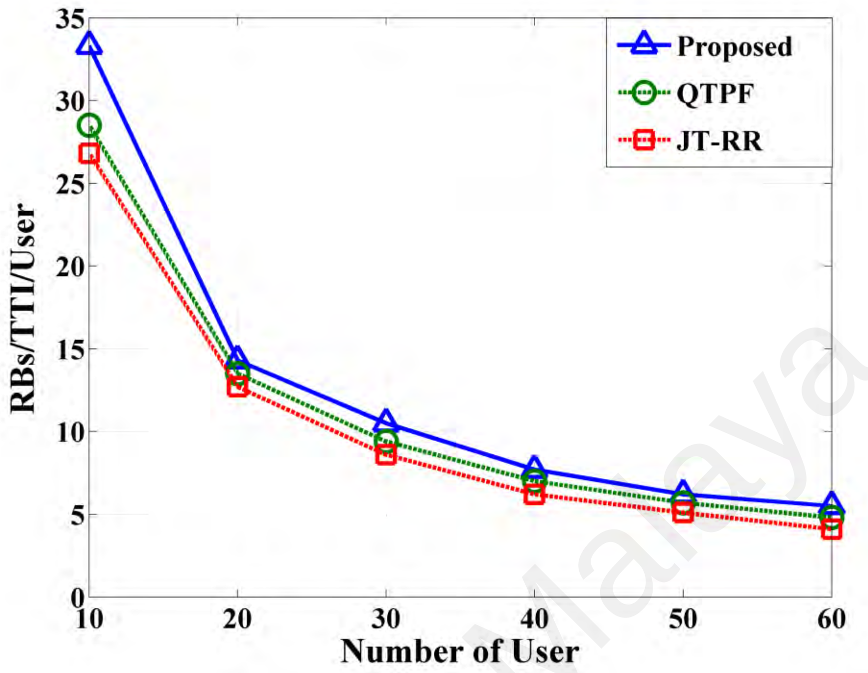

Figure 4.29: RBs per TTI per user for Rural user

Table 4.9: Improvement of the Proposed method for Rural user

Parameters/ Algorithms	QTPF (%)	JT-RR (%)
Cell-edge Throughput	54.1	31.0
Average Throughput	19.0	22.4
Average Cell Throughput	10.6	14.4
Spectral Efficiency	18.2	7.3
Fairness Index	4.3	2.4
Allocate RBs/TTI/User	10.1	18.6

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4.7.2 Urban

Urban simulation plot uses the COST231 pathloss model as this type of cell area generally contains several numbers of high rise buildings and other infrastructures. User distribution of Urban area is shown in Figure 4.30 for 50 users. The simulation settings of Urban and previous simulation plot 'Scenario 3' are the same. Therefore, the obtained simulations results are the same in both of these plots. However, this section analyzes the results in the context of the geographical area.

Figure 4.31, Figure 4.32, Figure 5.3 and Figure 5.4, show the average user throughput, throughput comparison for the different Urban user, cell-edge user throughput and average cell throughput, respectively. The cell-edge user throughput of urban user is lowest among the user of other geographical areas for having the highest level of noise and attenuation. However, the proposed method improves the average user and cell throughput by considering all these interference, delay and packet loss along with efficient RBs allocation and CC selection.

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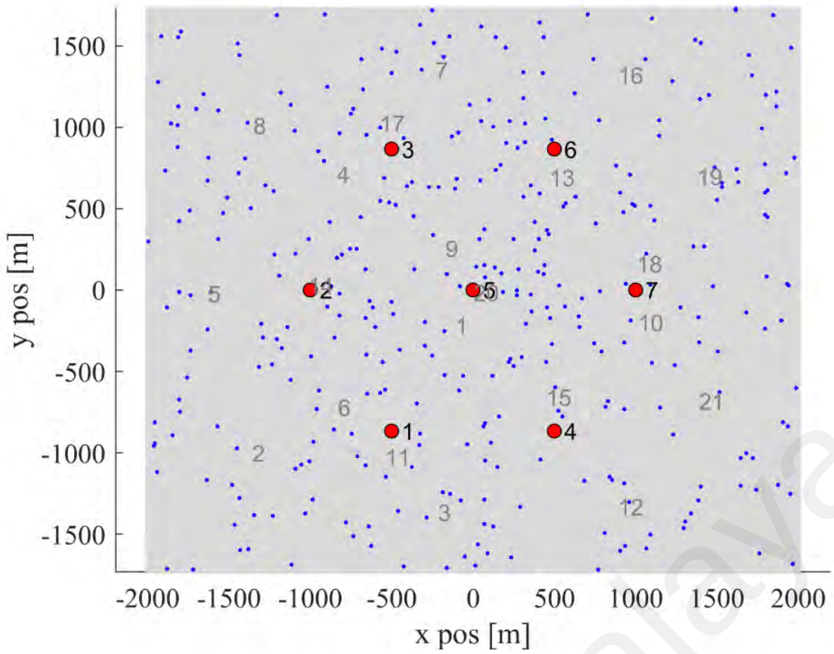

Figure 4.30: Distribution of 50 Urban user

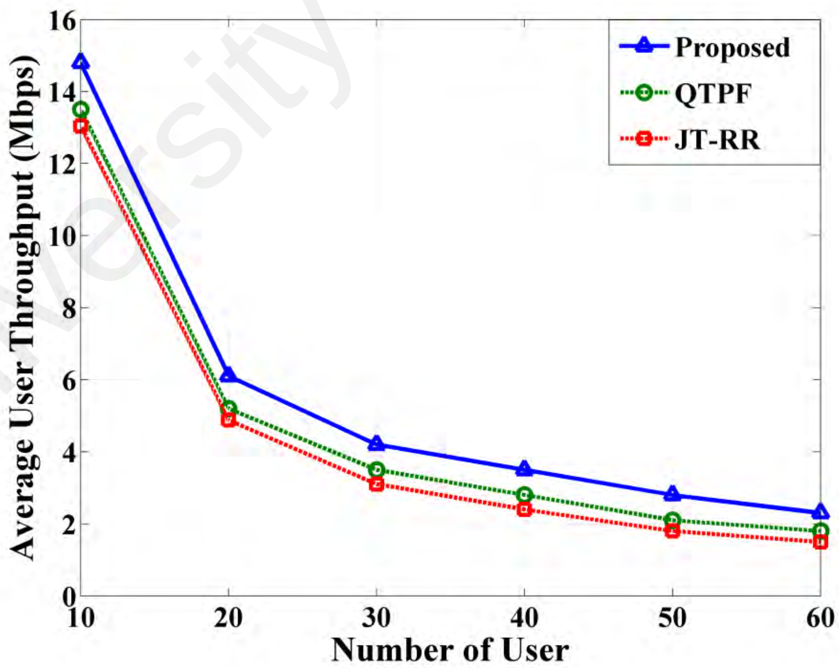

Figure 4.31: Average user throughput for Urban user

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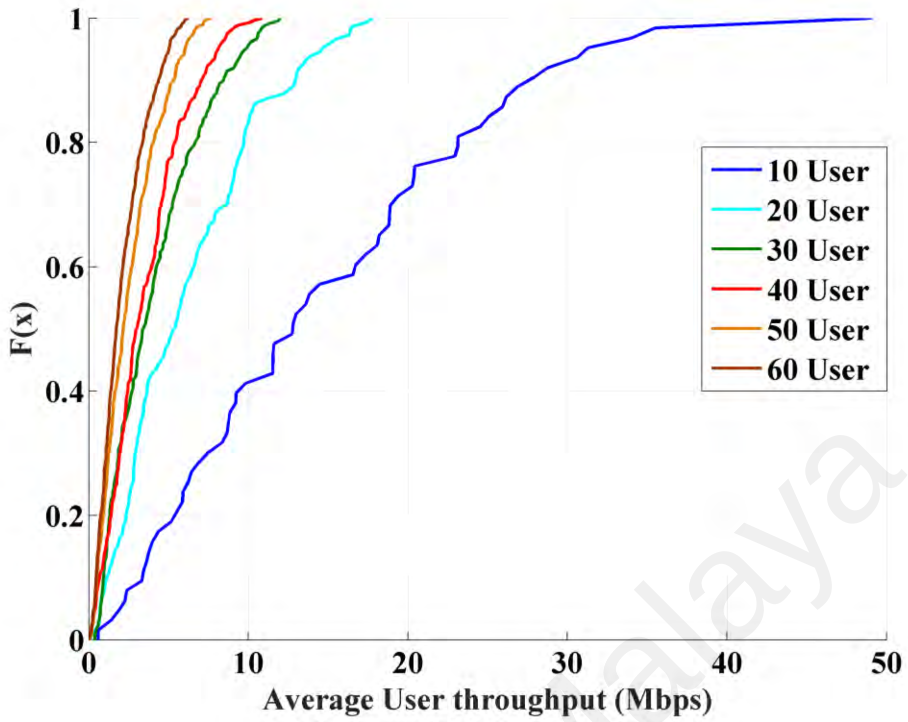

Figure 4.32: Throughput comparison for Urban user

Overall spectral efficiency and SINR and Spectral efficiency mapping for 40 Urban users are depicted in Figure 4.33 and Figure 5.5, respectively. Although having packet loss and high error rate for the cell-edge user in this urban area, the proposed method maintains good spectral efficiency compared to the user of other geographical areas. The RBs per TTI per user for the urban user in Figure 4.34 shows that all methods allocate an almost similar number of RBs. However, for considering delay parameters, probability of packet loss, error rate, queue condition and user throughputs the proposed method archives higher throughput thus, it has better spectral efficiency. On the other hand, QTPF and JT-RR do not consider any delay or error parameters which cause higher packet loss and lower efficiency.

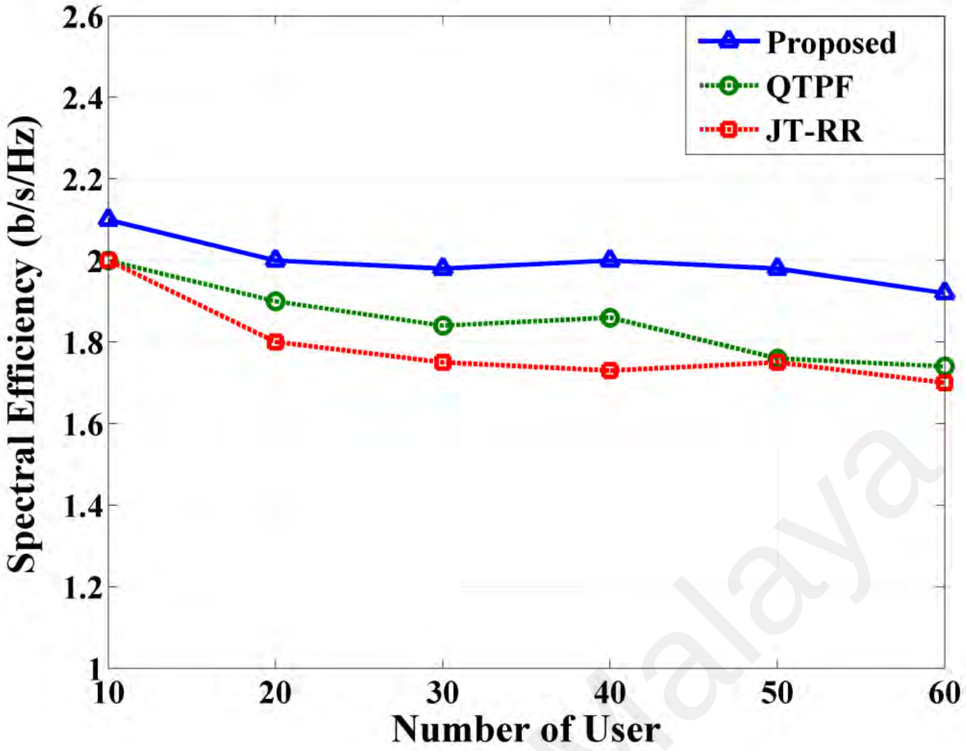

Figure 4.33: Spectral efficiency for the Urban user

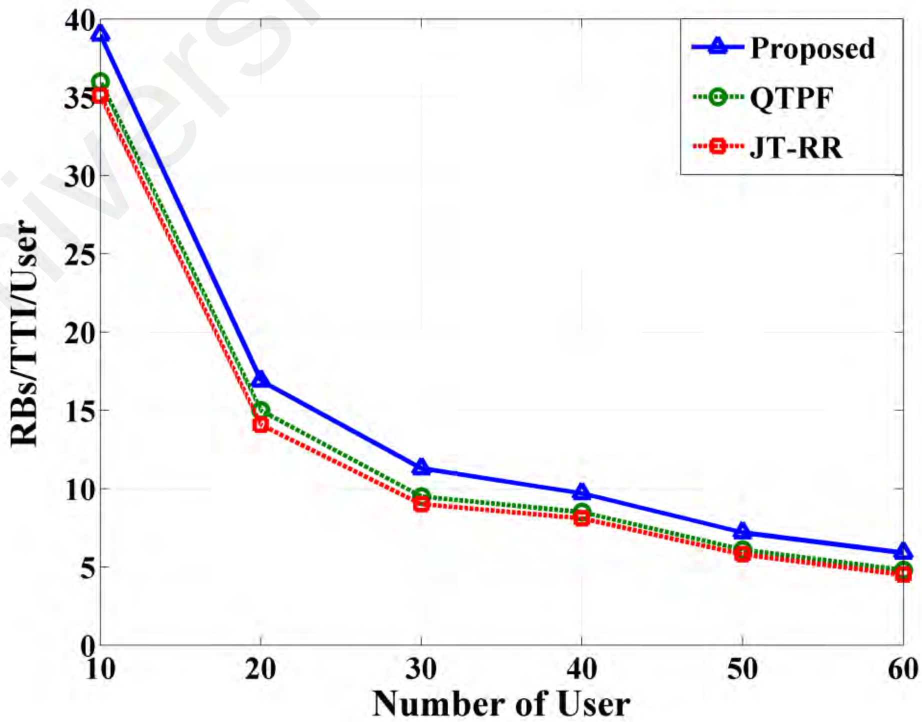

Figure 4.34: RBs per TTI per user for different methods

4.7.3 Suburban

Sub-urban simulation plot also uses the COST231 pathloss model as this type of cell area has high rise infrastructures like the urban area but fewer in number. Therefore, the throughput performance is close to the performance of the urban area. Figure 4.35, Figure 4.36 and Figure 4.37 show the cell-edge user throughput, average user throughput and average cell throughput of different methods, respectively. Cell-edge user throughput of Sub-urban area is higher than urban area but lower than rural area as the interferences in this area is higher than rural but lower than an urban area, respectively. However, the proposed method achieves a high average user and cell throughput as expected due to efficient RBs allocation and CC selection. Cell-edge user throughput decreases sharply when the number of users increases for all methods for lack of available resources and high interferences. By deploying CoMP and CA technique for the cell-edge user and efficient CC selection for all other users, the proposed method achieves higher average user and cell throughput than QTPF and JT-RR methods.

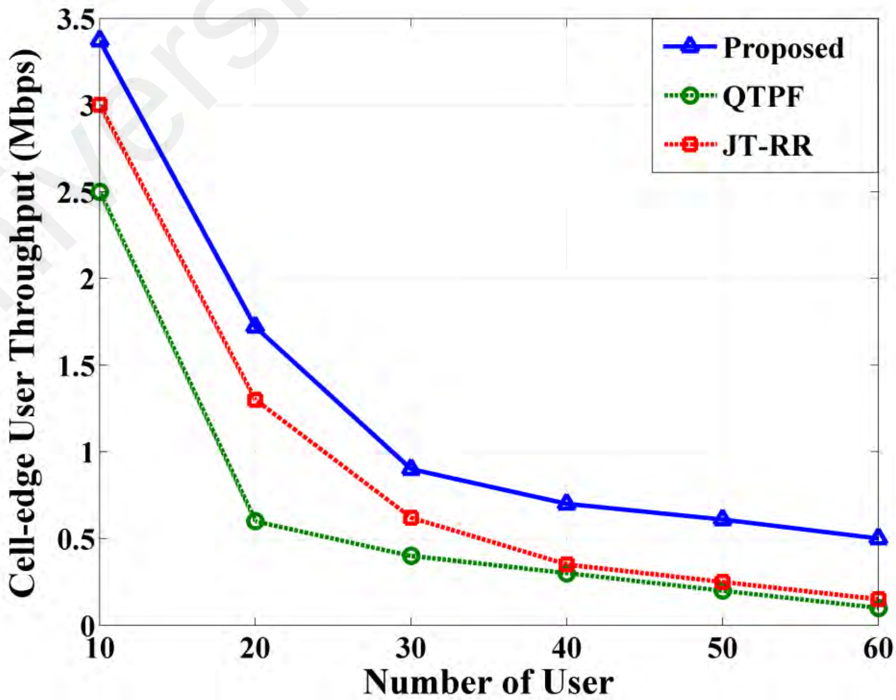

Figure 4.35: Cell-edge user throughput for Sub-Urban user

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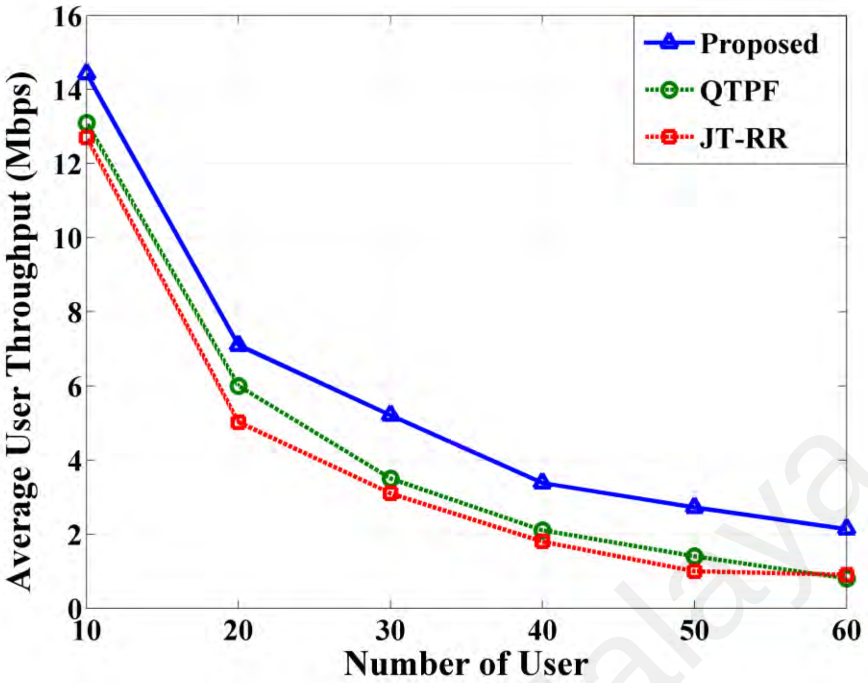

Figure 4.36: Average user throughput for Sub-Urban user

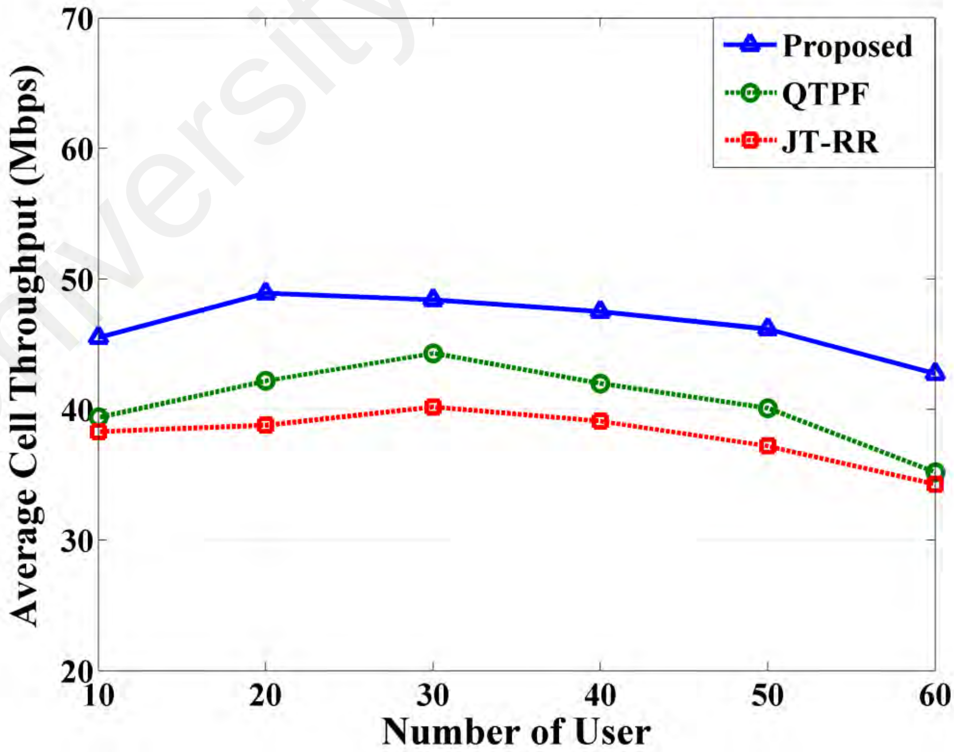

Figure 4.37: Average cell throughput for Sub-Urban user

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The overall spectral efficiency for the sub-urban user is shown in Figure 4.38. It is clear from the Figure 4.38 that the improvement of the proposed method is higher for a larger number of user due to the efficient RB and CC allocation, whereas the efficiency of other methods decreases sharply when a number of user increases. Although all methods allocate a similar number of RBs to the user as shown in Figure 4.40, QTPF and JT-RR methods have high packet loss and high data error rate which cause low throughput and low spectral efficiency.

Figure 4.39 shows that the fairness index of the proposed method is also higher than other existing methods. The overall improvement of the proposed method depicts in Table 4.10. The proposed method archives the highest improvement in cell-edge user throughput for deploying CoMP and CA to strengthen the received signal and to increase the bandwidth of cell-edge user.

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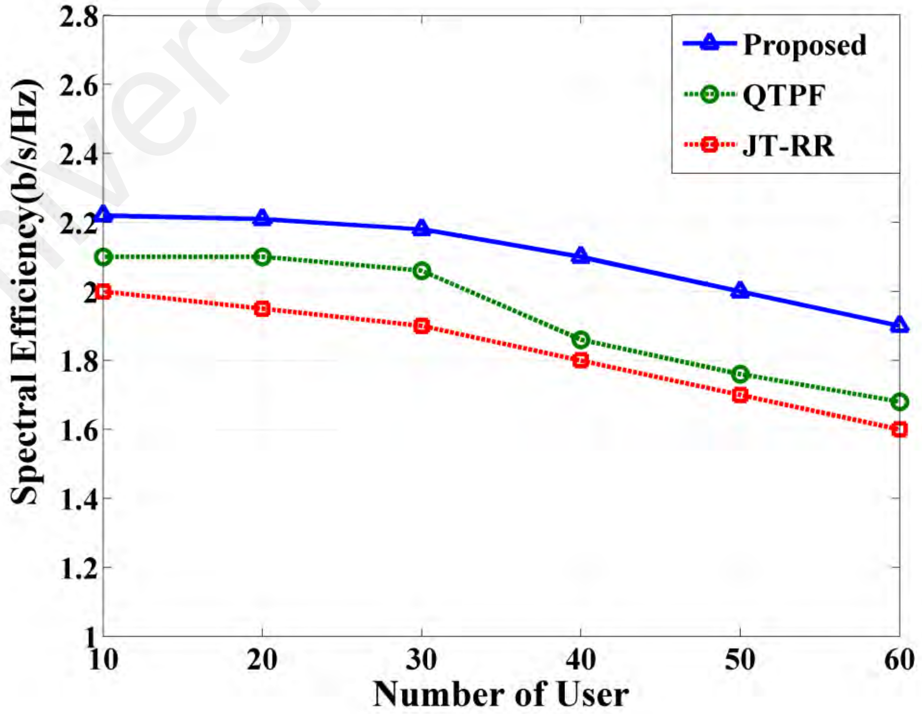

Figure 4.38: Spectral efficiency for the Sub-Urban user

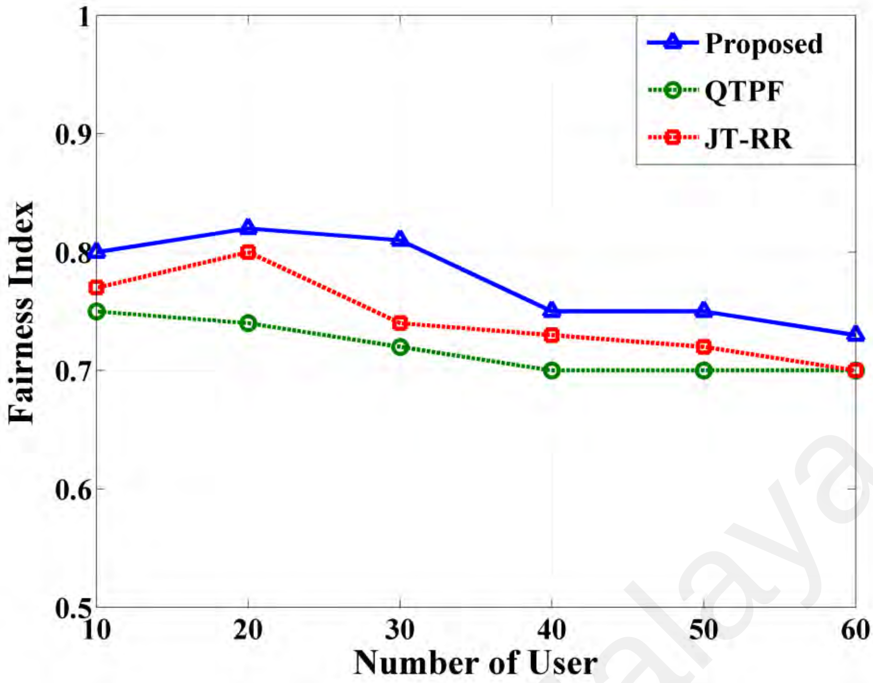

Figure 4.39: Fairness Index for Sub-Urban user

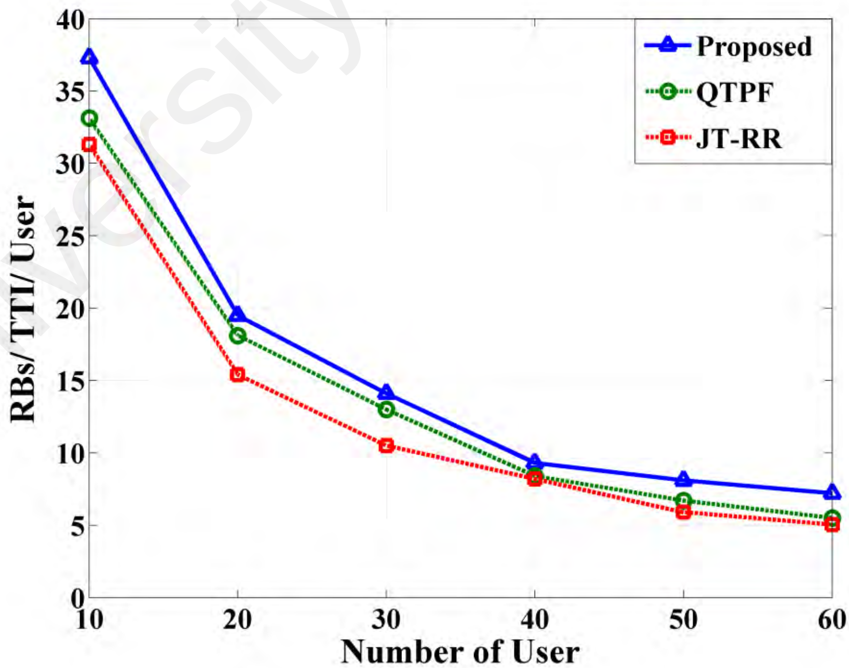

Figure 4.40: RBs per TTI per user for Sub-urban user

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Table 4.10: Improvement of the Proposed method for Suburban user

Parameters/ Algorithms	QTPF (%)	JT-RR (%)
Cell-edge Throughput	56.4	23.3
Average Throughput	34.4	41.6
Average Cell Throughput	13.7	19.0
Spectral Efficiency	8.5	13.3
Fairness Index	8.0	4.9
Allocate RBs/TTI/User	12.8	22.0

4.8 Performance Comparison of Individual Technologies

The approach of deploying different technologies affects the overall performance of the network. Therefore, this thesis compares the proposed method with other approaches. The simulation environment is similar to all these approaches to get the throughput. Figure 4.41 demonstrates that the proposed method which implements CoMP with CA achieves higher cell-edge throughput than the conventional CoMP without CA and CA without CoMP methods. Implementing the CA technique for the cell-edge user along with CoMP increases the number of allocated RBs and strengthens the desired signal by avoiding the interference from the adjacent cells. Moreover, the proposed method implements the effective eNB cooperation by considering queue length, and HOL delay for all CCs of each eNB. Thus, this approach improves the cell-edge user throughput. However, only increasing the bandwidth by using the CA technique cannot avoid the interference and unable to strengthen the received the signal. Furthermore, implementing CoMP technique alone without having efficient eNB cooperation method and without increasing the bandwidth provides insufficient RBs to enhance the user performance. Therefore, CoMP without CA achieves comparatively lower throughput than the other two approaches.

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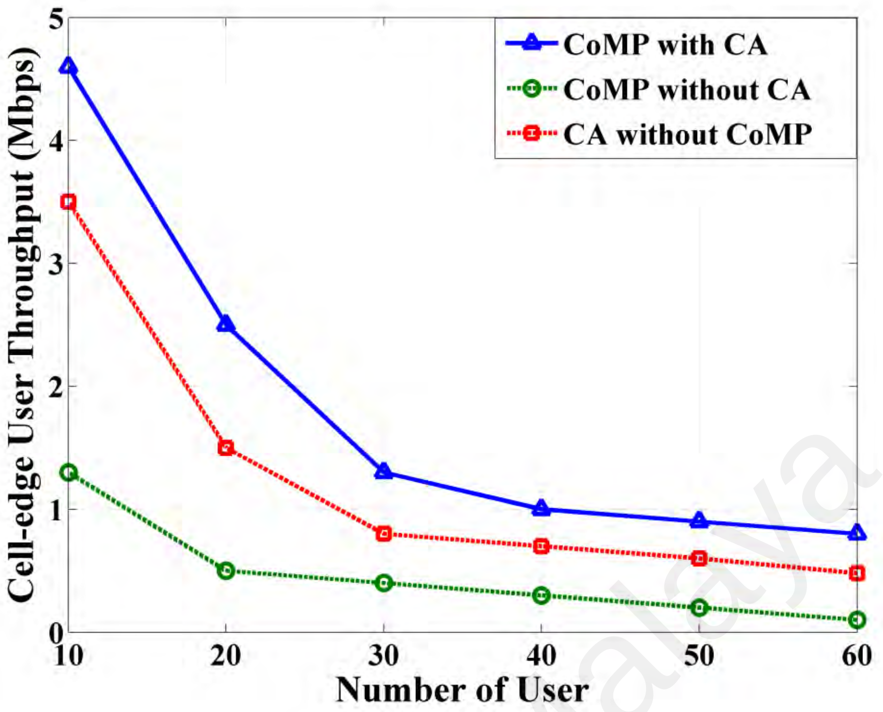

Figure 4.41: Cell-edge user throughput comparison for different technologies

4.9 Summary

This thesis deploys the proposed method along with QTPF and JT-RR methods to analyze the performance of different network loads, geographical areas, frequencies, user speeds, and technologies. Three types of network load are implemented and the proposed method improves its performance on an average of 46.1% and 37% regarding cell-edge user throughput; 18.4% and 25.8% regarding average user throughput higher than QTPF and JT-RR methods, respectively. Moreover, the performance of the proposed method has been analyzed in different user speeds and different frequencies. In three types of geographical areas, the average improvement of the proposed method is 52.7% and 37% regarding cell-edge user throughput; 22.13% and 27.67% regarding average user throughput compare to the QTPF and JT-RR methods, respectively which proves that it can be implemented in all scenarios. Furthermore, it is also proved from the obtained results that the proposed method which implements CoMP with CA performs better than implementing the individual method.

CHAPTER 5: CONCLUSION

5.1 Conclusion

This thesis investigates the problem of downlink radio resource management through CoMP and CA technique in LTE-A network. The problem involves with the selection of eNB with the corresponding CC and RB allocation of the selected CC according to the specific constraints. The main objectives of this work are to develop a method for implementing CoMP with CA for cell-edge user along with an efficient eNB coordination scheme, to design an efficient CC selection method with maximum 4 CCs for all users, and to implement MLWDF scheduling algorithm by considering delay parameters and probability of packet loss for CoMP and CA.

An improved method has been proposed for radio resource management which combines CoMP and CA based on an MLWDF packet scheduling algorithm. The adjacent cooperative eNBs transmit multiple CCs to the cell-edge user simultaneously to strengthen the received signal and to increase the channel bandwidth in the proposed network scenario whereas, the cell-center user has been allocated multiple CCs from the same attached eNB. The proposed method calculates the possible gain of all available CCs of the eNBs for all users and thus selects the eNB and the corresponding CC with the highest gain. The queue length of each CC from each cooperative eNB is considered while calculating the gain to balance the load among the CCs. The HOL delay, maximum delay budget, and the probability of packet loss are also considered during the RB allocation process. The probability of packet loss is estimated by the two-state model. Error probability and the probability of failure state to success state are used to calculate the probability of packet loss.

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The proposed method has been deployed in various simulation plots such as different traffic scenarios, user speeds, frequency bands, geographical areas, and technologies. QTPF and JT-RR scheduling approaches are also implemented to compare the performance with the proposed method. The obtained results from different traffic scenarios indicate that the proposed method performs on an average 41.5% and 22.1% higher than the existing methods regarding cell-edge user throughput and average user throughput, respectively. The performance of the proposed method also has been analyzed in different user speeds and different frequency sets. The simulation results of different geographical areas show that the proposed method achieves 44.9% higher in cell-edge user throughput and 24.9% higher in average user throughput than the other methods. The proposed method maintains the fairness among users while ensuring higher spectral efficiency in all simulation plots. It is also clear that CoMP with CA method achieves higher throughput than the individual method.

In summary, the proposed method which implements CoMP and CA technique with efficient eNB coordination scheme, CC selection method and MLWDF algorithm enhance the user throughputs as well as the overall system performance.

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5.2 Implementation and Future Work

This thesis proposed the resource allocation method for CoMP and CA which can be implemented in current LTE system to convert it into LTE-A as well as in the future 5G mobile communication system. Since the future 5G system might have small cell size, it will be useful to use the proposed method to combine the CoMP and CA (Gupta & Jha, 2015; Parvez, Rahmati, Guvenc, Sarwat, & Dai, 2018).

The enhanced Multiple input multiple outputs (MIMO) with CoMP technique can be included with the proposed method of this thesis for further improvement as a future work (Khawar, Abdelhadi, & Clancy, 2018). The enhanced MIMO technology such as massive MIMO (Hien Quoc Ngo, Ashikhmin, Yang, Larsson, & Marzetta, 2017; Prasad, Hossain, & Bhargava, 2017) and full-dimensional MIMO (FD MIMO) (Ji et al., 2017) with multiple dedicated antenna for each user can boost the received signal strength and the capacity of the cell thus, it can improve the overall performance of all users.

The signaling overhead for centralized cooperative CoMP communication among eNBs can be reduced by using an efficient and reliable backhaul protocol. The enhanced backhaul protocol can shorten the response time during the scheduling process which can increase the overall system performance (Marotta et al., 2017).

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Reference

3GPP, C. M., KPN, NTT DoCoMo, Sprint, T Mobile, Vodafone, Telecom Italia. (2007). Lte physical layer framework for performance verification, 3GPP Tech. Rep. TSG-RAN1, R1-070674. 3rd Generation Partnership Project (3GPP), Valbonne, France.

4G Mobile Broadband Evolution Release 11 & Release 12 and Beyond, Tec. Rep. FINAL v2. (February, 2014). Retrieved from 4G Americas, Bellevue, WA, USA: http://www.5gamericas.org/files/2614/0758/7473/4G_Mobile_Broadband_Evolution_Rel-11__Rel_12_and_Beyond_Feb_2014_-_FINAL_v2.pdf

Abdelaal, R. A., Elsayed, K. M., & Ismail, M. H. (2015). Optimized Joint Power and Resource Allocation for Coordinated Multi-point Transmission for Multi-user LTE-Advanced Systems. *Wireless personal communications, 83*(4), 2497-2518.

Agrawal, R., Bedekar, A., Gupta, R., Kalyanasundaram, S., Kroener, H., & Natarajan, B. (2014). *Dynamic point selection for LTE-advanced: algorithms and performance.* Paper presented at the Wireless Communications and Networking Conference (WCNC), 2014 IEEE.

Ahmadi, S. (2013). *LTE-Advanced: a practical systems approach to understanding 3GPP LTE releases 10 and 11 radio access technologies*: Academic Press.

Akyildiz, I. F., Gutierrez-Estevez, D. M., Balakrishnan, R., & Chavarria-Reyes, E. (2014). LTE-Advanced and the evolution to Beyond 4G (B4G) systems. *Physical Communication, 10*, 31-60.

Akyildiz, I. F., Gutierrez-Estevez, D. M., & Reyes, E. C. (2010). The evolution to 4G cellular systems: LTE-Advanced. *Physical Communication, 3*(4), 217-244.

Ali, M. S., & Synthia, M. (2015). *Performance analysis of JT-CoMP transmission In Heterogeneous Network over unreliable backhaul.* Paper presented at the Electrical Engineering and Information Communication Technology (ICEEICT), 2015 International Conference on.

Ameigeiras, P., Wigard, J., & Mogensen, P. (2004). *Performance of the M-LWDF scheduling algorithm for streaming services in HSDPA.* Paper presented at the Vehicular technology conference, 2004. VTC2004-Fall. 2004 IEEE 60th.

Anchora, L., Canzian, L., Badia, L., & Zorzi, M. (2010). *A characterization of resource allocation in LTE systems aimed at game theoretical approaches.* Paper presented at the 2010 15th IEEE International Workshop on Computer Aided Modeling, Analysis and Design of Communication Links and Networks (CAMAD).

Andersen, J. B., Rappaport, T. S., & Yoshida, S. (1995). Propagation measurements and models for wireless communications channels. *IEEE Communications magazine, 33*(1), 42-49.

University of Malaya

Andrews, M., Kumaran, K., Ramanan, K., Stolyar, A., Whiting, P., & Vijayakumar, R. (2001). Providing quality of service over a shared wireless link. *IEEE Communications magazine, 39*(2), 150-154.

Aragon-Zavala, A. (2008). *Antennas and propagation for wireless communication systems*: John Wiley & Sons.

Baker, M. (2012). From LTE-advanced to the future. *IEEE Communications magazine, 50*(2).

Basukala, R., Mohd Ramli, H., & Sandrasegaran, K. (2009). *Performance analysis of EXP/PF and M-LWDF in downlink 3GPP LTE system.* Paper presented at the Internet, 2009. AH-ICI 2009. First Asian Himalayas International Conference on.

Bhat, P., Nagata, S., Campoy, L., Berberana, I., Derham, T., Liu, G., . . . Yang, J. (2012). LTE-advanced: an operator perspective. *IEEE Communications magazine, 50*(2).

Boudreau, G., Panicker, J., Guo, N., Chang, R., Wang, N., & Vrzic, S. (2009). Interference coordination and cancellation for 4G networks. *IEEE Communications magazine, 47*(4).

Boujelben, M., Benrejeb, S., & Tabbane, S. (2014). Interference coordination schemes for wireless mobile advanced systems: a survey. *arXiv preprint arXiv:1403.3818*.

Brueck, S., Zhao, L., Giese, J., & Amin, M. A. (2010). *Centralized scheduling for joint transmission coordinated multi-point in LTE-Advanced.* Paper presented at the Smart Antennas (WSA), 2010 International ITG Workshop on.

Capozzi, F., Piro, G., Grieco, L. A., Boggia, G., & Camarda, P. (2013). Downlink packet scheduling in LTE cellular networks: Key design issues and a survey. *Communications Surveys & Tutorials, IEEE, 15*(2), 678-700.

Chand, P., Mahapatra, R., & Prakash, R. (2016). Energy efficient radio resource management for heterogeneous wireless network using CoMP. *Wireless Networks, 22*(4), 1093-1106.

Checko, A., Christiansen, H. L., Yan, Y., Scolari, L., Kardaras, G., Berger, M. S., & Dittmann, L. (2015). Cloud RAN for mobile networks—a technology overview. *IEEE Communications surveys & tutorials, 17*(1), 405-426.

Cheng, X., Gupta, G., & Mohapatra, P. (2013). *Joint carrier aggregation and packet scheduling in LTE-Advanced networks.* Paper presented at the Sensor, Mesh and Ad Hoc Communications and Networks (SECON), 2013 10th Annual IEEE Communications Society Conference on.

Choi, J.-G., & Bahk, S. (2007). Cell-throughput analysis of the proportional fair scheduler in the single-cell environment. *Vehicular Technology, IEEE Transactions on, 56*(2), 766-778.

Chung, W.-C., Chang, C.-J., & Teng, H.-Y. (2014). A green radio resource allocation scheme for LTE-A downlink systems with CoMP transmission. *Wireless Networks, 20*(6), 1409-1420.

University of Malaya

Chunye, W., Peter, S., & Zhang, L. (2012). *Performance analysis of Dynamic Point Selection in system level simulation.* Paper presented at the Communications and Networking in China (CHINACOM), 2012 7th International ICST Conference on.

Circuit Switched (CS) Fallback in Evolved Packet System (EPS); Stage 2, Release 11. (September 2012). (Vol. Technical Script 23.272): 3rd Generation Partnership Project (3GPP), Valbonne, France.

Coletti, C., Mogensen, P., & Irmer, R. (2011). *Performance analysis of relays in LTE for a realistic suburban deployment scenario.* Paper presented at the Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd.

Colombo, C., & Cirigliano, M. (2011). Next-generation access network: A wireless network using E-band Radio frequency (71–86 Ghz) to provide wideband connectivity. *Bell Labs Technical Journal, 16*(1), 187-205.

Correia, L. M. (2009). *A view of the COST 231-Bertoni-Ikegami model.* Paper presented at the Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conference on.

Cox, C. (2012). *An introduction to LTE: LTE, LTE-advanced, SAE and 4G mobile communications*: John Wiley & Sons.

Dahlman, E., Gudmundson, B., Nilsson, M., & Skold, A. (1998). UMTS/IMT-2000 based on wideband CDMA. *IEEE Communications magazine, 36*(9), 70-80.

Dahlman, E., Parkvall, S., & Skold, J. (2013). *4G: LTE/LTE-advanced for mobile broadband*: Academic press.

Damosso, E. (1999). *Digital mobile radio towards future generation systems: COST action 231*: European Commission.

Elfadil, H. E., Ali, M. A. I., & Abas, M. (2015). *Performance evaluation of joint processing coordinated multipoint transmission in LTE networks.* Paper presented at the Computing, Control, Networking, Electronics and Embedded Systems Engineering (ICCNEEE), 2015 International Conference on.

Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (Release 11). (December 2012). (Vol. TS 36.300). 3rd Generation Partnership Project (3GPP), Valbonne, France.

Evolved Universal Terrestrial Radio Access (E-UTRA), Physical Layer Procedures. (September 2012). (Vol. TS 36.213 V11.0.0). 3rd Generation Partnership Project (3GPP), Valbonne, France.

Fu, S., Wen, H., Wu, J., & Wu, B. (2015). Energy-Efficient Precoded Coordinated Multi-Point Transmission With Pricing Power Game Mechanism. *IEEE Systems Journal*(99), 1-10. doi:10.1109/JSYST.2015.2464218

University of Malaya

Fu, S., Wu, B., Wen, H., Ho, P.-H., & Feng, G. (2014). Transmission scheduling and game theoretical power allocation for interference coordination in CoMP. *IEEE Transactions on Wireless Communications, 13*(1), 112-123.

Fu, W., Kong, Q., Zhang, Y., & Yan, X. (2013, 16-18 May 2013). *A resource scheduling algorithm based on carrier weight in LTE-Advanced system with Carrier Aggregation.* Paper presented at the 2013 22nd Wireless and Optical Communication Conference.

Further advancements for E-UTRA physical layer aspects. (2010). (Vol. TR 36.814): 3rd Generation Partnership Project (3GPP), Valbonne, France.

Future spectrum requirements estimate for terrestrial IMT. (December, 2013). (Vol. ITU-R M.2290-0). ITU, Geneva.

General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access. (December 2011). (Vol. TS 23.401 V10.6.0). 3rd Generation Partnership Project (3GPP), Valbonne, France.

Ghosh, A., & Ratasuk, R. (2011). *Essentials of LTE and LTE-A*: Cambridge University Press.

Ginting, D., Fahmi, A., & Kurniawan, A. (2015). *Performance evaluation of inter-cell interference of LTE-A system using carrier aggregation and CoMP techniques.* Paper presented at the 2015 9th International Conference on Telecommunication Systems Services and Applications (TSSA).

Gupta, A., & Jha, R. K. (2015). A survey of 5G network: Architecture and emerging technologies. *IEEE Access, 3*, 1206-1232.

Heuveldop, N. (June 2017). *Ericsson Mobility Report*. Retrieved from Stockholm, Sweden,: https://www.ericsson.com/assets/local/mobility-report/documents/2017/ericsson-mobility-report-june-2017.pdf

Hosein, P. (2008). *Cooperative scheduling of downlink beam transmissions in a cellular network.* Paper presented at the GLOBECOM Workshops, 2008 IEEE.

Hunukumbure, M., & Vadgama, S. (2013). *Improving cell edge energy efficiency through CoMP beam-forming.* Paper presented at the Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th.

Huq, K. M. S., Mumtaz, S., Bachmatiuk, J., Rodriguez, J., Wang, X., & Aguiar, R. L. (2015). Green HetNet CoMP: Energy efficiency analysis and optimization. *IEEE Transactions on Vehicular Technology, 64*(10), 4670-4683.

Huq, K. M. S., Mumtaz, S., Rodriguez, J., & Aguiar, R. L. (2014). A novel energy efficient packet-scheduling algorithm for CoMP. *Computer Communications, 50*, 53-63.

Ikegami, F., Takeuchi, T., & Yoshida, S. (1991). Theoretical prediction of mean field strength for urban mobile radio. *IEEE Transactions on antennas and propagation, 39*(3), 299-302.

University of Malaya

International Telecommunication Union Guidelines for Evaluation of Radio Interface Technologies for IMT-Advanced. (2008). *ITU report* (Vol. ITU-R M.2135).

International Telecommunication Union Requirements Related to Technical Performance for IMT-Advanced Radio Interface(s). (2008). *ITU report* (Vol. ITU-R M.2134).

International Telecommunication Union Requirements, Evaluation Criteria and Submission Templates for the Development of IMT-Advanced. (2008). *ITU report* (Vol. ITU-R M.2134).

Irmer, R., Droste, H., Marsch, P., Grieger, M., Fettweis, G., Brueck, S., . . . Jungnickel, V. (2011). Coordinated multipoint: Concepts, performance, and field trial results. *IEEE Communications magazine, 49*(2), 102-111.

ITU-R, R. (2015). *Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300MHz and 100GHz*. Retrieved from https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.1411-6-201202-S!!PDF-E.pdf

Iwamura, M., Etemad, K., Fong, M.-H., Nory, R., & Love, R. (2010). Carrier aggregation framework in 3GPP LTE-advanced [WiMAX/LTE Update]. *IEEE Communications magazine, 48*(8).

Jain, R., Chiu, D.-M., & Hawe, W. R. (1984). *A quantitative measure of fairness and discrimination for resource allocation in shared computer system* (Vol. 38): Eastern Research Laboratory, Digital Equipment Corporation Hudson, MA.

Ji, H., Kim, Y., Lee, J., Onggosanusi, E., Nam, Y., Zhang, J., . . . Shim, B. (2017). Overview of full-dimension MIMO in LTE-advanced pro. *IEEE Communications magazine, 55*(2), 176-184.

Jia, J., Deng, Y., Chen, J., Aghvami, A. H., & Nallanathan, A. (2017). Availability Analysis and Optimization in CoMP and CA-enabled HetNets. *IEEE Transactions on Communications*.

Khawar, A., Abdelhadi, A., & Clancy, T. C. (2018). Coloacted MIMO Radar and CoMP Cellular System *Spectrum Sharing Between Radars and Communication Systems* (pp. 39-74): Springer.

Lee, D., Seo, H., Clerckx, B., Hardouin, E., Mazzarese, D., Nagata, S., & Sayana, K. (2012). Coordinated multipoint transmission and reception in LTE-advanced: deployment scenarios and operational challenges. *IEEE Communications magazine, 50*(2), 148-155.

Lee, H., Vahid, S., & Moessner, K. (2014). A survey of radio resource management for spectrum aggregation in LTE-advanced. *Communications Surveys & Tutorials, IEEE, 16*(2), 745-760.

Lee, K. K., & Chanson, S. T. (2002). Packet loss probability for real-time wireless communications. *Vehicular Technology, IEEE Transactions on, 51*(6), 1569-1575.

University of Malaya

Lee, W. C. (1990). Estimate of channel capacity in Rayleigh fading environment. *IEEE Transactions on Vehicular Technology, 39*(3), 187-189.

Li, J., Peng, M., Cheng, A., Yu, Y., & Wang, C. (2014). Resource Allocation Optimization for Delay-Sensitive Traffic in Fronthaul Constrained Cloud Radio Access Networks. *IEEE Systems Journal*(99), 1-12. doi:10.1109/jsyst.2014.2364252

Li, Q., Hu, R. Q., Qian, Y., & Wu, G. (2012). Cooperative communications for wireless networks: techniques and applications in LTE-advanced systems. *IEEE Wireless Communications, 19*(2).

Li, Z., Liu, Y., Zhang, Y., & Wu, W. (2016). Downlink CoMP resource allocation based on limited backhaul capacity. *China Communications, 13*(4), 38-48.

Liao, H.-S., Chen, P.-Y., & Chen, W.-T. (2014). An efficient downlink radio resource allocation with carrier aggregation in LTE-advanced networks. *IEEE Transactions on Mobile Computing, 13*(10), 2229-2239.

Lin, X., Andrews, J. G., & Ghosh, A. (2013). Modeling, analysis and design for carrier aggregation in heterogeneous cellular networks. *IEEE Transactions on Communications, 61*(9), 4002-4015.

Liu, L., Li, M., Zhou, J., She, X., Chen, L., Sagae, Y., & Iwamura, M. (2011). *Component carrier management for carrier aggregation in LTE-advanced system.* Paper presented at the Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd.

Long Term Evolution Protocol Overview. (October, 2008). (Vol. LTEPTCLOVWWP, Rev 0): Freescale Semiconductor, Inc. White paper.

López-Pérez, D., Guvenc, I., & Chu, X. (2012). *Theoretical analysis of handover failure and ping-pong rates for heterogeneous networks.* Paper presented at the Communications (ICC), 2012 IEEE International Conference on.

LTE Carrier Aggregation Technology Development and Deployment Worldwide, . (October 2014). Retrieved from http://www.4gamericas.org/files/8414/1471/2230/4G_Americas_Carrier_Aggregation_FINALv1_0_3.pdf

LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios, 3GPP TR 136.942 V9.0.1 Release 9. (2010). Retrieved from http://www.etsi.org/deliver/etsi_tr/136900_136999/136942/09.00.01_60/tr_136942v090001p.pdf

Lu, L., Li, G. Y., Swindlehurst, A. L., Ashikhmin, A., & Zhang, R. (2014). An overview of massive MIMO: Benefits and challenges. *IEEE journal of selected topics in signal processing, 8*(5), 742-758.

Lucent, A. (2009). The LTE network Architecture—A comprehensive tutorial. *Strategic Whitepaper*.

University of Malaya

Määttänen, H.-L., Hämäläinen, K., Venäläinen, J., Schober, K., Enescu, M., & Valkama, M. (2012). System-level performance of LTE-Advanced with joint transmission and dynamic point selection schemes. *EURASIP Journal on Advances in Signal Processing, 2012*(1), 1-18.

Mahmud, A., Hamdi, K. A., & Ramli, N. (2014). *Performance of fractional frequency reuse with comp at the cell-edge.* Paper presented at the Region 10 Symposium, 2014 IEEE.

Marotta, A., Giannone, F., Kondepu, K., Cassioli, D., Antonelli, C., Valcarenghi, L., & Castoldi, P. (2017). *Reducing CoMP control message delay in PON backhauled 5G networks.* Paper presented at the European Wireless 2017; 23th European Wireless Conference; Proceedings of.

Marsch, P., & Fettweis, G. P. (2011). *Coordinated Multi-Point in Mobile Communications: from theory to practice*: Cambridge University Press.

Marzetta, T. L. (2010). Noncooperative cellular wireless with unlimited numbers of base station antennas. *Wireless Communications, IEEE Transactions on, 9*(11), 3590-3600.

Medium Access Control (MAC) Protocol Specification, Release 11. (July 2013). (Vol. Technical Script 36.321): 3rd Generation Partnership Project (3GPP), Valbonne, France.

Meucci, F., Cabral, O., Velez, F. J., Mihovska, A., & Prasad, N. R. (2009). *Spectrum aggregation with multi-band user allocation over two frequency bands.* Paper presented at the Mobile WiMAX Symposium, 2009. MWS'09. IEEE.

Miao, G., Zander, J., Sung, K. W., & Slimane, S. B. (2016). *Fundamentals of Mobile Data Networks*: Cambridge University Press.

Miki, N., Iwamura, M., Kishiyama, Y., Anil, U., & Ishii, H. (2010). CA for bandwidth extension in LTE-advanced. *NTT Docomo Technical Journal, 12*(2), 10-19.

Mobile Spectrum Requirement Estimates: Getting The Inputs Right. (August 2014). Retrieved from Lichtenau, Germany,: http://www.lstelcom.com/fileadmin/content/marketing/Press_releases/IMT_Spectrum_Requirements_Final_Report_v107.pdf

Mosleh, S., Liu, L., & Zhang, C. (2016). Proportional-Fair Resource Allocation for Coordinated Multi-Point (CoMP) Transmission in LTE-Advanced. *IEEE Transactions on Wireless Communications, 15*(8), 5355 - 5367. doi:10.1109/TWC.2016.2557328

Mouly, M., Pautet, M.-B., & Foreword By-Haug, T. (1992). *The GSM system for mobile communications*: Telecom publishing.

Nasralla, M. M., Hewage, C. T., & Martini, M. G. (2014). *Subjective and objective evaluation and packet loss modeling for 3D video transmission over LTE networks.* Paper presented at the Telecommunications and Multimedia (TEMU), 2014 International Conference on.

University of Malaya

Network Architecture, Release 11, Section 4.1.4. (June 2013). (Vol. Technical Script 23.002). 3rd Generation Partnership Project (3GPP), Valbonne, France.

Ngo, H. Q., Ashikhmin, A., Yang, H., Larsson, E. G., & Marzetta, T. L. (2017). Cell-free massive MIMO versus small cells. *IEEE Transactions on Wireless Communications, 16*(3), 1834-1850.

Ngo, H. Q., Marzetta, T. L., & Larsson, E. G. (2011). *Analysis of the pilot contamination effect in very large multicell multiuser MIMO systems for physical channel models.* Paper presented at the Acoustics, Speech and Signal Processing (ICASSP), 2011 IEEE International Conference on.

Okamawari, T., Zhang, L., Nagate, A., Hayashi, H., & Fujii, T. (2011). *Design of Control Architecture for Downlink CoMP Joint Transmission with Inter-eNB Coordination in Next Generation Cellular Systems.* Paper presented at the Vehicular Technology Conference (VTC Fall), 2011 IEEE.

Osseiran, A. (2011). *Mobile and wireless communications for IMT-advanced and beyond*: John Wiley & Sons.

Packet Data Convergence Protocol (PDCP) Specification, Release 11. (March 2013). (Vol. Technical Script 36.323): 3rd Generation Partnership Project (3GPP), Valbonne, France.

Park, S. Y., Choi, J., & Love, D. J. (2014). Multicell cooperative scheduling for two-tier cellular networks. *IEEE Transactions on Communications, 62*(2), 536-551.

Parvez, I., Rahmati, A., Guvenc, I., Sarwat, A. I., & Dai, H. (2018). A survey on low latency towards 5G: RAN, core network and caching solutions. *IEEE Communications surveys & tutorials*.

Pateromichelakis, E., Shariat, M., ul Quddus, A., & Tafazolli, R. (2013). On the evolution of multi-cell scheduling in 3GPP LTE/LTE-A. *IEEE Communications surveys & tutorials, 15*(2), 701-717.

Pedersen, K. I., Frederiksen, F., Rosa, C., Nguyen, H., Garcia, L. G. U., & Wang, Y. (2011). Carrier aggregation for LTE-advanced: functionality and performance aspects. *IEEE Communications magazine, 49*(6).

Peng, M., Li, Y., Jiang, J., Li, J., & Wang, C. (2014). Heterogeneous cloud radio access networks: a new perspective for enhancing spectral and energy efficiencies. *IEEE Wireless Communications, 21*(6), 126-135.

Physical Channels and Modulation, Release 11, Section 4,. (September 2013). (Vol. Technical Script 36.211). 3rd Generation Partnership Project (3GPP), Valbonne, France.

Physical Channels and Modulation, Release 11, Sections 5.2, 6.2. (September 2013). (Vol. Technical Script 36.211). 3rd Generation Partnership Project (3GPP), Valbonne, France.

University of Malaya

Physical Channels and Modulation, Release 11, Sections 5.6, 6.12. (September 2013). (Vol. Technical Script 36.211): 3rd Generation Partnership Project (3GPP), Valbonne, France.

Physical layer aspects for evolved Universal Terrestrial Radio Access (UTRA), 3GPP TR 25.814 V7.1.0. (September 2006). Retrieved from http://www.qtc.jp/3GPP/Specs/25814-710.pdf

Prasad, K. S. V., Hossain, E., & Bhargava, V. K. (2017). Energy Efficiency in Massive MIMO-Based 5G Networks: Opportunities and Challenges. *IEEE Wireless Communications*.

Qamar, F., Dimyati, K. B., Hindia, M. N., Noordin, K. A. B., & Al-Samman, A. M. (2017). A Comprehensive Review on Coordinated Multi-Point Operation for LTE-A. *Computer Networks*.

Radio Link Control (RLC) Protocol Specification, Release 11,. (September 2012). (Vol. Technical Script 36.322): 3rd Generation Partnership Project (3GPP), Valbonne, France.

Radio Resource Control (RRC); Protocol Specification, Release 11. (September 2013). (Vol. Technical Script 36.331): 3rd Generation Partnership Project (3GPP), Valbonne, France.

Ragaleux, A., Baey, S., & Gueguen, C. (2016). Adaptive and generic scheduling scheme for lte/lte-a mobile networks. *Wireless Networks, 22*(8), 2753-2771.

Ramazanali, H., Mesodiakaki, A., Vinel, A., & Verikoukis, C. (2016). *Survey of user association in 5G HetNets.* Paper presented at the Communications (LATINCOM), 2016 8th IEEE Latin-American Conference on.

Ramos-Cantor, O. D., Belschner, J., Hegde, G., & Pesavento, M. (2017). Centralized coordinated scheduling in LTE-Advanced networks. *EURASIP Journal on Wireless Communications and Networking, 2017*(1), 122. doi:10.1186/s13638-017-0904-5

Rappaport, T. S. (1996). *Wireless communications: principles and practice* (Vol. 2): prentice hall PTR New Jersey.

Requirements for Further Advancements for Evolved Universal Terrestrial Radio Access (E-UTRA) (LTE-Advanced). (September 2012). (Vol. Technical Report 36.913 V11.0.0). 3rd Generation Partnership Project (3GPP), Valbonne, France.

Rhee, J.-H., Holtzman, J. M., & Kim, D.-K. (2003). *Scheduling of real/non-real time services: adaptive EXP/PF algorithm.* Paper presented at the Vehicular Technology Conference, 2003. VTC 2003-Spring. The 57th IEEE Semiannual.

Rhee, J.-H., Holtzman, J. M., & Kim, D. K. (2004). Performance analysis of the adaptive EXP/PF channel scheduler in an AMC/TDM system. *IEEE Communications letters, 8*(8), 497-499.

University of Malaya

Roessler, J. (2015). LTE-Advanced (3GPP Rel. 12) Technology Introduction White Paper. *München: Application Note-1MA252-Rohde & Schwarz International*.

Rumney, M. (2013). *LTE and the evolution to 4G wireless: Design and measurement challenges*: John Wiley & Sons.

Rupp, M., Schwarz, S., & Taranetz, M. (2016). *The Vienna LTE-Advanced Simulators*: Springer.

Rusek, F., Persson, D., Lau, B. K., Larsson, E. G., Marzetta, T. L., Edfors, O., & Tufvesson, F. (2013). Scaling up MIMO: Opportunities and challenges with very large arrays. *Signal Processing Magazine, IEEE, 30*(1), 40-60.

S. Songsong, F. C., G. Caili. (2009). *A resource scheduling algorithm based on user grouping for lte-advanced system with carrier aggregation.* Paper presented at the Int. Symp. Comput. Netw. and Multimedia Technology CNMT 2009.

Sadiq, B., Baek, S. J., & De Veciana, G. (2011). Delay-optimal opportunistic scheduling and approximations: The log rule. *IEEE/ACM Transactions on Networking (TON), 19*(2), 405-418.

Sadiq, B., Madan, R., & Sampath, A. (2009). Downlink scheduling for multiclass traffic in LTE. *EURASIP Journal on Wireless Communications and Networking, 2009*(1), 510617.

Sawahashi, M., Kishiyama, Y., Morimoto, A., Nishikawa, D., & Tanno, M. (2010). Coordinated multipoint transmission/reception techniques for LTE-advanced [Coordinated and Distributed MIMO]. *IEEE Wireless Communications, 17*(3), 26-34.

Service Requirements for the Evolved Packet System (EPS), Release 11. (September 2012). (Vol. Technical Script 22.278). 3rd Generation Partnership Project (3GPP), Valbonne, France.

Shakkottai, S., & Stolyar, A. L. (2002). Scheduling for multiple flows sharing a time-varying channel: The exponential rule. *Translations of the American Mathematical Society-Series 2, 207*, 185-202.

Shannon, C. E., & Weaver, W. (1949). *The mathematical theory of communication*: University of Illinois press.

Shen, Z., Papasakellariou, A., Montojo, J., Gerstenberger, D., & Xu, F. (2012). Overview of 3GPP LTE-advanced carrier aggregation for 4G wireless communications. *IEEE Communications magazine, 50*(2).

Singh, D. (2013). Performance Analysis of QOS-aware Resource Scheduling Strategies in LTE Femtocell Networks. *INTERNATIONAL JOURNAL OF ENGINEERING TRENDS AND TECHNOLOGY, 1*(4), 2994-2999.

Sklar, B. (1997). Rayleigh fading channels in mobile digital communication systems. I. Characterization. *IEEE Communications magazine, 35*(9), 136-146.

University of Malaya

Songsong, S., Chunyan, F., & Caili, G. (2009). *A resource scheduling algorithm based on user grouping for LTE-advanced system with carrier aggregation.* Paper presented at the Computer Network and Multimedia Technology, 2009. CNMT 2009. International Symposium on.

Stolyar, A. L., & Ramanan, K. (2001). Largest weighted delay first scheduling: Large deviations and optimality. *Annals of Applied Probability*, 1-48.

Sun, H., & Yang, T. (2015). *Performance Evaluation of Distributed Scheduling for Downlink Coherent Joint Transmission.* Paper presented at the Vehicular Technology Conference (VTC Fall), 2015 IEEE 82nd.

Svedman, P., Wilson, S. K., Cimini, L. J., & Ottersten, B. (2007). Opportunistic beamforming and scheduling for OFDMA systems. *IEEE Transactions on Communications, 55*(5), 941-952.

Tanbourgi, R., Singh, S., Andrews, J. G., & Jondral, F. K. (2014). *Analysis of non-coherent joint-transmission cooperation in heterogeneous cellular networks.* Paper presented at the Communications (ICC), 2014 IEEE International Conference on.

Taranetz, M., Blazek, T., Kropfreiter, T., Müller, M. K., Schwarz, S., & Rupp, M. (2015). Runtime precoding: enabling multipoint transmission in LTE-advanced system-level simulations. *IEEE Access, 3*, 725-736.

Technical specification group radio access network; coordinated multi-point operation for LTE physical layer aspects (release 11). (2011). (Vol. Technical Report 36.819): 3rd Generation Partnership Project (3GPP), Valbonne, France.

Tian, H., Gao, S., Zhu, J., & Chen, L. (2011). *Improved component carrier selection method for non-continuous carrier aggregation in LTE-advanced systems.* Paper presented at the Vehicular Technology Conference (VTC Fall), 2011 IEEE.

Tran, T.-T., Shin, Y., & Shin, O.-S. (2012). Overview of enabling technologies for 3GPP LTE-advanced. *EURASIP Journal on Wireless Communications and Networking, 2012*(1), 54.

Vienna LTE-A simulators, Institute of Telecommunications, Vienna University of Technology, Austria. (2016). Retrieved from https://www.nt.tuwien.ac.at/research/mobile-communications/vienna-lte-a-simulators/

Walfisch, J., & Bertoni, H. L. (1988). A theoretical model of UHF propagation in urban environments. *IEEE Transactions on antennas and propagation, 36*(12), 1788-1796.

Wang, H., Rosa, C., & Pedersen, K. (2011). *Performance analysis of downlink inter-band carrier aggregation in LTE-advanced.* Paper presented at the Vehicular Technology Conference (VTC Fall), 2011 IEEE.

Wang, Q., Jiang, D., Jin, J., Liu, G., Yan, Z., & Yang, D. (2009). *Application of BBU+ RRU based CoMP system to LTE-Advanced.* Paper presented at the

University of Malaya

Communications Workshops, 2009. ICC Workshops 2009. IEEE International Conference on.

Wang, Y., Pedersen, K., Mogensen, P. E., & Sørensen, T. B. (2009). *Resource allocation considerations for multi-carrier LTE-Advanced systems operating in backward compatible mode.* Paper presented at the Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on.

Wang, Y., Pedersen, K., Sørensen, T. B., & Mogensen, P. E. (2010). Carrier load balancing and packet scheduling for multi-carrier systems. *Wireless Communications, IEEE Transactions on, 9*(5), 1780-1789.

Wang, Y., Yang, X., & Yang, L. (2015). *Dynamic CoMP configuration for OFDMA networks under different user traffic scenarios.* Paper presented at the Software, Telecommunications and Computer Networks (SoftCOM), 2015 23rd International Conference on.

Whitepaper on Spectrum. (February, 2013). Retrieved from Huawei, Shenzhen, P.R. China,: www.huawei.com/ilink/en/download/HW_204545

Wireless technology evolution towards 5G: 3gpp release 13 to release 15 and beyond. (February, 2017). Retrieved from http://www.5gamericas.org/files/6814/8718/2308/3GPP_Rel_13_15_Final_to_Upload_2.14.17_AB.pdf

Xiaoyong, W., Dengkun, X., & Xiaojun, J. (2009). *A norvel power allocation algorithm under CoMP with CA.* Paper presented at the Broadband Network & Multimedia Technology, 2009. IC-BNMT'09. 2nd IEEE International Conference on.

Yang, Y., Hu, H., Xu, J., & Mao, G. (2009). Relay technologies for WiMAX and LTE-advanced mobile systems. *IEEE Communications magazine, 47*(10).

Yu, J., & Yin, C. (2016). Block-level resource allocation with limited feedback in multicell cellular networks. *Journal of Communications and Networks, 18*(3), 420-428.

Yu, W., Kwon, T., & Shin, C. (2013). Multicell coordination via joint scheduling, beamforming, and power spectrum adaptation. *IEEE Transactions on Wireless Communications, 12*(7), 1-14.

Yuan, G., Zhang, X., Wang, W., & Yang, Y. (2010). Carrier aggregation for LTE-advanced mobile communication systems. *Communications Magazine, IEEE, 48*(2), 88-93.

Zhang, H., Liu, H., Jiang, C., Chu, X., Nallanathan, A., & Wen, X. (2015). A practical semidynamic clustering scheme using affinity propagation in cooperative picocells. *IEEE Transactions on Vehicular Technology, 64*(9), 4372-4377.

Zhang, L., Liu, F., Huang, L., & Wang, W. (2010). *Traffic load balance methods in the LTE-Advanced system with carrier aggregation.* Paper presented at the Communications, Circuits and Systems (ICCCAS), 2010 International Conference on.

University of Malaya

Zhao, F., Miao, Y., & Chen, H. (2016). Joint beamforming and power control for auction-based spectrum allocation in CoMP systems. *Ad Hoc Networks*.

Zhao, J., Quek, T. Q., & Lei, Z. (2013). Coordinated multipoint transmission with limited backhaul data transfer. *IEEE Transactions on Wireless Communications, 12*(6), 2762-2775.

Zhou, W., Chen, W., Tan, Z., Chen, S., & Zhang, Y. (2011). *A modified RR scheduling scheme based CoMP in LTE-A system*. Paper presented at the IET International Conference on Communication Technology and Application (ICCTA 2011).

University of Malaya

LIST OF PUBLISHED AND SUBMITTED JOURNAL PAPERS

1. **Hasibur Rashid Chayon**, K. Dimyati, H. Ramiah, and A. Reza, "An Improved Radio Resource Management with Carrier Aggregation in LTE Advanced," Applied Sciences, vol. 7, p. 394, 2017. (**Published in ISI Q2 Journal**)
2. **Hasibur Rashid Chayon**, K. Dimyati, H. Ramiah, and A. Reza, " Enhance Quality of Service of cell-edge user by extending Modified Largest Weighted Delay First algorithm in LTE network," Symmetry, vol. 9, p. 81, 2017. (**Published in ISI Q2 Journal**)
3. Hindia MN, Reza AW, Noordin KA, **Chayon MHR** “A Novel LTE Scheduling Algorithm for Green Technology in Smart Grid.” PLoS ONE 10(4): e0121901, 2015 doi:10.1371/journal.pone.0121901 (**Published in ISI Q1 Journal**)
4. **Hasibur Rashid Chayon**, K. Dimyati, and H. Ramiah, " Downlink Radio resource management through CoMP and Carrier aggregation for LTE-Advanced Network," PLoS ONE. (**Under review in IEEE Access**)

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LIST OF PRESENTED CONFERENCE PAPERS

1. **Hasibur Rashid Chayon**, Kaharudin Dimyati and Harikrishnan Ramiah, " An Efficient Packet Scheduling Algorithm to Improve the performance of Cell-edge user in LTE System", IEEE 13th Malaysia International Conference on Communications (MICC) 2017, Johor Bahru, Malaysia.
2. **Hasibur Rashid Chayon** and Harikrishnan Ramiah, "Key Challenges and Potential Applications of LTE-Advanced ", IEEE Conference on Systems, Process and Control (ICSPC 2017), Malacca, Malaysia. (**Best Paper Award**)

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