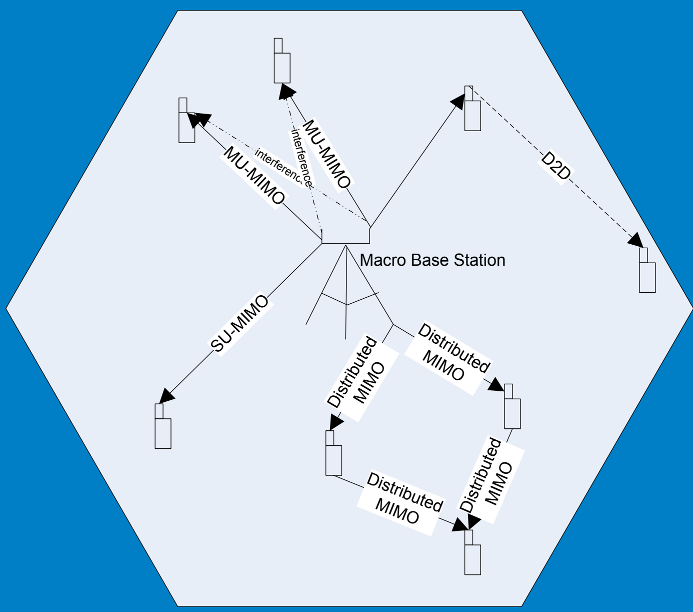
Department of Communications and Networking

Radio Resource Management for Efficient Deployment of Advanced Technologies with Evolution of LTE

Ankit Bhamri



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Radio Resource Management for Efficient Deployment of Advanced Technologies with Evolution of LTE

Ankit Bhamri

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Aalto University
School of Electrical Engineering
Department of Communications and Networking
Communications Engineering

Supervising professor
Prof. Jyri Hämäläinen, Aalto University, Finland

Thesis advisors
Prof. Florian Kaltenberger, Eurecom, France
Prof. Raymond Knopp, Eurecom, France

Preliminary examiners
Prof. Tapani Ristaniemi, University of Jyväskylä, Finland
Dr. Konstantinos Samdanis, Huawei, Germany

Opponent
Prof. Mohammed Elmusrati, University of Vaasa, Finland

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Abstract

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Ankit Bhamri

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Abstract

Cellular networks have been constantly evolving to improve the spectral efficiency of the system and provide high data rates. The third generation partnership Project (3GPP) introduced the long term evolution (LTE) standard with the primary aim of evolving the radio access technology and the system architecture. Since then, 3GPP LTE evolved to LTE-Advanced (LTE-A) to fulfill the requirements of international mobile telecommunications-advanced (IMT-A) set by international telecommunication union radio-communication sector (ITU-R), also defined as the fourth generation (4G) of mobile technology and recently, LTE-A has further evolved to LTE-A Pro. These markers are indications of major enhancements in the 3GPP LTE cellular networks. In order to enable this constant evolution, it is required to not only improve the existing features, but also introduce novel technologies. However, channelizing such new technologies from theoretical setup to more practical systems such as 3GPP LTE networks is quite non-trivial due to the strict constraints of the real-world.

The research work in this thesis deals with different aspects of radio resource management (RRM) to enable effective deployment of advanced wireless technologies with evolution of 3GPP LTE. The key contributions involve interference coordination in multi-user multiple input multiple output (MU-MIMO) system, fast synchronization to enable device-to-device (D2D), efficient resource allocation of control signaling in massive carrier aggregation (CA) and advanced medium access layer (MAC-layer) scheduling framework to deal with multi-user multi quality-of-service (multi-QoS) traffic conditions.

Extensive system and link level evaluations are conducted to examine the performance of proposed techniques in a 3GPP LTE and beyond framework and provide validation for applicability in industry.

Keywords 3GPP LTE, Carrier Aggregation, Device-to-Device, Hybrid-ARQ, Multi-user MIMO, Radio Resource Management, Scheduler

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Preface

The research work in this doctoral thesis has been conducted at the department of Communications and Networking at Aalto University School of Electrical Engineering, Finland, Mobile Communications department at Eurecom, France and at Nokia, Finland.

First of all, I would like to thank and express my sincere gratitude to Professor Jyri Hämäläinen at Aalto University, Finland for supervising me, extending his support and providing honest feedback during the entire tenure of my thesis. I really appreciate his guidance, help and patience in all matters related to the thesis. I would also like to thank Professor Florian Kaltenberger at Eurecom, France, without whom it would not have been possible to conduct and finish the majority of the research work in this thesis. He has always kept me motivated to continue and move forward by conducting good quality work. Moving ahead, I would like to express my sincere gratitude to Professor Raymond Knopp at Eurecom for providing me the opportunity to work with him. It has been one of the most fruitful experiences of working with him.

I would like to express my sincere gratitude to the pre-examiners Prof. Tapani Ristaniemi and Dr. Konstantinos Samdanis for their invaluable comments and recommendations for improving the quality of this thesis.

I am extremely thankful and feel fortunate to have worked along with some of the most experienced researchers in the field of communications and networking, with whom I had the opportunity to publish articles in reputed forums. I would like to extend my gratitude to all my co-authors including Professor Navid Nikaein at Eurecom; Dr. Kari Hooli, Timo Lunttila, Dr. Athul Prasad, Dr. Cassio Ribeiro, Dr. Zexian Li and Lars Lindh at Nokia.

I would specially like to thank Heikki Berg for providing me the opportunity to work at Nokia Research Center. I would also like to thank all my

other colleagues at Nokia, especially Johanna Pekonen, Karol Schober, Juha Heiskala, Dr. Panayiotis Papadimitriou and Juha Korhonen for their support. I would also like to thank all my colleagues at Eurecom, especially Dr. Imran Latif, Dr. Ngoc-Duy Nguyen, Dr. Tien Thinh Nguyen, Dr. Ayşe Ünsal and Dr. Tania Villa Trápala for their support and encouragement.

I also want to express my love and sincere gratitude to my parents and wife for their continuous support and motivation. They have always encouraged me to work towards the completion of my thesis. I would also like to thank all my friends and family for believing in me.

Helsinki, December 4, 2016,

Ankit Bhamri

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I A. Bhamri, J. Hämäläinen, F. Kaltenberger and R. Knopp. Minimizing the Effect of Feedback Delay in a Multi-User System through Adaptive Feedback Scheduling. In *2013 IEEE 78th Vehicular Technology Conference (VTC Fall)*, Las Vegas, USA, pp. 1 - 5, Sep. 2013.

II A. Bhamri, F. Kaltenberger, R. Knopp and J. Hämäläinen. Improving MU-MIMO Performance in LTE-(Advanced) by Efficiently Exploiting Feedback Resources and through Dynamic Scheduling. In *2013 IEEE Wireless Communications and Networking Conference (WCNC)*, Shanghai, China, pp. 563 - 567, April 2013.

III A. Bhamri, F. Kaltenberger, R. Knopp and J. Hämäläinen. Smart Hybrid-ARQ (SHARQ) for Cooperative Communication via Distributed Relays in LTE-advanced. In *2011 IEEE 12th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, San Francisco, USA, pp. 41 - 45, June 2011.

IV A. Bhamri, Z. Li, L. Lindh and C. Ribeiro. Primary Synchronization Signal Detection Method for Device-to-Device in LTE-Rel 12 and beyond. In *2015 IEEE 82nd Vehicular Technology Conference (VTC Fall)*, Boston, USA, pp. 1 - 5, Sep. 2015.

V A. Bhamri, K. Hooli and A. Prasad. Overview of Uplink Control Channel for Carrier Aggregation enhancements in LTE Rel. 13. In *2015 IEEE Conference on Standards for Communications and Networking (CSCN)*, Tokyo, Japan, pp. 78 - 82, Oct. 2015.

VI A. Bhamri, K. Hooli and T. Lunttila. Massive Carrier Aggregation in LTE –Advanced Pro: Impact on Uplink Control Information & Corresponding Enhancements. *IEEE Communications Magazine*, vol. 54, no. 5, pp. 92 - 97, May 2016.

VII A. Bhamri, N. Nikaein, F. Kaltenberger, J. Hämäläinen and R. Knopp. Pre-processor for MAC-layer Scheduler to Efficiently Manage Buffer in Modern Wireless Networks. In *2014 IEEE Wireless Communications and Networking Conference (WCNC)*, Istanbul, Turkey, pp. 1544 - 1549, April 2014.

VIII A. Bhamri, N. Nikaein, F. Kaltenberger, J. Hämäläinen and R. Knopp. Three-Step Iterative Scheduler for QoS Provisioning to Users Running Multiple Services in Parallel. In *2014 IEEE 79th Vehicular Technology Conference (VTC Spring)*, Seoul, South Korea, pp. 1 - 5, May 2014.

Author's Contribution

Publication I: "Minimizing the Effect of Feedback Delay in a Multi-User System through Adaptive Feedback Scheduling"

The author is the main contributor of this work, and with support from the other authors, has analytically derived the impact of feedback delay on the performance of moving users for closed-loop transmit beamforming and proposed velocity-based feedback scheduling algorithm for efficient utilization of resources.

Publication II: "Improving MU-MIMO Performance in LTE-(Advanced) by Efficiently Exploiting Feedback Resources and through Dynamic Scheduling"

The author is the main contributor of this work, and has developed a dynamic scheduling algorithm for MU-MIMO systems in 3GPP LTE, as well as implemented it in a system level simulator, with support from the other authors.

Publication III: "Smart Hybrid-ARQ (SHARQ) for Cooperative Communication via Distributed Relays in LTE-advanced"

The author is the main contributor of this work, and has developed hybrid automatic repeat request (HARQ) schemes for dual-hop relay network to optimize end-to-end performance and implemented the entire framework in a system level simulator, with support from other authors.

Publication IV: "Primary Synchronization Signal Detection Method for Device-to-Device in LTE-Rel 12 and beyond"

The author is the main contributor of this work, and proposed robust detection method for synchronization signals in D2D to enable faster acquisition of timing and frequency parameters, with support from other authors. The author is also resposible for link level analysis with relevant performance metrics for synchronization signal detection.

Publication V: "Overview of Uplink Control Channel for Carrier Aggregation enhancements in LTE Rel. 13"

The author is the main contributor of this work, and has analyzed the limitations of control signaling resources to support enhanced CA in LTE-A Pro, with support from other authors

Publication VI: "Massive Carrier Aggregation in LTE –Advanced Pro: Impact on Uplink Control Information & Corresponding Enhancements"

The author is the main contributor of this work, and with support from other authors, has investigated the possible enhancements for supporting large uplink control information to enable enhanced CA in LTE-A Pro. The author has also been responsible for investigating the link level performance of the proposed enhancements.

Publication VII: "Pre-processor for MAC-layer Scheduler to Efficiently Manage Buffer in Modern Wireless Networks"

The author is the main contributor of this work, and has developed a framework with pre-processor for MAC-layer scheduler including two-dimensional buffer management that enable more efficient allocation of resources to multiple users running multiple internet applications simultaneously, with support from other authors

Publication VIII: "Three-Step Iterative Scheduler for QoS Provisioning to Users Running Multiple Services in Parallel"

The author is the main contributor of this work, and has developed a three-step iterative downlink scheduler for QoS-aware resource management for multi-user multi-QoS traffic flow, with support from other authors

List of Abbreviations and Symbols

Abbreviations

3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
ACK	Acknowledgment
AS	Access Stratum
AWGN	Additive White Gaussian Noise
BS	Base Station
CA	Carrier Aggregation
CAGR	Computed Annual Growth Rate
CC	Component Carriers
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
CS	Circuit Switching
CSI	Channel State Information
CSIT	Channel State Information at the Transmitter
D2D	Device-to-Device
DCI	Downlink Control Information
DFT	Discrete Fourier Transform
DMRS	DeModulation Reference Signal
EB	Exabyte
FD	Frequency Domain
FDD	Frequency Division Duplex

FDMA	Frequency Division Multiple Access
FD-MIMO	Full Dimension Multiple Input Multiple Output
Gbps	Gigabits per second
GBR	Guaranteed Bit Rate
HARQ	Hybrid Automatic Repeat Request
IA	Interference Aware
IMT-A	International Mobile Telecommunications Advanced
IP	Internet Protocol
ITU-R	International Telecommunication Union Radio-communication Sector
LAA	License Assisted Access
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
LTE-A Pro	Long Term Evolution Advanced Pro
M2M	Machine-to-Machine
MAC	Medium Access Layer
MIMO	Multiple Input Multiple Output
MTC	Machine Type Communication
MU	Multi-User
MU-MIMO	Multi-User Multiple Input Multiple Output
NACK	Non-Acknowledgment
NAS	Non Access Stratum
OCC	Orthogonal Cover Code
OFDMA	Orthogonal Frequency Division Multiple Access
PD2DSS	Primary Device-to-Device Synchronization Signal
PDCP	Packet Data Convergence Protocol
PDN-GW	Packet Data Network Gateway
PDP	Power Delay Profile
PF	Proportional Fair
PHY	Physical
PMI	Precoding Matrix Indicator
PRB	Physical Resource Block
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel

PUSCH	Physical Uplink Shared Channel
QCI	Quality-of-Service Class Identifier
QoS	Quality-of-Service
RAT	Radio Access Technology
RBG	Resource Block Group
RE	Resource Element
RLC	Radio Link Control
RM	Reed Muller
RR	Round Robin
RRC	Radio Resource Control
RRM	Radio Resource Management
SAE	System Architecture Evolution
SCFDMA	Single Carrier Frequency Division Multiple Access
SD2DSS	Secondary Device-to-Device Synchronization Signal
SNR	Signal-to-Noise Ratio
SR	Scheduling Request
SSS	Secondary Synchronization Signal
SU-MIMO	Single User Multiple Input Multiple Output
TD	Time Domain
TDD	Time Division Duplex
TDL	Tapped Delay Line
TDMA	Time Division Multiple Access
TM	Transmission Mode
TTI	Transmission Time Interval
UCI	Uplink Control Information
UE	User Equipment

Symbols

${}_2F_3$	Hypergeometric function
APIT	Average packet inter-arrival time
BMT	Block maximum possible throughput

BS	Buffer size
$\mathrm{Buffer}_{\mathrm{weight}}$	Buffer weight
f	User velocity distribution function
$\mathbf{h}$	Channel variable
h	Channel vector
J_0	Zero order Bessel function
J_1	First order Bessel function
K	Number of user in single cell
$\mathrm{Latency}_{\mathrm{weight}}$	Latency weight
MPT	Maximum possible throughput of system
NU	Number of active users
PIT	Packet inter-arrival time
PMD	Packet maximum allowable delay
n	Noise
r	Received signal
s	Transmitted signal
t	Time instant
T	Transpose of matrix
TBS	Total buffer size
$\mathrm{TGPT}_{\mathrm{weight}}$	Throughput weight
TL	Traffic level
v	User velocity
$\mathbf{w}$	Transmit weight vector
w	Transmit weight
X	Total number of pedestrian users
Y	Total number of urban users
Z	Total number of high velocity users
γ	User SNR distribution
λ	Carrier wavelength
τ	Total feedback delay

1. Introduction

This chapter introduces the readers to the general background of the research topics to comprehend the motivation for conducting this work. Furthermore, it outlines the objective and the corresponding contributions of the thesis. The chapter is concluded with a brief summary of the published articles that constitute this doctoral thesis.

1.1 Motivational Background

The global mobile data traffic has been increasing at a stupendous rate. According to [27], mobile data traffic has grown 4,000-fold over the past 10 years and almost 400-million-fold over the past 15 years and it is expected to grow at a computed annual growth rate (CAGR) of 57 percent between 2015 and 2020 to reach around 30 Exabyte (EB) of monthly data as shown in Figure 1.1. Besides the increase in the amount of data traffic, the average data rates are also expected to increase at a CAGR of 26 percent during this period. In addition, network operators and service providers are expected to meet user demands of seamless connectivity and ubiquitous experience.

In order to satisfy these ever-growing needs and requirements, the wireless community is striving for innovations, in terms of both the technologies and the process of bringing them to the market. The process of translating the theoretical benefits from advanced technologies to the practical gains in real world is quite non-trivial since they are required to work within certain constraints and limitations. Most of the wireless technologies need to be effectively implemented to work along with these constraints and deliver promised gains in wireless networks. The 3GPP has emerged as one of the widely accepted body for standardizing new technologies to enable more advanced wireless networks such as 3GPP LTE.

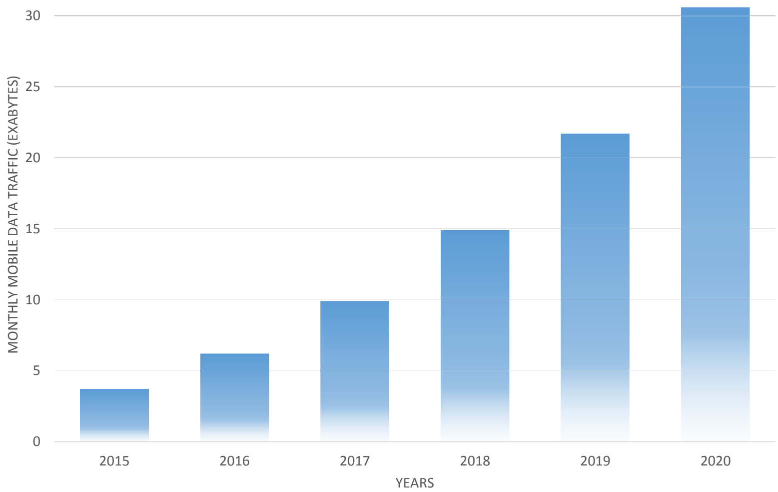

Figure 1.1. Forecast for Monthly Mobile Data Traffic [27]

This is quite evident from the statistics that the number of LTE subscriptions have reached 1.2 billion in 2016 [36]. 3GPP LTE has been constantly evolving with the addition of new technology features and reaching new milestones with higher spectral efficiency and increased data rates.

Figure 1.2 illustrates a generic process cycle of new technology from its invention to deployment in practical scenarios. Quite often, new technology

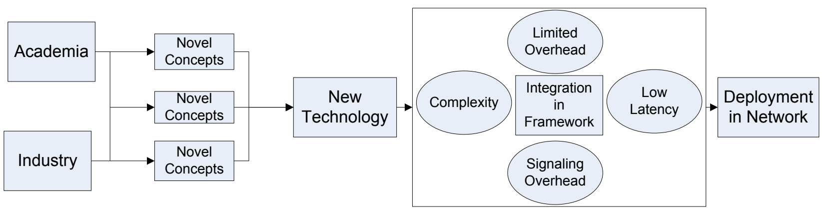

Figure 1.2. Generic Process for Deployment of New Technologies

is a combination of several novel concepts conceived in academia and industry. Once the technology has proven theoretical benefits and promising practical gains, they are considered for possible integration into a practical framework with real-world constraints. Figure 1.2 shows some of the constraints such as limited frequency spectrum, low latency requirements, reduced implementation complexity and optimal signaling overhead [34, 68, 98]. These constraints are quite crucial and impact the feature design for their effective integration into the framework. Especially, these constraints are inter-related and collectively impact the usage of radio resources in terms of both frequency and time. In fact, the generic problem can be defined as finding an optimal trade-off between the radio resource usage and expected performance of the system, and this is broadly referred as RRM. In 3GPP LTE framework, RRM encompasses a wide range of techniques and procedures, including scheduling, resource allocation for data and signaling, interference management, cell search and synchronization, power control, etc. [21, 58, 70, 76, 77, 85, 102].

The wide applicability of RRM techniques to enable efficient implementation and deployment of advanced technologies in wireless networks has been the primary source of motivation to conduct research in this direction. After defining the broad area of research in RRM, the next step was to select a framework into which key advanced technologies need to be integrated by utilizing RRM techniques. Finally, the last, but the most crucial step has been to find the key technologies that require advanced RRM techniques for effective implementation. In addition, they must have long-term applicability in wireless networks. Figure 1.3 describes the flowchart with motivational reasons for each step of this research flow.

Figure 1.3 shows that the broad area of research has been identified as advanced RRM techniques and 3GPP LTE (including LTE-A and LTE-A Pro) is chosen as the practical framework to conduct relevant research work. The main reason to select the 3GPP LTE framework is its wide acceptance as global wireless standard and deep penetration of LTE networks into the market. Furthermore, 3GPP LTE is constantly evolving by identifying new technologies and remains competent standard for future networks. Henceforth, the research work summarized in this thesis has spanned from evolution of LTE to LTE-A to LTE-A Pro as the latest generation in 3GPP. Most challenging and interesting step in this research flow has been to identify key technologies that require advanced RRM methods. In addition, the technologies are expected to have a long term impact in future networks. These reasons motivated to explore three main technologies: MU-MIMO to allow spatial multiplexing of users, D2D to enable direct communication between mobile devices and CA to combine different carriers for wider transmission bandwidth [31, 39, 87]. MU-MIMO exploits the maximum system capacity by scheduling multiple users to be able to simultaneously access the same channel using the spatial degrees of freedom offered by MIMO. MU-MIMO is expected to have a long applicability for future networks as well. D2D communication that enables

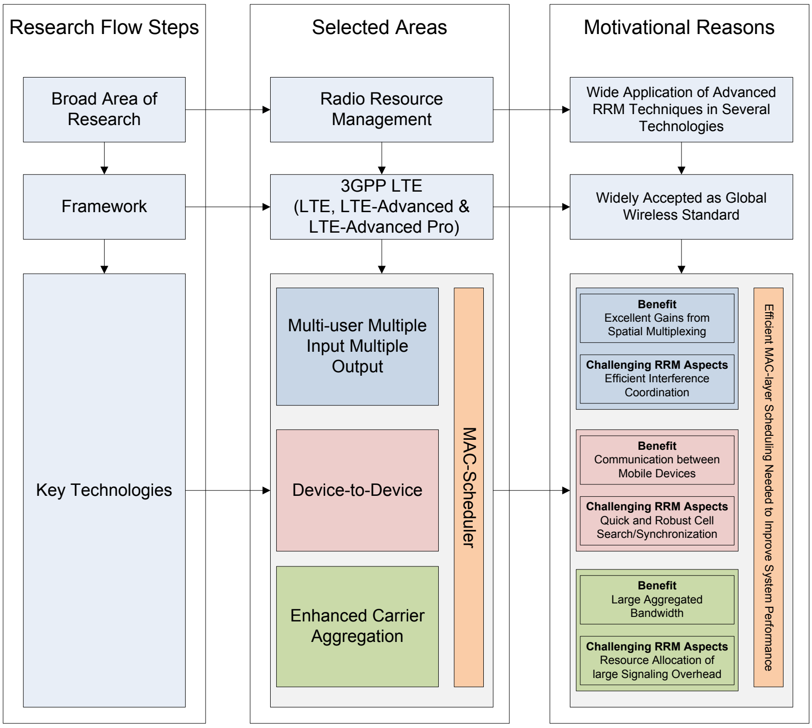

Figure 1.3. Research Flow with Motivational Reasons

direct communication between nearby mobiles is an innovative feature of next-generation cellular networks that would facilitate the interoperability between critical public safety networks and ubiquitous commercial networks. CA enables to increase the peak user data rates and overall capacity of the networks and to exploit fragmented spectrum allocations. MAC-layer scheduling framework has also been explored due to its applicability across various technologies [23]. Moreover, the traffic pattern has also evolved with modern networks and therefore it is important to design advanced scheduling methods. These technology features have been well studied in academia for quite some time now, but there exists several challenges in order to fully exploit their gains in a constrained real-world environment. Specifically, the main RRM related topics that are addressed in this thesis are: effective interference coordination in MU-MIMO by dynamic scheduling, HARQ schemes for distributed MIMO system, cell synchronization in D2D, efficient resource allocation for signaling overhead in CA and advanced scheduling framework to deal with multi-user multi-QoS MAC-layer traffic flow.

1.2 Objective and Contribution of the Thesis

The main objective of the thesis is to make the aforementioned technologies much more efficient in 3GPP LTE framework by developing advanced RRM methods. In generic terms, the objective can be simply put as:

"Abridging the gap between what is expected from wireless technologies and what they provide in real-world scenarios"

More specifically, the key objectives and corresponding contributions of this thesis are outlined as follows:

1. Interference coordination in MU-MIMO systems to minimize the impact of interference coming from other users that are transmitting on the same physical resources of time and frequency using spatial multiplexing. This topic specifically deals with the issues faced when MU-MIMO was first introduced in 3GPP LTE Release 8. With very limited support in the specifications, MU-MIMO could not provide promised gains and in some cases, performed worse than single user MIMO (SU-MIMO) [32, 57]. In addition to conventional MU-MIMO, the concept of distributed MU-MIMO via relay transmission [73] is also addressed and new HARQ schemes are proposed to improve the end-to-end performance.

2. Faster synchronization in D2D communications by designing robust detection method for synchronization signals that decreases the acquisition time. This relates to the introduction of D2D in 3GPP LTE Release 12 [7]. In D2D, synchronization signals have been designed such that they are transmitted with much higher periodicity in comparison to legacy downlink synchronization signals [4], and therefore it is required to have more robust detection so that the timing and frequency information is acquired within an optimal time duration.

3. Efficient resource allocation for supporting extremely large control signaling overhead to enable CA enhancements in 3GPP LTE Release 13 [10]. CA was first introduced in 3GPP LTE release 10 to ideally provide aggregated transmission bandwidth up to 100 MHz. Further support was added in Release 11 and Release 12 [87]. In Release 13, ma-

jor enhancements were proposed to enable even much wider aggregated bandwidth. Although, this would increase the frequency resources for data transmission, but it posed serious implications to accommodate very large signaling overhead that is required to support CA on such a massive scale. In this work, we address these key limitations and investigate solutions that allows efficient resource allocation for signaling.

4. Designing a scheduling framework that deals with the issue of efficiently scheduling resources when there are multiple users requesting multiple services with different quality-of-service requirements (QoS) at the same time [23, 52]. The primary objective of this framework is not just to develop a novel scheduling algorithm but also to improve the performance of existing scheduling algorithms.

1.3 Thesis Structure

The structure of the thesis is as follows: Chapter 2 provides the literature background of the research topics that are dealt in this thesis. Mainly, a generic background on RRM methods, MU-MIMO system, D2D communications, CA and MAC-layer scheduling is provided. Chapter 2 also describes the overall system model that is utilized to study and evaluate performance of developed methods. Moving forward, Chapter 3 discusses the impact of delay and velocity of users on feedback, interference coordination and HARQ in multi-user (MU) system. Chapter 4 summarizes the synchronization procedure in D2D communications system and the corresponding detection methods. In Chapter 5, the topic of CA is presented, including limitations of existing features and the corresponding enhancements to efficiently allocate resource for control signaling. Chapter 6 describes the MAC-layer scheduling framework that is developed to deal with multi-user multi-QoS traffic flow. Finally, the thesis is concluded in Chapter 7, along with a brief description of relevant future work.

1.4 Summary of Publications

The research work conducted for this thesis constitutes of 8 original publications that are grouped in four categories, each of this group corresponds to the four main objectives defined in the previous section. Publications I, II and III broadly deal with the RRM method of interference coordination and related sub-topics in MU-MIMO system. Publication IV proposes robust detection method for synchronization signals that results in improved synchronization process. Publications V and VI deals with resource allocation aspect of RRM for control signaling overhead to enable massive CA. The last group that consists of Publications VII and VIII deals with the MAC-layer scheduling aspect of RRM and propose a framework to deal with complex traffic flows.

Publication I deals with issue of feedback delay in a multi-user system. In order to have effective interference coordination, getting reliable channel state information (CSI) via feedback is a crucial step [67]. In this publication, the impact of feedback delay and user mobility is studied for closed-loop transmit beamforming. The investigation is conducted for different group of users categorized on the basis of their velocity. Based on this analysis, an adaptive feedback-scheduling algorithm is proposed to minimize the effect of feedback delay and user velocity on the performance of the system. Generalized performance measuring analysis is done for the proposed algorithm and simulations are carried out to validate the analysis. This ensures that the feedback is available at the transmitter with reduced delay and hence can be utilized for selecting and scheduling multiple users with effective interference coordination, which is dealt in Publication II.

In Publication II, the primary goal is to efficiently use the system resources for MU-MIMO in LTE. It is proposed here to support finer granularity feedback i.e. sub-band feedback method. Firstly, it is proposed to exploit the sub-band feedback for providing more frequent update of channel directional information which is defined as precoding matrix indicator (PMI) in LTE [84]. Secondly, this finer granularity feedback is utilized to develop a dynamic scheduling algorithm. Multiple users are prescheduled such that they cause minimum interference to each other, the expected system performance is then compared to the case of SU-MIMO and finally the one with better performance is actually scheduled. Moreover, since this is done on a sub-band basis, therefore it allows dynamic switching between MU-MIMO and SU-MIMO at finer granularity.

In Publication III, distributed MIMO system is investigated. Distributed MIMO also known as cooperative MIMO is used to transmit information from source to destination via two different nodes (relay nodes in this study) that are considered as distributed antennas of the same transmitter. In this publication, HARQ schemes are developed and analyzed for such distributed system. The main motivation is to develop HARQ schemes such that the maximum number of retransmission are reduced to enable better usage of resource and improve end-to-end throughput.

In Publication IV a detection method for primary synchronization signal (PSS) in D2D is proposed. D2D primary synchronization signals (D2DPSS) are based on the synchronization signals in downlink, but with stringent constraints and parameters such as increased periodicity of synchronization signals transmission and low power transmission. Therefore, it becomes necessary to develop a robust detection method for faster acquisition time.

In Publication V, CA enhancements in 3GPP LTE Release 13 are investigated. Main motive of this paper is to study the control resources structure for supporting the expansion of CA to larger number of aggregated component carriers (CCs). Increasing the number CCs has challenging implications on the existing control signaling support both in the downlink and uplink. More specifically in this publication, possible increase in payload for uplink control information (UCI) is investigated, the limitation of existing specifications is analyzed and a simple yet effective solution to provide reasonable support for transmitting uplink control information with larger payload is proposed.

In Publication VI, the focus is on new enhancements for extending CA in 3GPP LTE Release 13. Efficient transmission of UCI on uplink resources is investigated. Different formats for transmission on physical uplink control channel (PUCCH) have been defined in 3GPP LTE-A to support different scenarios. For the CA framework in LTE-A, PUCCH format 3 and format 1b with channel selection are defined to transmit the UCI for up to 5 CCs and they are insufficient when the amount of UCI increases along with the number of aggregated carriers. In this article, design features for new PUCCH formats are studied and potential candidates are investigated including the structure of new PUCCH formats, the key aspects including channel coding, reference signals, multiplexing, and mapping to resources are addressed.

In Publication VII, a scheduling framework with preprocessor for two-dimensional buffer management on per-user per-service basis (multi-user multi-QoS) is proposed. The basic idea is that the scheduling algorithm is applied at even finer resolution. In contemporary frameworks, most of the schedulers allocate resources on user basis, with the user belonging to a particular QoS class. However, in modern networks, the user can demand several services belonging to different QoS classes simultaneously. Therefore, a modular framework to improve the performance of existing scheduling algorithms is designed. A comparative analysis of traditional scheduling algorithms is provided to show the gains of the proposed framework.

In Publication VIII, a three-step iterative downlink scheduler is proposed for resource management at per-user per-service level by utilizing the framework defined in Publication VII. The scheduler performs sorting in multiple iterations on the basis of three weights: throughput weight, latency weight and buffer weight. The allocation of resources is done to satisfy the promised QoS to all the services of every user. A comparison is carried out with traditional scheduling algorithms in terms of system throughput, fairness index and percentage of satisfied guaranteed bit-rate users.

2. Background and System Framework

3GPP agreed upon the requirements and the performance targets for LTE in [1]. In order to ensure competitiveness for a long term in the future, an evolved radio access technology was considered by 3GPP. Main requirements of 3GPP LTE were reduced latency, higher user data rates, increased spectral efficiency, improved capacity and reduced cost for network operators. These requirements motivated the enhancements to the radio interface and also to the network architecture. The goal of the system architecture evolution (SAE) effort in 3GPP was not only to enable these enhancements, but also to develop a framework for an evolution and migration of existing systems to a packet-optimized system that supports mobility and service continuity across heterogeneous access networks. This goal was set since it was envisioned that Internet Protocol (IP)-based services would be provided through various access technologies [60, 65]. The 3GPP LTE has been one of the most significant accomplishments in the series of mobile telecommunication systems. From the radio aspects, the 3GPP has evolved over three multiple access technologies: Time-division and Frequency-division multiple access (TDMA/FDMA), code division multiple access (CDMA) which later on developed as wideband CDMA (WCDMA) (owing to 5 MHz carrier bandwidth) and finally it adopted orthogonal frequency-division multiple access (OFDMA) which has been a widely accepted multiple access technology for quite some time now. 3GPP LTE along with SAE comprises of the Evolved Packet System where both the core network and the radio access are fully packet-switched.

The first version of the 3GPP LTE was made available in Release 8 of the 3GPP specification series. It utilized the technology developments from the preceding wireless standards to its benefit, but without the constraints of backward compatibility. The key highlights of 3GPP LTE Re-

lease included OFDMA in downlink, single-carrier frequency division multiple access (SCFDMA) in uplink, multiple input multiple output (MIMO) antennas, flat radio architecture, implementation in bandwidths of 1.4, 3.5, 5, 10, 15 and 20 MHz bandwidth for different deployment scenarios. Since then, 3GPP has constantly rolled out new releases with much higher performance targets and with more advanced technologies. The key releases with significant additions have been marketed with new markers for LTE. 3GPP LTE evolved to LTE-A in Release 10 to satisfy the requirements of IMT-A as set by the ITU-R [47]. In 3GPP LTE-A, the key innovations include a flexible advanced antenna and pilot design, close to optimal link adaptation, hierarchical control signaling, a flexible multiple access scheme, relaying, carrier aggregation (CA), device-to-device (D2D) and flexible spectrum use [97]. Following the completion of latest Release 13, the 3GPP LTE is now evolved to LTE-A Pro [8]. The key technologies that are already included and are under consideration include full-dimension MIMO (FD-MIMO), license-assisted access (LAA), CA enhancements, machine-type communications (MTC), latency reduction, V2X communication and enhanced downlink multi-user transmission using superposition coding [59].
Although the LTE has been evolving with the addition of more advanced technologies, challenges have also grown related to different aspects of 3GPP LTE framework. In the area of RRM, there is a constant need to develop more effective yet low-complexity techniques. In the following sections of this chapter, we particularly discuss the RRM techniques and technologies relevant to the research work conducted in this thesis.

2.1 Radio Resource Management

The primary objective of RRM in wireless communication networks is to efficiently share the limited resources of frequency and time, while optimizing the trade-off between the radio resource usage and the performance of the system [29, 66, 94]. It encompasses several techniques ranging from scheduling, resource allocation, power control, interference coordination, cell search and synchronization, handovers, radio link or connection monitoring and connection establishment and re-establishment [16, 38, 85, 86]. In 3GPP LTE, RRM is designed to handle the several challenges posed by the fundamental characteristics of the LTE system. In [93], requirements to support the RRM methods in LTE are specified.

In this chapter, the following aspects of RRM relevant to the work are discussed: interference coordination, cell search and synchronization, resource allocation and scheduling.

2.1.1 Interference Coordination Aspect of RRM

Interference coordination is an important aspect of RRM to deal with interference that can originate from the transmitters using the same set of radio resources [18, 54]. In fact, the interference coordination schemes can have an impact on the overall network planning and scheduling mechanisms [19]. In OFDMA systems such as LTE, the transmission resource is divided into time and frequency [85]. The same time and frequency resources can be re-used within the same cell via spatial multiplexing or simply in other cells. This can cause serious interference among the transmitted signals that are intended to be received separately by the receiver(s). In order to deal with this interference, different methods are used in combination with advanced receivers. Interference coordination is one such method, which is broadly defined as the process of coordinating the transmission at one or more transmit nodes by sharing and utilizing the CSIT [20]. There can be different classes of interference coordination with respect to the degree of distribution of the coordinating nodes [19], which impacts the system performance gain.

2.1.2 Cell Search and Synchronization Aspect of RRM

In order to access the cell, the user equipment (UE) must follow the cell search procedures which consists of a series of synchronization stages to determine the time and frequency parameters [85, 88, 90]. These parameters are necessary for timing and frequency synchronization between the transmitter and receiver, proceeding which an active communication link establishment. The two types of synchronization signals are defined in LTE downlink: primary synchronization signals (PSS) and secondary synchronization signals (SSS). The detection of these two signals not only enables time and frequency synchronization, but also provides the UE with the physical layer identify of the cell and the cyclic prefix length, and informs the UE whether the cell used frequency division duplex (FDD) or time division duplex (TDD). Therefore, it is required to implement robust detection method for these signals that allows fast synchronization [104]. Such a synchronization can either be initial synchronization within a cell or a neighboring cell identification to allow future handover.

2.1.3 Resource Allocation Aspect of RRM

Radio resources are very limited, therefore it is utmost important to efficiently utilize these resources. In addition to transmission of data on radio resources, there is also the signaling overhead that is very important since it facilitates features such as cell search, synchronization, channel estimation, HARQ and feedback information [44, 56, 85]. Therefore, one of the most challenging aspect in 3GPP LTE system is to find an optimal trade-off between the allocation of resources to signaling overhead and the performance gain. As signaling overhead depends on the feature to be implemented, it can range from few bits to hundreds of bits. As the allocation of resources to signaling overhead increases, the resource pool for data decreases. At the same time, if insufficient amount of resources are used to transmit signaling information, there is possibility of poor coverage for signaling, which in turn impacts the performance of data transmission. Hence, it is important to optimally distribute resources between data and signaling.

2.1.4 Scheduling Aspect of RRM

In order to reach the target QoS in terms of delay, guaranteed bit-rate (GBR), throughput and fairness, the MAC-layer scheduling framework is one the most significant components in 3GPP LTE protocol stack [37]. Scheduling framework involves allocation of resources to several users waiting to be scheduled based on one or more decision parameters. A number of scheduling algorithms have been proposed and implemented in the past [14, 69]. In scheduling, the decision-making process is complex as it involves a number of factors such as channel quality information (CQI), QoS requirement, interference management, buffer size, network traffic, etc [103, 105]. Conventional scheduling algorithms such as proportional-fair, round-robin, max-throughput results in sub-optimal performance in multi-user multi-QoS traffic flow in wireless networks, where multiple users can request multiple services at the same time [23]. An advanced scheduling framework is needed to deal with such modern wireless networks that are required to support not only the high traffic conditions, but several parallel traffic flows.

2.2 Multi-User MIMO System

MU-MIMO is a spatial multiplexing of multiple users to transmit on the same time and frequency resources in a given transmission time interval (TTI) as shown in Figure 2.1. Basically in MU-MIMO, a limited number of users are selected for simultaneous communication from a set of active users in a cell. This is in contrast to SU-MIMO, where only a single user is selected from the active set of users for communication. As a result, MU-MIMO is expected to provide high spectral efficiency in comparison to SU-MIMO and the theoretical performance gain is expected to increase with increasing number of transmit antennas, since it allows communication with increased number of users [50, 99]. However, the benefits of MU-MIMO come at a price. One of the main issues with MU-MIMO is to deal with the interference coming from other users. In order to exploit MU-MIMO, there needs to be a separation between the spatial streams that are intended for different users. In this ideal scenario streams are orthogonal to each other. The direction of the streams can be adjusted by applying beamforming at the transmitter, also known as precoding. A number of precoding techniques have been proposed to minimize the interference and to improve the performance of MU-MIMO [22, 55, 80, 91]. In 3GPP LTE, there are only limited codebooks that are used for precoding and therefore it is not always possible to have ideally separate spatial streams [12, 96]. In Chapter 3 of the thesis, utilization of the available codebooks for interference coordination in MU-MIMO is proposed.

2.2.1 Feedback

The main requirement for implementing most of the precoding techniques is to have a reliable channel state information at the transmitter (CSIT) [82]. This is usually received as feedback from the receiver via a feedback channel. In 3GPP LTE, the feedback is mainly comprised of channel quality information (CQI), rank indicator (RI) and precoding matrix indicator (PMI) [5]. PMI indicates the channel directional information, based on which the transmitter performs beamforming and also the scheduling of user is done for interference coordination. In ideal scenario, this feedback information is instantly received perfectly at the transmitter. However, in practical systems, the feedback suffers from delay and other transmission errors. Therefore, it is an important requirement to implement a reliable feedback mechanism for exploiting the benefits of MU-MIMO. In this the-

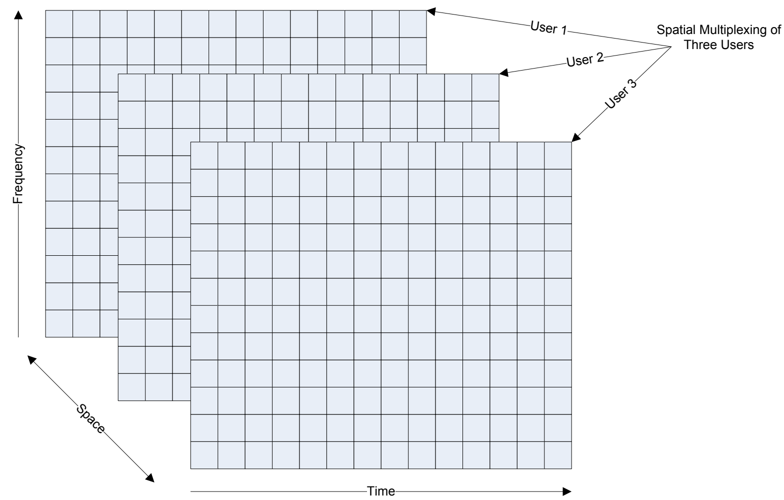

Figure 2.1. MU-MIMO: Spatial Multiplexing on Resource Grid

sis, the impact of feedback delay is also studied and an adaptive feedback mechanism is proposed in Chapter 3.

2.2.2 Distributed System

Another aspect of MIMO systems that is studied in this thesis is the distributed MIMO communication. It is a specific type of MIMO communication that transmits via a distributed array of antennas [61, 75]. The distributed array of antennas is basically antennas on separate nodes. Figure 2.2 depicts a simple example of a distributed communication system with a source transmitting to the destination via relay nodes by applying coordinated beamforming at the antennas of the relay nodes so that their respective streams are received without interference at the destination. Due to this coordination, approach is also referred to as cooperative communication. The main benefits of distributed MIMO are spatial diversity gains and better coverage to the cell-edge users [72, 95].

2.3 Device-to-Device Communication

D2D communication is defined as a direct communication between users that can either be in-coverage of the base station, partial-coverage or out-of-coverage of the base station as shown in Figure 2.3. D2D was first proposed in [62] to allow multi-hop communication. The main motiva-

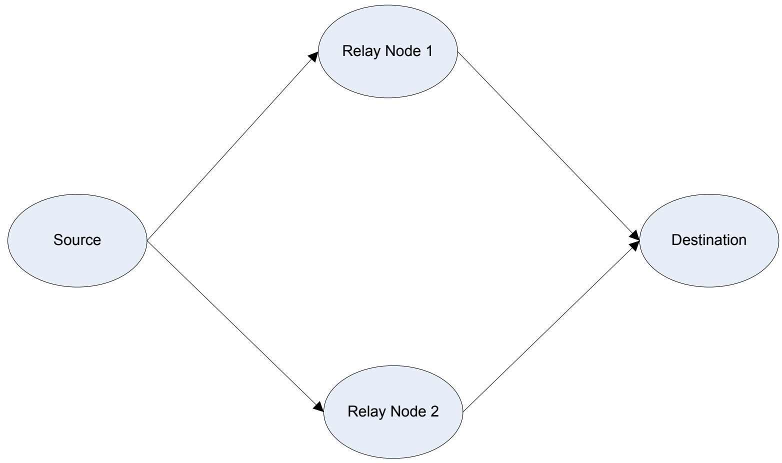

Figure 2.2. Distributed MIMO Communication

tion to introduce D2D was to enable communication between users when one or more users are not within the range of direct communication with base station. Since then, D2D was been well investigated in [15, 31, 51]. In terms of performance, D2D allows enhanced spectral efficiency, by improving throughput, energy efficiency, delay and fairness. D2D use-cases include multicasting, machine-to-machine (M2M) communication, cellular offloading, etc. As a result, D2D is among the latest technologies that has been standardized by 3GPP LTE in Release 12 with main focus on public safety use cases [7]. More details regarding the relevant aspects of D2D in 3GPP LTE are discussed in Chapter 4, where RRM issues related to synchronization in D2D are addressed.

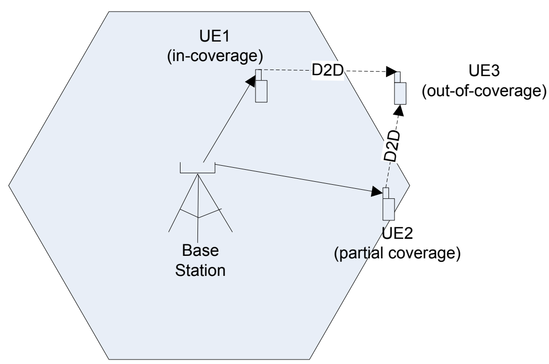

Figure 2.3. Device-to-Device Communication

2.3.1 Synchronization

D2D synchronization is an important pre-requisite to establish communication between users. D2D synchronization procedure involves a synchronization source that transmits the synchronization signal required by user to obtain time and frequency parameters [48]. In general, the synchronization procedure is similar to that between base station and user. However, the requirements in terms of performance and constraints for D2D in practical scenario are different [7]. Therefore robust detection of these synchronization signals is crucial for D2D.

2.4 Carrier Aggregation

Due to limited amount of contiguous frequency bands and consequently smaller bandwidth, 3GPP introduced bandwidth extension in LTE-A via CA to achieve peak data rates up to 1 Gigabits per second (Gbps) [41, 101]. CA is the technology for combining chunks from frequency spectrum to have a wider aggregated bandwidth available for transmission. In 3GPP LTE Release 8/9, maximum transmission bandwidth of 20 MHz is allowed [2], but it is insufficient to meet the requirement of 100 MHz bandwidth set by IMT-Advanced [47]. Therefore, CA up to 5 component carriers (CCs) was introduced in 3GPP LTE Release 10.

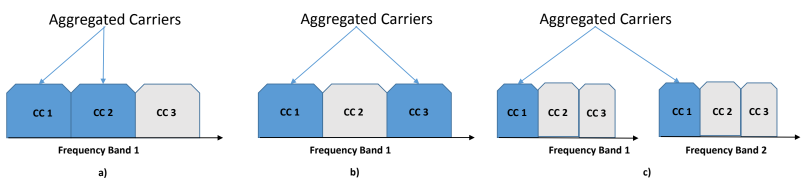

Figure 2.4. Illustration of different types of Carrier Aggregation: a) intra-band contiguous; b)intra-band con-contiguous; c)inter-band non-contiguous

Figure 2.4 shows the different types of CA that are defined depending up on the aggregation of CCs: intra-band contiguous CA when contiguous carriers are aggregated within the same band, intra-band non-contiguous CA when non-contiguous carriers are aggregated within the same band and inter-band non-contiguous CA when the non-contiguous carriers are aggregated from different bands. Only limited configurations for intra-band and inter-band CA was introduced in LTE Release

10. Following the introduction of CA, further extensions enabled inter-band time-division duplex (TDD) with different uplink-downlink configurations, CA with multiple uplink timing advance in Rel. 11 and aggregation of carriers with different frame structures through FDD and TDD CA in Release 12 [87]. Furthermore, 3GPP specified support for enhanced CA up to 32 CCs in the recently concluded 3GPP LTE-A Pro Release 13. The work conducted in this thesis deals with this extension of CA, its impact on control signaling overhead and corresponding enhancements in terms of resource allocation for control signaling as discussed in Chapter 5.

2.4.1 Control Signaling

In order to support CA, necessary enhancements to both downlink and control signaling are required. In general, the focus in 3GPP has been to deploy CA in the downlink. This results in increased control signaling overhead in the uplink to provide feedback corresponding to all the aggregating CCs. The control resources necessarily do not scale directly in proportion to the number of carriers, therefore more efficient resource allocation for control signaling overhead is needed. Specially for supporting downlink CA up to 32 CCs in Release 13 and beyond, the uplink control signaling overhead becomes quite large [9]. Therefore, signaling overhead is one of the challenging aspects of CA that has been dealt in this thesis.

2.5 MAC-layer Scheduling

3GPP LTE has been designed as a completely PS network without any dependency on circuit-switching (CS). This allows fast packet scheduling over shared radio resources and provides the opportunity to develop more advanced scheduling techniques. Moreover, packet-switching has enabled cross-layer functioning between the physical layer and MAC-layer. With cross-layer integration, it is possible to have channel aware scheduling for exploiting multi-user diversity and also interference coordination as discussed earlier. In addition to the physical layer aspects, the MAC-layer scheduling framework is mainly required to serve different QoS classes defined in 3GPP LTE [33]. The QoS level of granularity in 3GPP LTE is called as a bearer, which is a packet flow established between the packet data network gateway (PDN-GW) and the user [13]. Each bearer serves a specific QoS and is denoted by a value that is referred to as QoS class identifier (QCI). 3GPP LTE has standardized nine QCI, each of which is characterized by specific: resource type, priority, packet delay budget and packet error loss rate as shown in Table 2.1. Broadly, the bearers are classified as GBR bearer that has dedicated network resources and non-GBR bearer without dedicated network resources. The priority order of QCI is another important factor to design the decision algorithm such that highest priority QCI gets served first.

QCI	**Resource Type**	**Priority**	**Packet Delay Budget**	**Packet Error Loss Rate**
1	GBR	2	100 ms	10^{-2}
2	GBR	4	150 ms	10^{-3}
3	GBR	3	50 ms	10^{-3}
4	GBR	5	300 ms	10^{-6}
5	Non-GBR	1	100 ms	10^{-6}
6	Non-GBR	6	300 ms	10^{-6}
7	Non-GBR	7	100 ms	10^{-3}
8	Non-GBR	8	300 ms	10^{-6}
9	Non-GBR	9	300 ms	10^{-6}

Table 2.1. QCI in 3GPP LTE [13]

For providing these desired QoS levels, scheduler is responsible for sharing resources between users and serving application requests. Some of the traditional schedulers widely used in the industry are: proportional-fair (PF) [45], round-robin (RR) [89] and maximum-throughput [83]. Most of the existing scheduling frameworks have been designed to deal with users belonging to a single QoS class and therefore apply scheduling algorithms at the user level. However, with the evolution of networks and advanced mobile devices, not only the data traffic has increased, but the traffic pattern has evolved as well. Most of the users are able to request multiple applications with different QoS requirement simultaneously, that can be referred to as multi-user multi-QoS traffic flow. Then, with the traditional framework, there is inefficient management of resources and sub-optimal system performance. Therefore, in this work, a generic scheduling framework is proposed in Chapter 6 to deal with multi-user multi-QoS traffic flow.

2.6 System Framework

2.6.1 3GPP LTE Nomenclature

The research conducted in this thesis has been done within the framework of 3GPP LTE. In this section, the general aspects of 3GPP that are relevant and common to all the topics in this thesis are discussed.

3GPP LTE Protocol Stack

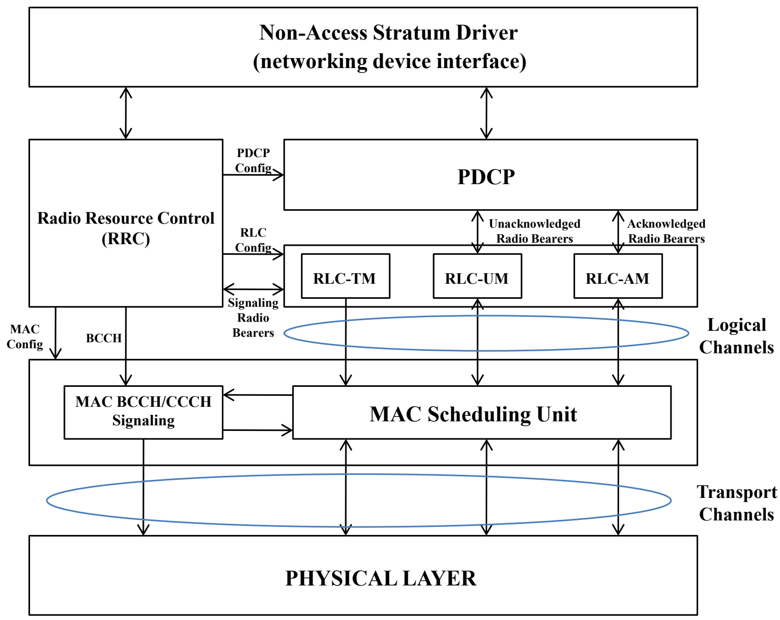

Figure 2.5. 3GPP LTE Protocol Stack [17]

Figure 2.5 shows the overall protocol stack of the 3GPP LTE and beyond. It is mainly divided into access stratum (AS) and non-access stratum (NAS). The AS is comprised of layer 1 and layer 2, while NAS comprises of upper layers that act as the interface with the networking device. Layer 1 consists of the physical layer and layer 2 consists of user plane protocols including MAC layer, radio link control (RLC) layer and packet data convergence protocol (PDCP) layer and control plane protocols consisting of radio resource control (RRC) [85]. There are also interfaces between different layers that are defined as channels. The channels interfacing the physical layer with MAC-layer are called transport channels and that interfacing the MAC layer with RLC layer are called logical channels. This thesis deals with aspects of physical layer and MAC-layer that are discussed in the subsequent chapters.

Transmission Resource Structure

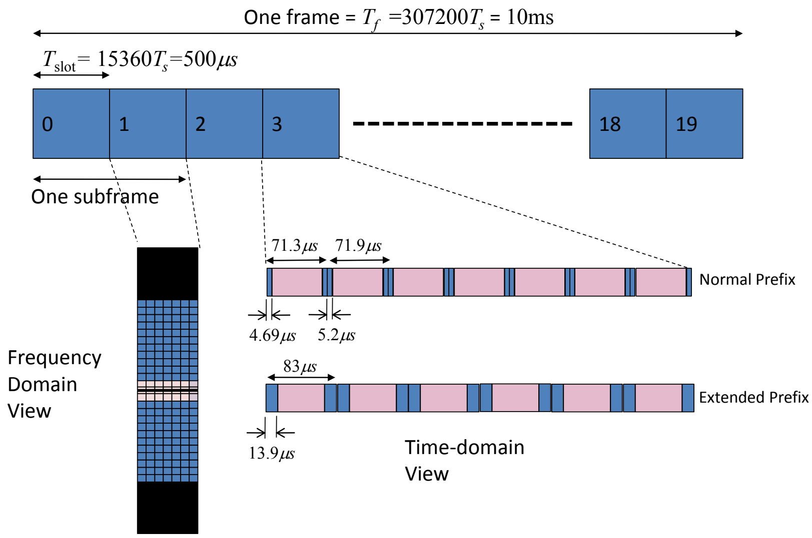

Figure 2.6. 3GPP LTE Transmission Resource Structure [17]

Figure 2.6 shows the transmission structure in time domain (TD) and frequency domain (FD). In FD, the transmission bandwidth consists of a number of physical resource blocks (PRB) with each one of them corresponding to a size of 180 KHz. Depending on the channel bandwidth, the number of PRBs is defined. Furthermore, each PRB is divided into 12 subcarriers with an individual spacing of 15 KHz. The subcarrier is termed as a resource element (RE) which is the smallest unit of a transmission resource. These PRBs with REs are mapped onto the contiguous TD symbols for downlink/uplink transmission. In the TD, the largest unit of time is a radio frame which corresponds to a duration of 10 ms. Each frame is then further subdivided into 10 subframes of 1 ms, each of which is split into 2 slots of 0.5 ms. Each slot comprises either 6 TD symbols in case of the extended cyclic prefix (CP) mode or 7 symbols for the normal CP mode.

Since the introduction of LTE in Release 8 of 3GPP, there has been a constant evolution with new releases by introducing new enhancements. However, all the specification enhancements have been made on top of this protocol stack and transmission resources structure. Therefore, this framework is valid for all the topics studied in this thesis.

2.6.2 Overall System Model

The overall system model used in the thesis is a cellular environment consisting of a single macro base station and multiple users as shown in Figure 2.7. The user can either be static or mobile depending up on the specific requirements. The four subsystems relevant to particular research topics are: SU-MIMO system, MU-MIMO system, distributed MIMO system and D2D communication system. Chapter 3 utilize the MU-MIMO subsystem, Chapter 4 utilizes the D2D subsystem, Chapter 5 is based on SU-MIMO subsystem and Chapter 6 also utilizes SU-MIMO subsystem, with multiple users.

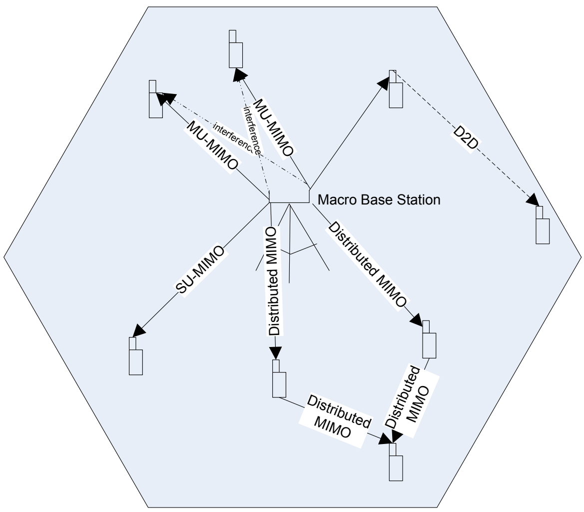

Figure 2.7. Overall System Model

With this system model, the performance evaluation is performed for the techniques proposed in this thesis work. Specifically, both the system level and link level simulations are done depending up on the scope of the proposed techniques. In Chapter 4, which deals mainly with interference coordination in MU-MIMO, system level simulations are required to evaluate the overall impact on the system throughput performance. In Chapter 5, the main enhancement is done at the receiver at the physical layer, therefore link level simulations are done for performance evaluation in terms of specific performance metric relevant to synchronization signal detection. Chapter 5 utilizes the link level simulation setup to measure the trade-off between the resource allocation for control signaling overhead and the impact on the performance in terms of block error rate due to channel conditions. In Chapter 6, system level simulations are done to measure the performance of the proposed scheduling framework in terms of system throughput, fairness and percentage of satisfied users with GBR.

3. Interference Coordination and Hybrid-ARQ in Multi-User MIMO System

This chapter mainly deals with radio resource management issues in multi-user and distributed MIMO systems as studied in Publications I, II and III. Specifically, the impact of delay and user velocity on feedback is studied and adaptive feedback scheduling algorithm is proposed to minimize the impact of feedback delay on transmit beamforming. It is then studied how the feedback can be effectively used along with simple enhancements in 3GPP LTE Release 8 to improve the system performance of downlink MU-MIMO by interference coordination using dynamic scheduling. Furthermore, more advanced type of MIMO communication system known as distributed MIMO is studied and HARQ schemes are proposed to reduce the number of end-to-end retransmissions and improve end-to-end throughput.

3.1 Problem Description

There are three main issues addressed in this chapter.

1. The fundamental problem is to analyze the combined effect of user velocity and delay on feedback quality for all users in a closed-loop transmit beamforming system and design an efficient feedback scheduler as proposed in Publication I. When the channel is time-variant, the feedback provided by the user might get outdated by the time it is actually used for beamforming [53]. The rate of channel variation is directly related to the velocity of the user with respect to base station [49]. Therefore the system performance is dependent on user's feedback delay and velocity [43].

2. MU-MIMO provides marginal gain over SU-MIMO due to inadequate

support in 3GPP LTE Release 8 specifications [32]. In addition, it is shown that MU-MIMO is more sensitive to the accuracy of the CSIT in comparison to SU-MIMO [78, 79]. In 3GPP LTE Release 8, only transmission mode (TM) 5 is dedicated for MU-MIMO and it utilizes only wide-band feedback for providing the precoding matrix indicator (PMI) at the transmitter. This basically means that only two bits (for two transmit antennas) of PMI feedback is used for the entire bandwidth which is insufficient to fulfill the requirements mentioned in [78]. Therefore, the main issue is to improve the granularity of feedback with only minimum increase in overhead and utilize this feedback for more efficient interference coordination using dynamic scheduling as described in Publication II.

3. In the distributed system studied in Publication III, different relays are considered as antennas of a single source, for which, the multiple antenna techniques can be implemented with the motivation to exploit macro-diversity gain, obtained as a result of uncorrelated fading along independent channel paths from relays to destination [74]. One of the main issues involved in such systems is to design an efficient HARQ scheme that reduces the number of retransmissions for end-to-end communication. In 3GPP LTE, maximum number of retransmissions allowed for a single link are four. In this distributed setup, there are four links and therefore the total number of retransmissions can be quite high [46, 71]. Hence, the need to implement HARQ is evident.

3.2 Modeling, Proposed Solutions and Performance Investigation

3.2.1 Adaptive Feedback Scheduling

Modeling

For this study, there are three main components in modeling: system model, feedback model and user categorization model. A system with a stationary base station having 2 transmit antennas and K mobile users with single receive antenna is used. Closed-loop transmit beamforming is applied at the downlink transmission based on feedback received from the user. The received signal is

$$r(t) = (\mathbf{h}(t)\mathbf{w})s(t) + n(t) \tag{3.1}$$

where $s(t)$ is the transmitted signal, $n(t)$ is zero-mean Gaussian noise, $\mathbf{w} = (w_1, w_2)^T$ consist of transmit weights for the two antennas and $\mathbf{h}(t) = (h_1(t), h_2(t))$ consist the channel vectors. The time-correlation of the channel is given by Jakes model [30].

The feedback information is received by the base station only after certain feedback delay τ which consists of round-trip and processing delay. Figure 3.1 shows the feedback delay model.

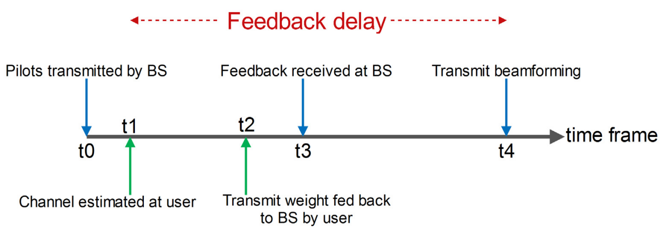

Figure 3.1. Feedback Delay Model ©2013 IEEE

The users are categorized into three groups on the basis of their velocity as: pedestrian, urban and high-velocity. Pedestrian users have a decreasing velocity distribution function given by $f(v) = a + vb$, where $a > 0$ and $b < 0$, urban users distribution is given as $f(v) = a$, where $a > 0$ and high-velocity users have an increasing type function given by $f(v) = av$, where $a > 0$. Figure 2 in Publication I shows these different user groups.

Feedback Scheduling Design

An adaptive feedback scheduling is proposed here to minimize the impact of user velocity and delay on feedback and thus to improve the transmit beamforming performance. In order to design the scheduling, a theoretical analysis is done to quantify the impact of feedback delay and user velocity on the received signal-to-noise ratio (SNR). The SNR for pedestrian, urban and high velocity users are derived in Publication I and given by Equations 3.2, 3.3 and 3.4, respectively here.

$$\begin{aligned}\gamma_{\text{pedestrian}} =& a v_{\text{max,ped}} + \frac{b}{2} v_{\text{max,ped}}^2 + \frac{\pi c_N b}{8} v_{\text{max,ped}}^2 \\ & \left[J_0(\frac{2\pi\tau}{\lambda} v_{\text{max,ped}})^2 + J_1(\frac{2\pi\tau}{\lambda} v_{\text{max,ped}})^2 \right] + \\ & \frac{a\pi c_N}{4} v_{\text{max,ped}}\ {}_2F_3(0.5, 0.5; 1, 1.5, 1; \\ & -(\frac{2\pi\tau}{\lambda} v_{\text{max,ped}})^2)\end{aligned} \tag{3.2}$$

$$
\begin{aligned}
\gamma_{urban} =& [a v_{\max,\text{urb}} + \frac{a\pi c_N}{4} v_{\max,\text{urb}} \\
& {}_2F_3(0.5, 0.5; 1, 1.5, 1; -(\frac{2\pi\tau}{\lambda} v_{\max,\text{urb}})^2)] \\
& -[a v_{\min,\text{urb}} + \frac{a\pi c_N}{4} v_{\min,\text{urb}} \\
& {}_2F_3(0.5, 0.5; 1, 1.5, 1; -(\frac{2\pi\tau}{\lambda} v_{\min,\text{urb}})^2)]
\end{aligned}
\tag{3.3}
$$

$$
\begin{aligned}
\gamma_{\text{high}} =& [\frac{a}{2} v^2_{\max,\text{high}} + \frac{\pi c_N a}{8} v^2_{\max,\text{high}} \\
& \left[J_0(\frac{2\pi\tau}{\lambda} v_{\max,\text{high}})^2 + J_1(\frac{2\pi\tau}{\lambda} v_{\max,\text{high}})^2 \right]] \\
& -[\frac{a}{2} v^2_{\min,\text{high}} + \frac{\pi c_N a}{8} v^2_{\min,\text{high}} \\
& \left[J_0(\frac{2\pi\tau}{\lambda} v_{\min,\text{high}})^2 + J_1(\frac{2\pi\tau}{\lambda} v_{\min,\text{high}})^2 \right]]
\end{aligned}
\tag{3.4}
$$

where $J_1(.)$ is the Bessel function of first order and ${}_2F_3(\cdot)$ is mathematical function called hypergeometric function in 9.14.1 of [42].

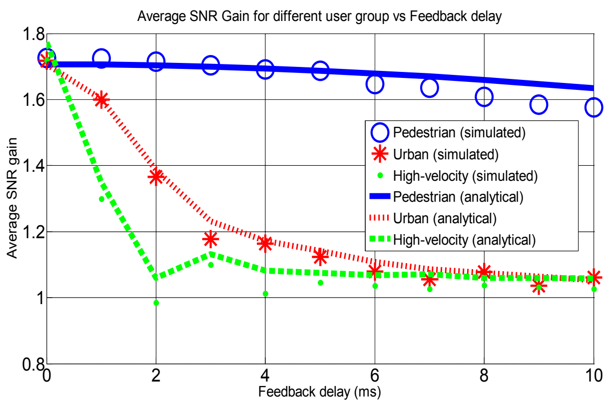

Figure 3.2. Feedback Delay Analysis ©2013 IEEE

Figure 3.2 validates the analytical expressions by plotting the SNR values for different feedback delay and three user groups. This analysis shows that the pedestrian user group is mostly unaffected by feedback delay and the performance degrades significantly for urban and high-velocity groups. Based on this analysis, velocity group dependent feedback scheduler is proposed that is aware of the user group and schedules them in the following order: high-velocity, urban and pedestrian users. As a result, the users belonging to the highest velocity group will experience least feedback delay and the users belonging to the lowest velocity group will have the largest feedback delay. Then the average SNR gain using this velocity-group dependent feedback user algorithm is simply given as

$$\gamma_{\text{average}} = \frac{\sum \gamma_{\text{pedestrian},x} + \sum \gamma_{\text{urban},y} + \sum \gamma_{\text{high-velocity},z}}{K} \tag{3.5}$$

where x, y and z refer to pedestrian, urban and high-velocity users, respectively and they are in total K users. Signal-to-noise ratios (SNR) for pedestrian, urban and high-velocity user groups are $\gamma_{\text{pedestrian},x}$, $\gamma_{\text{urban},y}$ and $\gamma_{\text{high-velocity},z}$, that are derived from Equations 3.2, 3.3 and 3.4, respectively. Figure 3.3 depicts the proposed feedback scheduling mechanism.

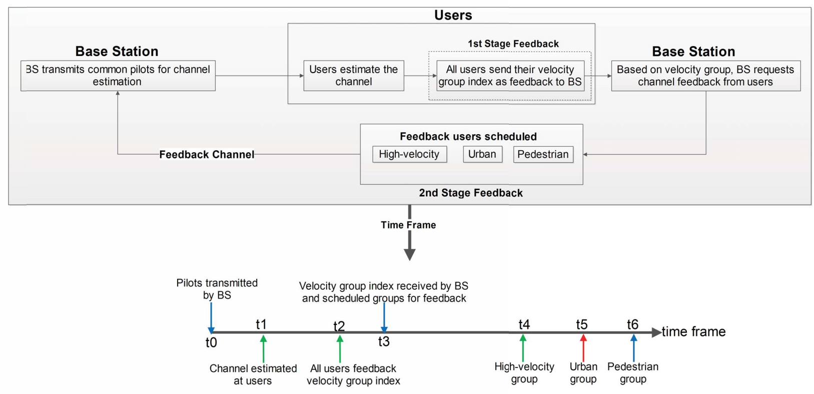

Figure 3.3. Feedback Scheduling Mechanism ©2013 IEEE

Performance Investigation

The performance comparison is done in terms of average SNR gain for different numbers of feedback bits. The performance of the proposed sched-

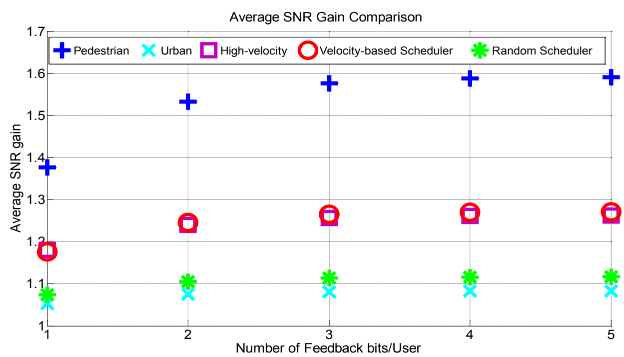

Figure 3.4. Feedback Delay Analysis ©2013 IEEE

uler is compared with a random feedback scheduler that does not consider any specific factors for decision making. Key simulation parameters include 10 users that are divided into group of 3 pedestrian, 5 urban and 2 high velocity users. Based on this setup, the performance curves are shown in Figure 3.4. Considerable gain is observed with the proposed scheduler in comparison to random scheduling. In addition to overall performance, the performance for each group is also independently compared. It can be observed that even though the pedestrian group is scheduled at the last, still it has the best performance. The urban user group's performance is better than that of random scheduling and high-velocity group performs similar random scheduling. These performance improvements are achieved as a result of this scheduling algorithm which adapts according to the user velocity groups.

3.2.2 Interference Coordination with Dynamic Scheduling in MU-MIMO

Modeling

The system model consists of a K users having one antenna each and a base station with 2 transmit antennas. With two transmit antennas at the base station, at maximum two users can be scheduled in the same time-frequency resources for downlink. With this system model, 8-tap Rayleigh fading channel for downlink and 1-tap Ricean channel for uplink is used [25, 63]. The channels for different users transmitting at the same time are correlated depending on their locations. The users are randomly distributed in a single cell and are moving according to the mobility model described in [6]. Noise is modeled as additive white Gaussian noise (AWGN) with zero mean and unit variance at the receiver. For robust downlink detection at the user in MU-MIMO transmissions, a low complexity interference-aware (IA) receiver is used, based on the principle of maximizing the channel of the desired signal and minimizing the interference channel [40].

Dynamic Scheduling

In order to fully exploit the benefits of MU-MIMO, dynamic scheduling of users is proposed, consisting of two main components: finer granularity feedback and pre-processing algorithm. They are depicted in Figure 3.5 that shows a basic communication chain for the MU-MIMO.

In 3GPP LTE Release 8, only wide-band feedback method for PMI is utilized for MU-MIMO that allows only two bits of feedback to provide the user's PMI to the BS. This is not enough to extract sizable gains from MU-

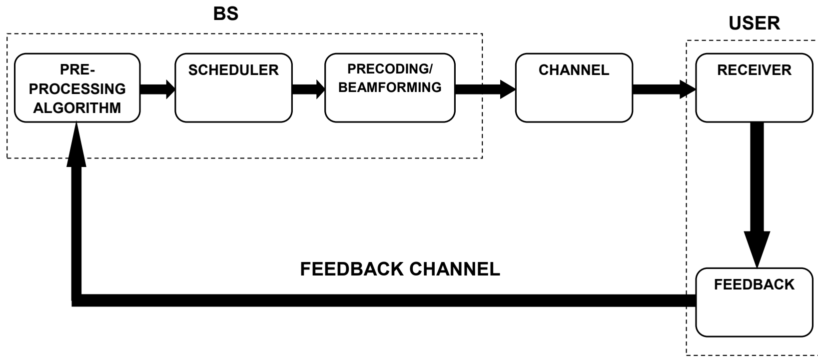

Figure 3.5. MU-MIMO Communication Chain ©2013 IEEE

MIMO [5]. Therefore, a sub-band feedback method for MU-MIMO would prove more beneficial. For this purpose, a new downlink control information (DCI) format 1E is proposed for 3GPP LTE Release 8 that allows the base station to indicate to the users that they should send sub-band feedback. This is enabled with only three additional bits. The details of the proposed DCI format are shown in Publication II. Utilizing this finer granularity sub-band feedback, a dynamic scheduling algorithm is designed. Figure 3.6 shows the sequential steps involved in this scheduling algorithm.

A compatible pair of users with orthogonal PMIs is selected for every sub-band such that it ensures minimization of interference from other user and maximization of desired signal at the receiver. The precoding matrix for a pair of orthogonal PMIs in LTE can be given as

$$\frac{1}{\sqrt{4}}\begin{bmatrix} 1 & 1 \\ q & -q \end{bmatrix}$$

where $q = \{+1, -1, +j, -j\}$. Therefore, the received signal by the first user is

$$r_1 = \frac{1}{\sqrt{4}}(h_{11}^* + qh_{21}^*)s_1 + \frac{1}{\sqrt{4}}(h_{11}^* - qh_{21}^*)s_2 + n \tag{3.6}$$

where s_1 and s_2 are the complex symbols for user 1 and user 2 respectively, h_{11}^* is the transpose of the channel from transmit antenna 1 to user 1, h_{21}^* is the transpose of the channel from transmit antenna 2 to user 1 and n is the noise. In the received signal, the first term is the desired part which is maximized and second term is interference which is minimized because of this scheduling. This scheduling algorithm also takes those scenarios into account when SU-MIMO might be expected to have better throughput than MU-MIMO. Therefore, this algorithm does not blindly

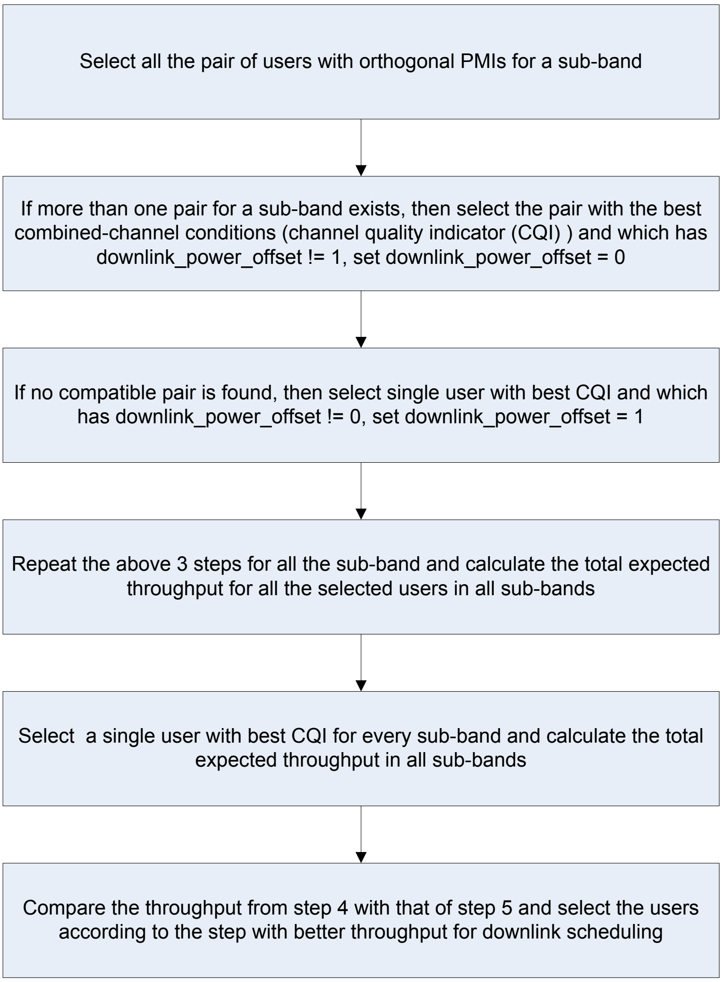

Figure 3.6. Dynamic Scheduling Algorithm ©2013 IEEE

schedule users for MU-MIMO transmission, but rather follow a dynamic approach for switching between MU-MIMO and SU-MIMO to provide optimal system level performance.

Performance Investigation

The performance comparison is presented in terms of average system throughput. The results are obtained from system level simulations involving all the protocol layers in 3GPP LTE architecture. The key simulation parameters are transmission bandwidth of 5 MHz with 7 sub-bands and full buffer traffic. Detailed parameters are given in Publication II. Figure 3.7 gives the performance comparison in terms of average sys-

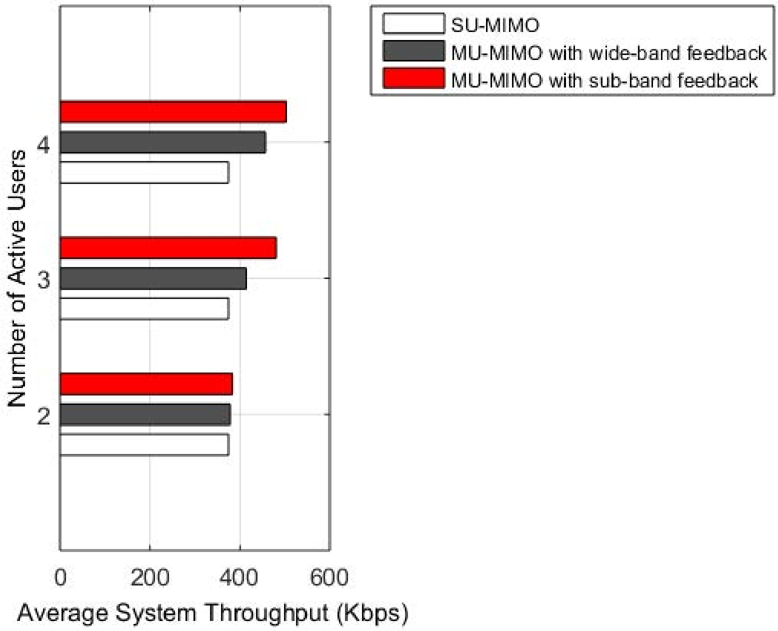

Figure 3.7. System Throughput Comparison ©2013 IEEE

tem throughput. Three key observations are made. Firstly, the average throughput for MU-MIMO with sub-band feedback is better than that of wide-band feedback for any number of users. Secondly, the average throughput increases with increasing number of users. This is because the probability of finding orthogonal users increases with increasing number of users. Thirdly, it is observed that the performance of MU-MIMO in 3GPP LTE Release 8 is almost same as SU-MIMO when there are only two active users in the system. However, the performance improves clearly for MU-MIMO with increasing number of users.

3.2.3 Hybrid-ARQ in Distributed System

Modeling

The system model consists of a user equipment as source node, a destination which is the base station and two relay nodes in the between the source and destination. The relay nodes determined here are Type 1 according to 3GPP LTE Release 10 specifications [64]. The simulator for this research was developed for a uni-directional transmission of information from source to destination via decode-cooperate-forward technique at the relay nodes. Tapped-Delay Line (TDL) channel with a Ricean model is used for the analysis [81]. It is a frequency selective channel model with an exponentially decaying power-delay profile (PDP), with each channel path being independent of each other. In order to enable distributed communication via the antennas of relay nodes, different cooperative schemes can be used. In this analysis, two cooperation methods namely distributed Alamouti [8] and distributed linear delay diversity [9] are utilized.

Smart Hybrid-ARQ Schemes

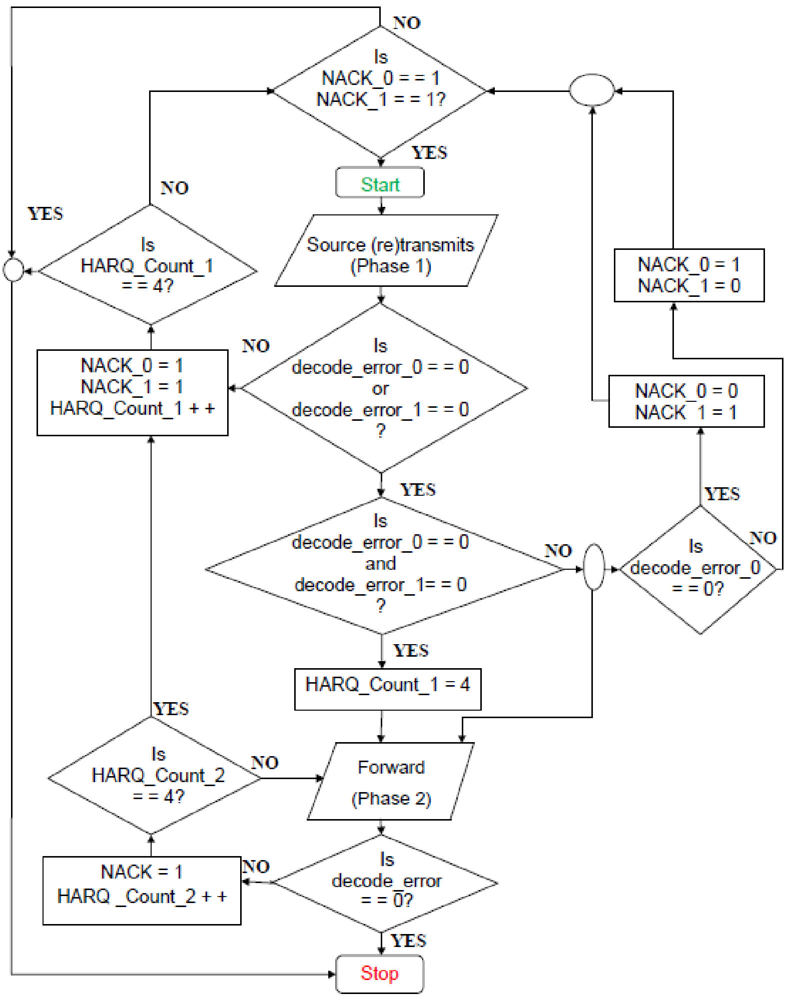

Figure 3.8. HARQ Scheme 1 ©2013 IEEE

In order to improve the end-to-end performance, efficient HARQ schemes are needed to fully utilize the benefits of cooperative schemes. The cooperative system of distributed relays establishes end-to-end link in two phase transmission: phase 1 is transmission from source to relays and phase 2 is from relays to destination, with phase 2 establishing the link even when just one relay decodes the signal. Based on this, two HARQ schemes are designed that are shown in Figure 3.8 and Figure 3.9.

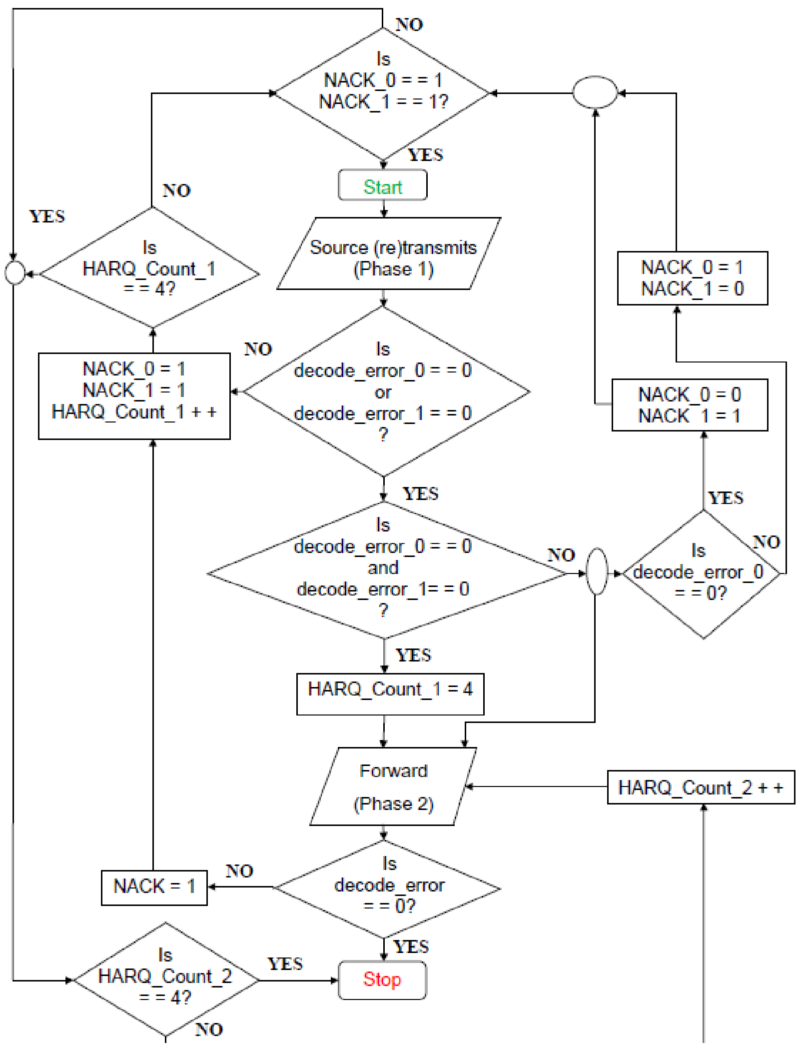

Figure 3.9. HARQ Scheme 2 ©2013 IEEE

Scheme 1 is based on having retransmissions in phase 2 irrespective of the state of the system, which means if the final destination decodes incorrectly then the scheme initiates retransmissions in phase 2 between forwarding relay(s) and destination and continue till the destination decodes correctly or till maximum number of retransmissions is reached for phase 2. When the retransmissions for phase 2 are exhausted, then it demands retransmissions in phase 1 if the number of retransmissions were not reached initially. The benefit of this approach is that it do not initiate retransmissions in phase 1 if already both relays were forwarding in phase 2. Contrary to Scheme I, Scheme 2 do not initiate retransmissions in phase 2 if the destination decodes signal incorrectly. Rather, when destination decodes incorrectly, it sends non-acknowledgment (NACK) to the forwarding relay(s), and instead of initiating retransmissions in phase 2 after receiving NACK from destination, the relay(s) send NACK to the source and the source starts retransmissions, if the maximum number of retransmissions are not exhausted.

Performance Investigation

The performance comparison is shown in terms of end-to-end throughput. The results are obtained from system level simulations with key simulation parameters as: transmission bandwidth of 5 MHZ, carrier frequency of 2 GHz and 1 transmit and 2 receive antennas at all nodes. Detailed parameters are shown in Publication III. The performance results are shown in Figure 3.10 for both the cooperative schemes using HARQ Scheme 1 (called as SHARQ 1) and Scheme 2 (called as SHARQ 2). For baseline reference, simple scenarios with a single relay and no HARQ are also shown. There are mainly three key observations from the performance

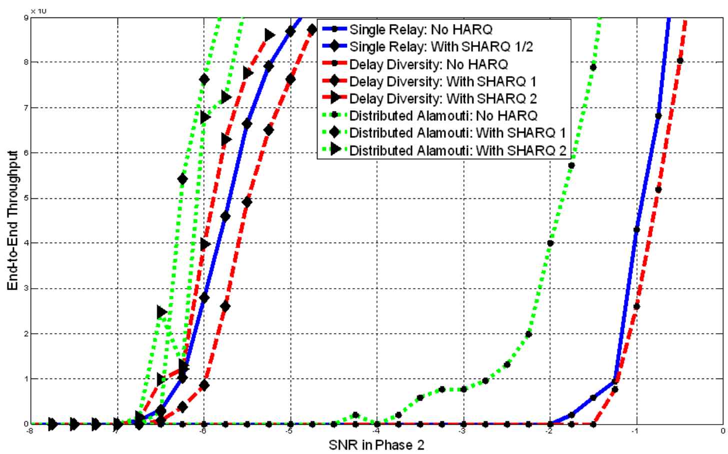

Figure 3.10. End-to-end Throughput Comparison ©2011 IEEE

curves. First, both the cooperation methods provide better performance with HARQ rather than single transmission without HARQ. Second, distributed Alamouti performs better than delay diversity method. Lastly, there is only a marginal difference in the performance of the two HARQ schemes.

3.3 Summary

In this chapter, we addressed different aspects of MU systems and proposed solutions that improves the system performance. The issues addressed here include the impact of delay and mobility on feedback, interference coordination in MU-MIMO and large number of HARQ retransmissions in distributed MIMO system. The key findings can be summarized as follows. First, we quantify the impact of delay and mobility on feedback and utilize this information to propose an adaptive feedback scheduling algorithm that allows the transmitter to receive feedback while it is still valid and can be effectively used for beamforming. Through simulation studies, we are able to demonstrate gains in terms of received SNR with adaptive feedback scheduling. Second, we study the performance of existing MU-MIMO framework in 3GPP LTE Release 8 and propose enhancements that allow finer granularity feedback using existing codebooks. This finer granularity feedback is then utilized to implement dynamic scheduling of multi users in MU-MIMO system. One of the main outcomes of this work is that MU-MIMO performs better than SU-MIMO when there are large number of active users in the system and finer granularity feedback is utilized for scheduling. Lastly, we propose HARQ schemes for a distributed MIMO system that improves the end-to-end performance by reducing the total number of retransmissions and thus reducing the overall delay.

4. Synchronization in Device-to-device Communication

3GPP studied the radio aspects of D2D as proximity service in [7] and introduced the specifications in Release 12. The main focus of D2D in 3GPP LTE Release 12 is on public safety use cases. In this chapter, the synchronization procedures in D2D communication are investigated that are described in Publication IV. A description of the new synchronization signals introduced for D2D is given and relevant issues are addressed to enable faster synchronization between the devices involved in D2D communication. The main proposal deals with robust detection method for D2D synchronization signals.

4.1 Problem Description

Similar to legacy communication involving BS, D2D operation also consists of synchronization procedures to establish and maintain communication between the users. D2D synchronization procedure involves a synchronization source that transmits the synchronization signal required by user to obtain timing and frequency synchronization. There are two types of D2D synchronization signals: primary D2D synchronization signals (PD2DSS) and secondary D2D synchronization signals (SD2DSS), that are based on the existing signals used for synchronization in LTE downlink as defined in 3GPP LTE Release 8 [4]. However, specific parameters and constraints are designed according to the requirements of D2D. Due to this, mainly two issues exists with synchronization signals detection in D2D.

1. First, all D2D signals are single carrier frequency division multiplexed (SCFDM) and transmitted at a low power. Therefore, the detector should be able to detect them at lower SNR levels.

2. Second, D2D synchronization signals are transmitted with a periodicity of 40 ms which is much longer in comparison to periodicity of 5 ms in downlink communication. Therefore, the detection method needs to be robust and time efficient so that the acquisition period is not long.

State-of-the-art detection involves correlating the received signal with the known base sequences (that are used to generate synchronization signals) and comparing them with the detection threshold to find out the corresponding peaks and hence the PSS symbol location [92]. More advanced methods involves averaging the correlations over two or more periods and comparing them with the threshold [100]. Since most of the other existing methods are designed for downlink PSS detection and hence are not the optimal solution for PD2DSS detection because of the modifications in D2D.

4.2 Modeling and Detection of Synchronization Signals

The system model used for this study involves one BS and two users, with one of the users being in-coverage of the BS and the other in out-of-coverage. The in-coverage user is synchronized with the BS and the out-of-coverage must initiate synchronization with in-coverage user, before proceeding to further communication.

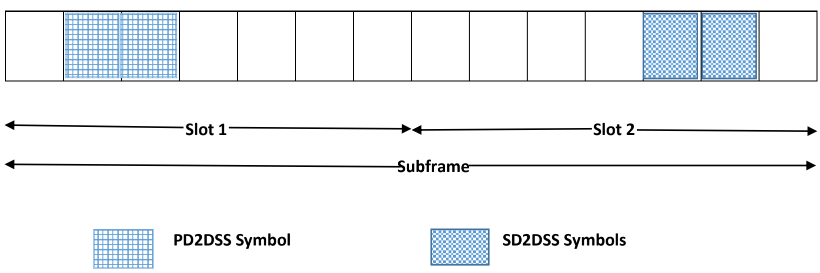

Figure 4.1. Synchronization Signals in D2D ©2015 IEEE

Figure 4.1 shows the position of D2D synchronization signals within a 3GPP LTE subframe with normal cyclic prefix. In contrast to single PSS and SSS in downlink, there are two PD2DSS and two SD2DSS symbols within a subframe. PD2DSS is located at symbols 1 and 2, and SD2DSS is located at symbols 11 and 12. In the frequency domain, both PD2DSS and SD2DSS are of length 63 and occupy the 6 central PRBs, similar to downlink synchronization signals.

4.2.1 Detection Method

The most crucial step in the detection is the PD2DSS detection. If the PD2DSS detection is done correctly, then only SD2DSS detection can happen correctly. Therefore, the proposed methods here deal with PD2DSS detection method. The detection method utilizes the two PD2DSS symbols within a subframe in an efficient way. The basic principle for this detection method is based on the following information:

1. There are two PD2DSS symbols in a subframe.

2. The relative symbol-wise distance between the two PD2DSS symbols is known at the receiver.

Figure 4.2 shows the proposed algorithm. Steps 5-6 are crucial for this method and key performance differentiator in comparison to existing detection methods [92, 100]. Instead of relying on the peaks detected from step 4, the method utilizes the information that an additional PD2DSS symbol is present within the subframe at a pre-defined relative symbol-wise distance. Further refinement of detected peaks is carried out in step 5, where the detected peaks and detection threshold are correlated with the peaks and detection threshold at a known relative symbol-wise distance between PD2DSS symbols in the same subframe. Due to selective summing of correlations, the method has two main benefits from the implementation point of view. First, summing of correlations is not required at all locations, thereby reducing the complexity of the algorithm. Second, double peak detection at step 4 and step 6 respectively ensures robustness against incorrect detection.

4.3 Performance Investigation

The results are generated using a link level simulator based on 3GPP LTE specifications and is compatible with 3GPP LTE D2D assumptions in Release 12. Publication IV specifies all the key simulation parameters.

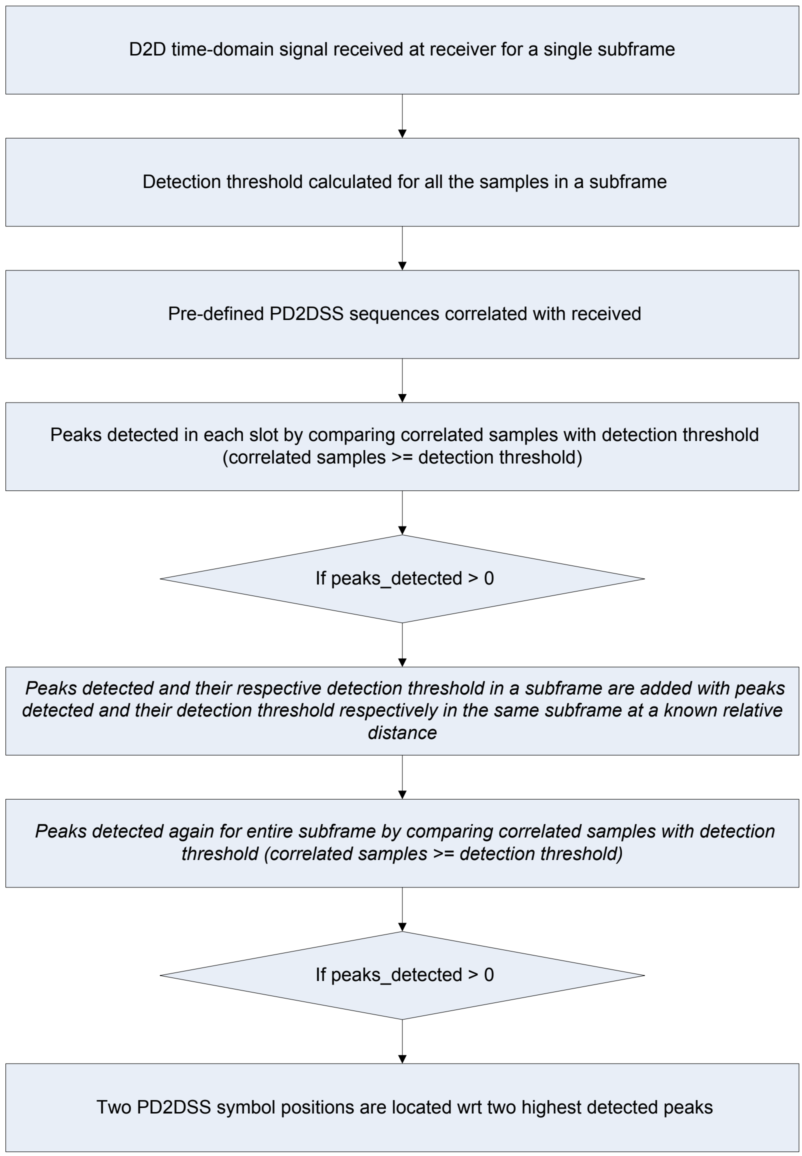

Figure 4.2. Detection Algorithm ©2015 IEEE

There are mainly two metrics used as performance indicator of synchronization signal detection: the probability of correctly detecting the presence of synchronization signal within a subframe, which is defined as hit-rate and the probability of incorrect detection, which is called false-alarm rate. It is required to have a target of 90 percent hit-rate and under 5 percent false-alarm rate. Figure 4.3 compares the performance of the proposed detection with single peak detection method in terms of

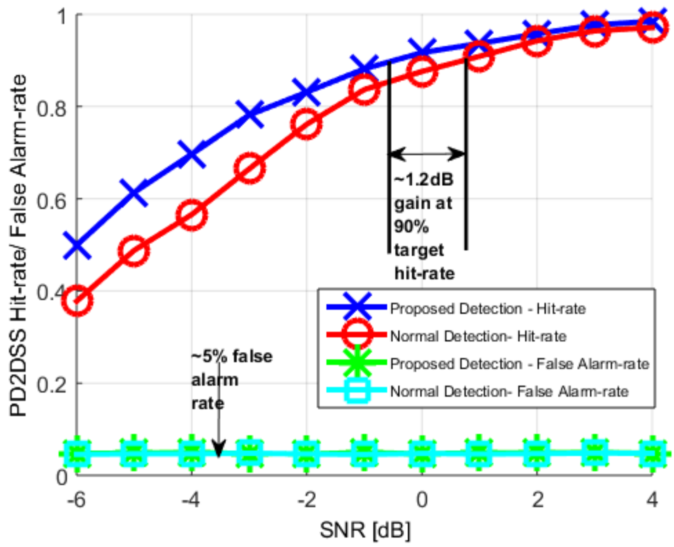

Figure 4.3. Detection Method Performance ©2015 IEEE

SNR gains to achieve target performance metric. The proposed detection method reach the target performance at -0.5 dB in comparison to 0.75 dB with normal detection method, thus providing a gain for more than 1 dB. Consequently, the acquisition time is reduced for given SNR level with the proposed detection method.

4.4 Summary

In this chapter, we addressed the D2D synchronization procedure in 3GPP LTE Release 12 and proposed a robust detection method for PD2DSS. This detection method allows correctly detecting the synchronization signals at lower SNR due to an extra correlation factor, while at the same time maintaining a low implementation complexity due to selective summing. As a result, the synchronization time is reduced for D2D communication.

5. Control Signaling Allocation in Carrier Aggregation

Frequency spectrum as a radio resource is very fragmented and limited. For more efficient utilization of spectrum, CA up to 5 CCs was introduced in 3GPP LTE Release 10 that allowed operators to turn their investment in additional LTE carriers into marketable high data rates by aggregating fragmented chunks of frequency spectrum. This has encouraged operators to deploy CA with even larger number of CCs. Therefore, due to limited support for CA in 3GPP LTE Release 12, expansion of CA beyond 5 CCs was proposed for 3GPP LTE Release 13, with main focus on downlink CA [6]. In this chapter, the impact on uplink control signaling due to expansion of downlink CA up to 32 CCs in 3GPP LTE Release 13 is studied and required enhancements are investigated as described in Publications V and VI.

5.1 Problem Description

In order to extend the CA framework beyond 5 CCs, a number of enhancements are required as specified in [10]. The key issue here is the impact of extension on the control signaling overhead. In order to support downlink CA beyond 5 CCs, uplink control information (UCI) overhead increases significantly and the problem arises due to the fact that the resources used to transmit this information do not increase with increasing number of CCs. Most of the uplink control signaling overhead is transmitted on physical uplink control channel (PUCCH) and until 3GPP LTE Release 12, PUCCH transmission is allowed only on the primary carrier and not on secondary CCs. Figure 5.1 shows an example of how the combined UCI overhead is transmitted only on primary carrier in order to support the aggregation of 5 CCs in downlink. The main problem can be described as efficient resource allocation for very large uplink control signaling over-

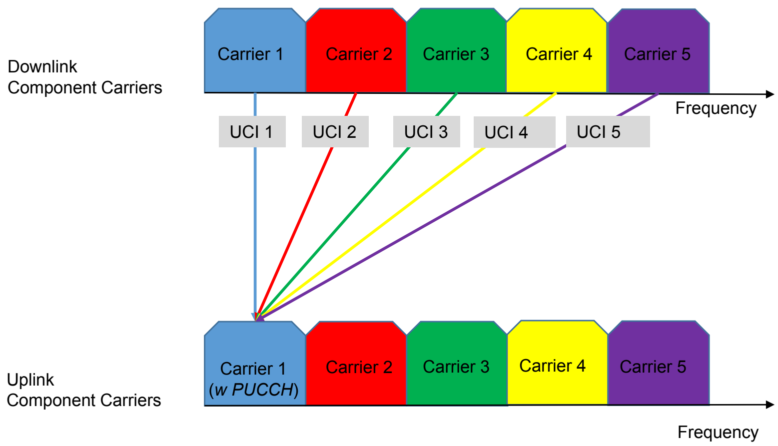

Figure 5.1. Example of Combined Uplink Control Information Overhead on Primary Uplink Carrier to Support Downlink Carrier Aggregation for Five Component Carriers ©2016 IEEE

head within the constraints and limitations of CA in 3GPP LTE.

5.2 Signaling Overhead and Resource Allocation for Control Signaling

5.2.1 Signaling Overhead

UCI consists of HARQ-ACK feedback information, CSI and scheduling requests (SR). For transmission with spatial multiplexing, two bits of HARQ feedback is transmitted on uplink for every downlink component carrier. In case of FDD and symmetric uplink/downlink frame structure in TDD, up to 64 bits of HARQ-ACK feedback needs to be transmitted on a single uplink subframe for downlink CA up to 32 CCs, assuming spatial multiplexing is supported on all component carriers. Moreover, extreme cases of asymmetric uplink/downlink frame structure in TDD would result in even larger payloads. Table 5.1 shows examples of payload sizes (after spatial bundling) for different configurations that could be supported on a uplink primary cell for DL CA up to 32 CCs in future cellular networks [9]. Although Table 5.1 shows all possible configurations for CA with different FDD/TDD frame structures, it may not be necessary to support the extreme cases, at least for CA enhancements in 3GPP Release 13. The new PUCCH formats are expected to support quite large payload.

Configuration			HARQ-ACK payload(bits)
FDD			32
TDD	0	TDD-FDD CA	32
		TDD-FDD CA	63
	1	TDD CA	64
		TDD-FDD CA	95
	2	TDD CA	128
		TDD-FDD CA	159
	3	TDD CA	96
		TDD-FDD CA	189
	4	TDD CA	128
		TDD-FDD CA	190
	5	TDD CA	288
		TDD-FDD CA	319
	6	TDD CA	32
		TDD-FDD CA	94

Table 5.1. HARQ-ACK Feedback Payload for Different Configurations ©2016 IEEE

5.2.2 Resource Allocation for Control Signaling

From the point of view of this thesis, major contribution has been investigation of PUCCH enhancements to support larger HARQ-ACK payload in 3GPP LTE Release 13.

Investigation of Existing PUCCH Formats

The first phase of the study involves evaluating the possibility of using existing PUCCH formats for CA until 3GPP Release 12 to support larger payloads. PUCCH format 1b with channel selection and format 3 were introduced for CA in 3GPP LTE Release 10 to support payload up to 4 bits and 22 bits, respectively. Format 1b with channel selection is limited to very small payload and do not provide much scope to larger payload. However, possible modifications to PUCCH format 3 can result in supporting larger payloads. According to specifications in 3GPP LTE Release 12, a set of 4 resources is configured by RRC signaling, of which one resource is then dynamically indicated for PUCCH format 3 transmission. One possible solution is multiple PUCCH format 3 transmission that allows the usage of more than one resource. The main advantage of this solution is that by dividing the payload among a number of PUCCH resources, the risk of losing all HARQ information in the case of detection failure is reduced. If one of the PUCCH transmissions fails another one may still be successful. However, since more resource blocks are used for signaling overhead, therefore more resource blocks result in decreased resources for data channel carrying useful information.

Investigation for New PUCCH Formats

There are three main aspects that have been considered for designing new formats.

1. Channel Coding: Channel coding scheme used for UCI on PUCCH format 3 is Reed-Muller (RM) code [85], which is optimal only for small size of codewords. Therefore for larger payload, RM coding as such is not the best choice. The coding scheme should be able to support a varying number of input bits ranging from 10s to 100s. Convolution Coding is considered optimal for such codewords sizes and moreover, it is already used for other channels in 3GPP LTE. Therefore, no additional modification in terms of new channel coding implementation would be required in the specifications.

2. Code-division multiplexing (CDM): In format 3, orthogonal cover code (OCC) sequences are applied to the SCFDMA symbols used for carrying UCI. These sequences are discrete Fourier transform (DFT) sequences of length 5, allowing for multiplexing of up to 5 format 3 transmissions within the same PRB [2]. As a result, only 12 QPSK modulated data symbols with HARQ information can be transmitted in a single slot. Therefore, to increase the PUCCH capacity, it is considered to either reduce the OCC sequence length to a smaller number or completely remove the CDM support. With a smaller OCC sequence length, the control information is spread over smaller number of SC-FDMA symbols thus providing more information for additional control information.

3. Demodulation reference signals (DMRS): PUCCH format 3 structure consists of two DMRS symbols per slot and one DMRS per slot for normal CP and extended CP, respectively. In case of normal CP, there is a possibility to reduce the DMRS symbol to one per slot for new formats. This would provide an additional symbol per slot for UCI feedback transmission. Link level simulations are required to investigate the impact

on detection with reduced DMRS for channel estimation.

Based on these aspects, a number of potential candidates for new PUCCH formats have been investigated.

- Candidate 1: This is based on existing PUCCH format 3 as the entire structure is the same except for the channel coding. Instead of using the RM channel coding, candidate 1 is proposed to use convolution coding as it is expected to provide better coding gains for slightly larger size codewords.

- Candidate 2: This candidate is proposed as a hybrid of PUCCH format 3 and PUSCH structure. The main proposals include using convolutional coding, only one DMRS symbol in the middle of 7-symbol time slot and OCC length of 3. Therefore, it provides more resources and better channel coding and still the possibility to multiplex 3 users on same PRB for PUCCH transmission.

- Candidate 3: With this candidate, no OCC is considered, but two DMRS symbols similar to format 3 are proposed. In addition, convolutional coding is used, similar to candidate 1 and 2. This ensures that there is no compromise in terms of channel estimation since there is no change in the number of DMRS symbols, but there is no possibility of multiplexing.

- Candidate 4: This candidate has been included as one of new PUCCH formats in 3GPP LTE Release 13 and is called as PUCCH format 4. The generic design is shown in Figure 5.2 and it is introduced Release 13 to support relatively higher range of the payload sizes over 100 bits [11]. This structure is similar to PUSCH as it has one DMRS symbol/slot and no CDM is supported. Due to the lack of support for CDM, only a single PUCCH format 4 can be transmitted on a single PRB. Thus it can accommodate the largest payload in comparison to any other PUCCH format. This enables the transmission of 144 QPSK modulated symbols in a single PRB.

- Candidate 5: It has been added as the second new PUCCH format in

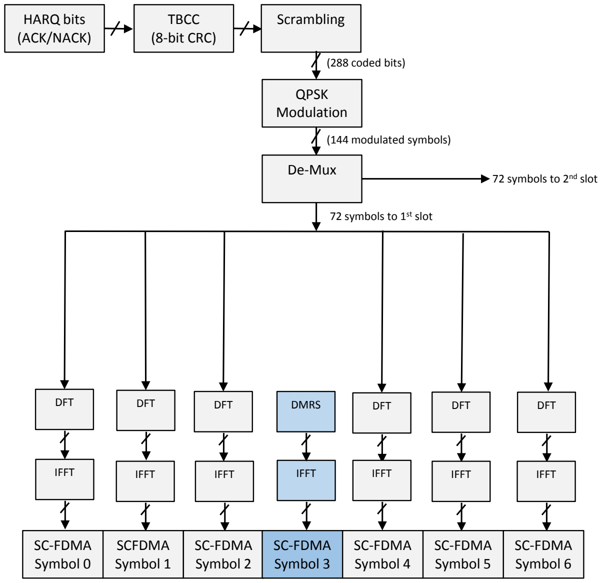

Figure 5.2. Candidate 4 added as PUCCH Format 4 ©2016 IEEE

Release 13 and called as PUCCH format 5. Figure 5.3 shows the design structure.

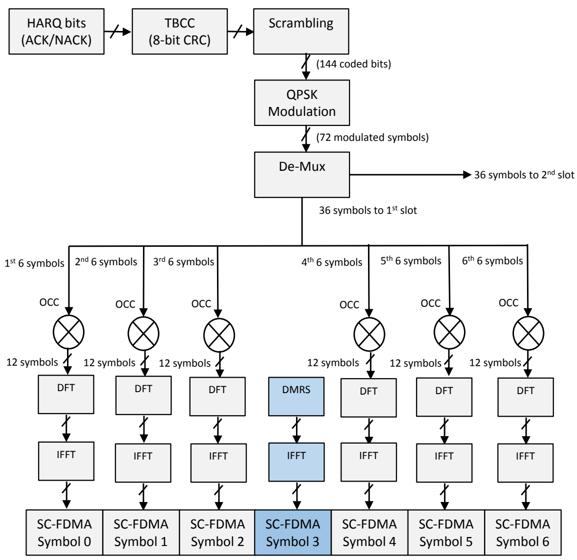

Figure 5.3. Candidate 4 added as PUCCH Format 5 ©2016 IEEE

It is introduced to support payload under 100 bits. In comparison to

PUCCH format 4, the key structural difference is the support for CDM. OCC sequence of length 2 is applied in this format, which allows simultaneous transmission of two PUCCH format 5 on the same PRB. As a result, only 72 QPSK modulated symbols can be transmitted in a single PRB. This format provides a trade-off between PUCCH format 3 and PUCCH format 4 in terms of maximum supported payload and multiplexing capacity.

5.3 Performance Investigation

For performance evaluation, a link level simulator is utilized. The simulation assumptions are based on the agreements made in 3GPP LTE Release 13 for investigation of new PUCCH formats. Publication VI shows all the key parameters that are used to generate the results. For the sake of investigation HARQ-ACK payload sizes ranging from 22 – 200 bits are used. Mainly two performance metrics for PUCCH formats are used in 3GPP: ACK missed detection probability with 1 percent target and NACK-to-ACK error probability with 0.1 percent target [3]. For the overall performance, the SNR required to achieve the combined performance target for 1 percent ACK missed detection probability and 0.1 percent NACK-to-ACK error probability is plotted against payload sizes.

Figure 5.4(a) evaluates the performance of existing PUCCH format 3.

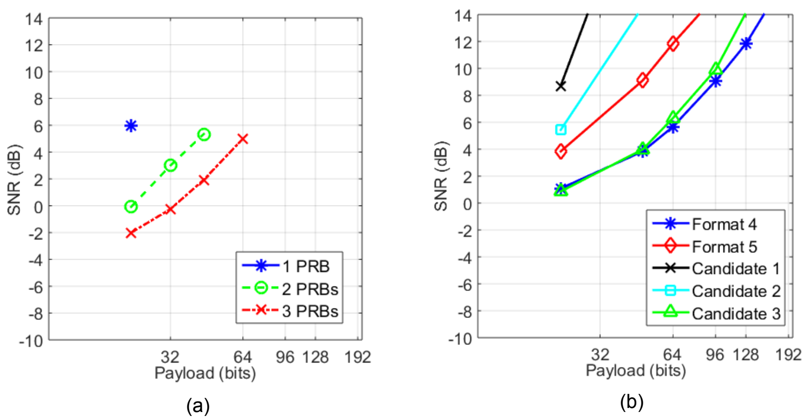

Figure 5.4. Required SNR vs Payload for combined target of 1 percent ACK missed detection probability and 0.1 percent NACK-to-ACK error probability (a) PUCCH format 3 compared with similar structure allocated larger bandwidth; (b) New PUCCH formats and other candidates with 1 PRB ©2016 IEEE

Results for multi-PRB allocation with up to 3 PRBs are also shown. It can be seen that the required SNR to achieve target for 22 bits payload is 6dB for 1 PRB allocation. For 2 and 3 PRBs, twice and thrice the payload is supported at approximately 6dB, respectively. However, this would provide a limited increase in the supported payload sizes and is not considered sufficient enough for CA up to 32 CCs. In Figure 5.4(b), the performance of new PUCCH Formats 4 and 5 is evaluated along with other candidates that have been considered. Format 4 is able to support the largest payload for a given SNR. It performs better than candidate 3 and thus showing that 1 DMRS symbol/slot is an optimal solution. Candidate 1 has the worst performance which shows that convolution coding is not the preferred coding scheme for lower payload as format 3 with RM code performs better at 22 bits payload and single PRB allocation. PUCCH Format 5 is a good trade-off between format 3 and format 4 since it performs better than format 3 in terms of required SNR and at the same time allowing multiplexing factor of 2 in comparison to no multiplexing in format 4.

5.4 Summary

In this chapter, we analyzed the existing support for control signaling transmission for CA enhancements in 3GP LTE-A Pro. In the studied methods, one of the basic solution is to use multiple resources to transmit control information using existing PUCCH formats. However, such method could only support slightly larger control signaling overhead and therefore new candidates for PUCCH formats have been studied. The main outcomes include the investigation of several factors such as channel coding, reference signal design and multiplexing that are important for designing the new PUCCH formats. Performance comparison is presented for different candidates in terms of target performance metric. Based on such investigation, two new PUCCH formats have been specified in 3GPP LTE-A Pro Release 13.

6. MAC-layer Scheduling Framework

This chapter deals with the MAC-layer scheduling framework for PS modern wireless networks such as 3GPP LTE, as described in Publication VII. In order to efficiently handle multi-user multi-QoS traffic flow, two-dimensional buffer management is proposed for improving the performance of existing scheduling algorithms by introducing a pre-processor block. Furthermore, a three-step iterative scheduler is also proposed to fully exploit two-dimensional buffer management framework as described in Publication VIII.

6.1 Problem Description

Modern mobile devices are capable of simultaneously running multiple internet applications. These applications may have different QoS requirements. Moreover, there can occur multiple users requesting such applications at the same time. This leads to multi-user multi-QoS traffic flow. As an example, Figure 6.1 shows K users requesting N applications simultaneously. Depending up on the QoS requirement, each application is mapped to a corresponding logical channel. Traditional scheduling frameworks are usually designed to deal with users having single QoS class and therefore apply the scheduling algorithm at the user level [23, 24, 103]. Such framework would lead to inefficient buffer management and suboptimal system performance in multi-user multi-QoS traffic conditions. In the traditional MAC, the scheduling algorithm optimally allocates resources to users based on the assumption of user belonging to single QoS. Therefore, the main problem to be addressed here is to design an efficient framework that does two-dimensional buffer management in multi-user multi-QoS environment, while at the same time can be easily integrated into the existing system framework.

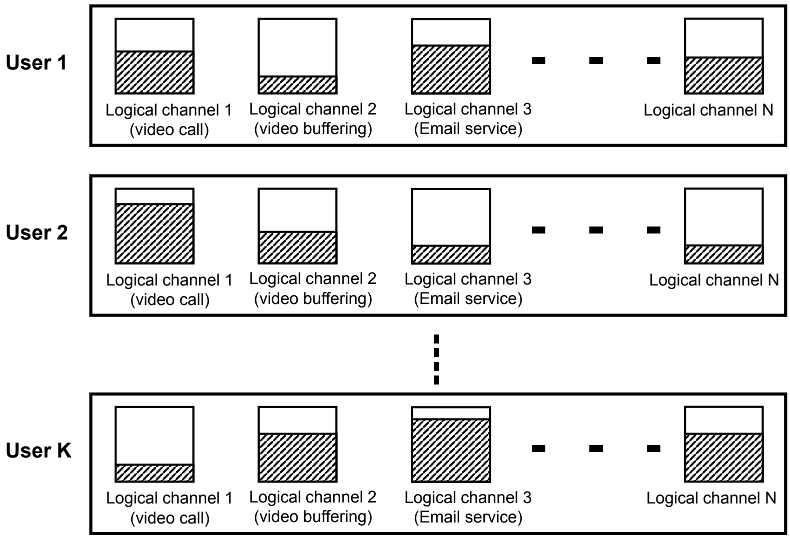

Figure 6.1. Multi-user Multi-flow Traffic Buffer ©2014 IEEE

6.2 Modeling and Proposed Solutions

6.2.1 Modeling

Scheduling framework for downlink transmission from the base station to the users is considered for an all-IP PS 3GPP LTE network. The analysis considers downlink transmission to K users having N logical channels. Every logical channel is associated with a service belonging to specific QoS class. Depending up on the service requests, there is a buffer queue in the respective logical channel of a user. Multiple users requests multiple services at the same time, thus resulting in multiple buffer queues waiting to be scheduled. Each buffer queue is identified by a set of parameters that are utilized for designing the framework and scheduling algorithm's decision making.

Framework Parameters

For pre-processing buffer and making scheduling decision, a subset of parameters are described that are categorized into different groups depending up on their interface with MAC-layer within the framework. All the parameters have a subscript that indicates the interface with MAC. b stands for MAC-buffer interface, p stands for MAC-PHY interface and s represents system-defined parameters. The parameters are categorized as packet-level, logical channel-level, user-level and system-level. Specific details of parameters in each group are discussed in Publication VII and VIII.

6.2.2 Proposed Framework Architecture

The main design criteria for this framework is to have an efficient two-dimensional buffer management at per-user per-service level which results in finer resolution for scheduling algorithms. In addition, this framework provides a generic solution to enhance the performance of existing scheduling algorithms for different wireless standards. Figure 6.2 shows the framework with all the blocks and their corresponding interfaces. Figure 6.2 shows the interfaces and the primary modules of the frame-

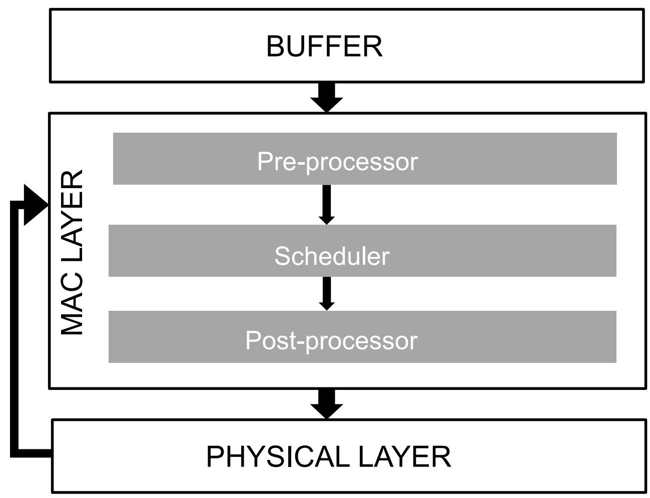

Figure 6.2. MAC-layer Scheduling Framework ©2014 IEEE

work. The interfaces consists of MAC-buffer and MAC-PHY interface. Firstly, the MAC-buffer interface shares the packet information of users and logical channels with the MAC-layer. Through this interface, a two dimensional structure of users and logical channels along with their associated parameters is created. These parameters informs the scheduler about traffic characteristics of every service. Secondly, the MAC-PHY interface allows interaction between physical and MAC layer via channels. The physical layer receives the feedback information from the BS and forwards it to MAC through MAC-PHY interface. This facilitates the channel-aware decision making by using channel quality information for calculating the expected throughput for a user and consequently for the entire system.

The MAC-layer is composed of three sub-blocks: pre-processor, scheduler and post-processor. Pre-processor represents a novel extension to the traditional scheduling framework. The primary purpose of the pre-processor is to convert the two-dimensional buffer of *users* $\times$ *logical channels* into a single dimension of blocks. As a result of this pre-processor, the scheduler module receives input in terms of block and its associated parameters. The traditional one-dimensional framework can easily be converted to this two-dimensional framework with the addition of this module and existing scheduling algorithms do not require to change in order to be implemented with this framework. Once the conversion to single dimension is done in the pre-processor, the first task of scheduler module is to deal with sorting of blocks based on any applied scheduling algorithm such as PF, RR, etc. The post-processor implementation depends on the wireless standard. The mapping of users to resource elements in the frequency domain is applied based on the specifications of the system. In 3GPP LTE, the selection of resource block groups (RBGs) for a particular service of a user is done by post-processor. Number of RBGs depends on the system bandwidth [5]. In LTE, RBGs are the smallest unit of frequency resources that can scheduled for a user.

6.2.3 Three-step Iterative Scheduler

As discussed in previous section, any scheduling algorithm can be integrated with the proposed framework to provide better performance. In this section, a new scheduling algorithm is designed to fully exploit the potential of two-dimensional buffer management in the proposed framework. This algorithm can be divided into three steps.

1. **Conversion**: This step is defined in previous section to convert two-dimensional buffer of users and logical channels into a single dimension of blocks.

2. **Sorting**: Sorting is iteratively done in three steps based on three calculated weights: throughput weight, latency weight and buffer weight given by Equations 6.1, 6.2 and 6.3, respectively.

$$\mathrm{TGPT}_{\mathrm{weight}} = \frac{BMT_j}{MPT} \tag{6.1}$$

$$\text{Latency}_{\text{weight}} = \frac{PRT}{PMD} \tag{6.2}$$

$$\text{Buffer}_{\text{weight}} = \frac{BS_j}{TBS \times NU} \tag{6.3}$$

where BMT_j is the maximum possible throughput for a block with index j, MPT is the maximum possible throughput of the system, PRT is packet remaining time in the buffer, PMD is packet maximum-allowable delay, BS_j is the buffer size of a block with index j, TBS is total buffer size and NU is number of active users.

3. **Allocation**: Once the blocks are sorted, the resources are allocated to the blocks. The number of resources that are allocated to each block is given by the QoS requirement and buffer size. The blocks with higher QoS requirement are allocated more number of resources in order to satisfy the guaranteed bit rate. The detailed algorithm for allocation of resources to sorted blocks is described in Publication VIII.

6.3 Performance Investigation

For performance investigation, a system level simulator based on 3GPP LTE is used. The key parameters include a transmission bandwidth of 5 MHZ, 9 logical channels for each QCI as described in Chapter 2. In the traffic generator, the average packet size and average inter-arrival time for each service based on [28] and [26] are utilized. The actual inter-arrival time between two packets for a given service of a user (block) is affected by $\mathrm{TL_b}$ (ranging on [0,1]) and given as

$$\text{APIT} = \begin{cases} \frac{\mathrm{PIT_b}}{\mathrm{TL_b}}, & \text{if } \mathrm{TL_b} \neq 0 \\ \text{no traffic}, & \text{otherwise} \end{cases} \tag{6.4}$$

where $\mathrm{PIT_b}$ is packet inter-arrival time and $\mathrm{TL_b}$ is traffic level for a user in a logical channel and it is randomly generated. The performance comparison is done in terms of total system throughput, fairness index and the percentage of users with satisfied guaranteed bit rate. Firstly, we investigate the performance of proposed framework. This is done by utilizing three existing scheduling algorithms and comparing their performance with and without the framework. The three scheduling algorithms measured are PF, RR and max-throughput [27]. Figures 6.3, 6.4 and 6.5 show

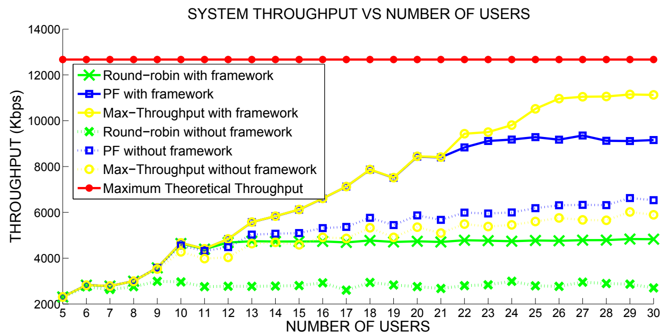

Figure 6.3. Throughput Performance for Framework ©2014 IEEE

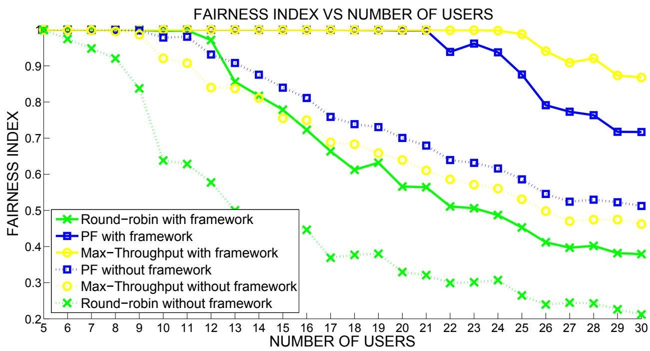

Figure 6.4. Fairness Performance for Framework ©2014 IEEE

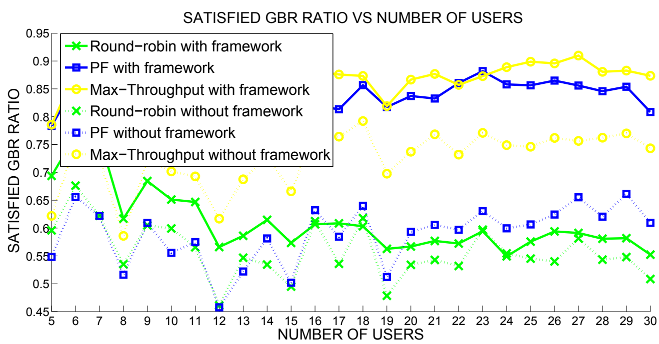

Figure 6.5. Satisfied GBR Performance for Framework ©2014 IEEE

that the proposed framework not only increases the throughput but also results in improved fairness index and provides better quality of service to users with higher percentage of satisfied GBR. Even with large number of active users, the fairness index and percentage of satisfied users is quite significant. However, it can be seen that the performance is still quite behind the theoretical maximum throughput and therefore, there is

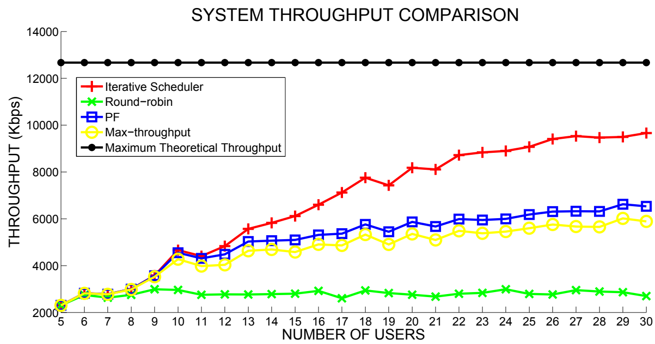

Figure 6.6. Throughput Performance for Three-step Iterative Scheduling Algorithm ©2014 IEEE

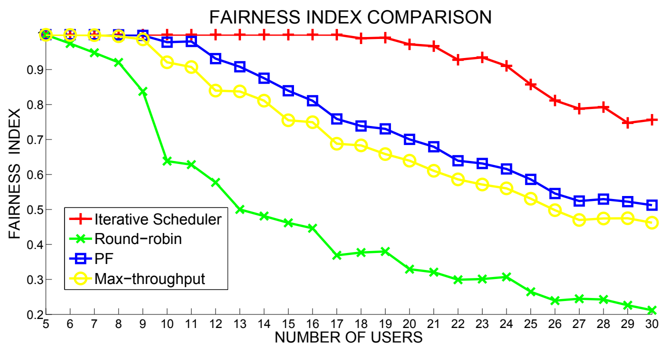

Figure 6.7. Fairness Performance for Three-step Iterative Scheduling Algorithm ©2014 IEEE

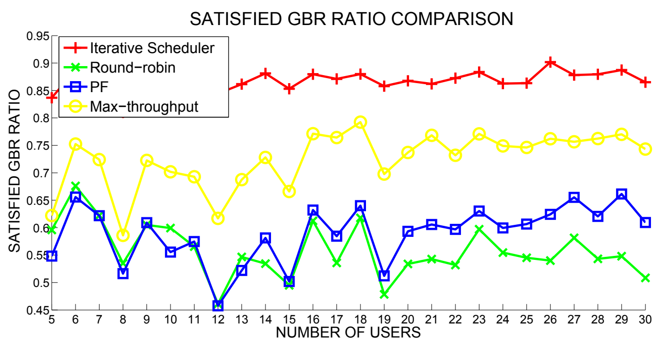

Figure 6.8. Satisfied GBR Performance for Three-step Iterative Scheduling Algorithm ©2014 IEEE

scope for further improvement. Therefore, a three-step iterative scheduling algorithm was proposed.

Figures 6.6, 6.7 and 6.8 show the performance comparison of proposed scheduling algorithm with the existing three algorithms. These performance curves are all produced with the new framework and hence providing a fair comparison. It can be clearly observed that the proposed scheduling algorithm outperforms all the other existing algorithms in terms of all three performance metrics.

6.4 Summary

In this chapter, we addressed the issue of multi-user multi-QoS traffic flow and proposed a scheduling framework to improve the performance of different scheduling algorithms by two dimensional buffer management. The proposed framework is applicable to PS network and designed as a module to be easily integrated to the MAC-layer. One of the main outcomes of this work includes the improvement of existing scheduling algorithms by utilizing this framework. Furthermore, a new scheduler algorithm is also proposed that is specifically designed to full utilize this framework and provide performance gain in terms of throughput, fairness-index and percentage of satisfied GBR users.

7. Conclusions

Cellular networks have been constantly evolving with the advent of advanced technologies to cater the ever-growing demands of high data rates, seamless connectivity and ubiquitous broadband experience. One of the main challenge has been to efficiently use the limited radio resources for integrating new technologies effectively within the constraints of real-world networks. Radio resource management has been one of the key aspects to enable the evolution of wireless networks such as 3GPP LTE. In 3GPP LTE, an evolved radio interface along with new SAE was introduced. Since then, 3GPP LTE has been evolving and has required more advanced RRM techniques to deal with new challenges posed by new technologies. Therefore, in this thesis, advanced techniques of RRM are studied and evaluated to efficiently enable advanced technologies in 3GPP LTE framework. RRM deals with several aspects in 3GPP LTE cellular networks such as power control, scheduling, cell search and synchronization, cell reselection, handover, interference management, radio link monitoring, and connection establishment and re-establishment, etc. In this work, four broad aspects related to RRM have been investigated.

First, RRM methods to deal with interference coordination in MU-MIMO systems was studied. MU-MIMO was introduced in 3GPP LTE to allow spatial multiplexing of multiple users for increasing the spectral efficiency. In theory, MU-MIMO provides significant gains in comparison to SU-MIMO. However, the practical gains for 3GPP LTE Release 8 MU-MIMO were not significant and in fact SU-MIMO performed better that MU-MIMO in certain scenarios. This has been mainly due to very limited support for MU-MIMO in 3GPP LTE Release 8. Therefore, in this thesis, one of the main motivations has been to improve the overall system performance with MU-MIMO. This has been done mainly with advanced interference coordination techniques by minimizing the interference between the participating users and maximizing their own signal. Finer granularity feedback have been utilized and a dynamic scheduling of users by switching between SU-MIMO and MU-MIMO on a sub-band basis is proposed. System level simulations in a 3GPP compliant simulator have been done to demonstrate the gains from proposed methods. Other aspects related to feedback delay, feedback scheduling methods and hybrid-ARQ in multi-user systems are also studied in this context. The main outcomes include quantifying the impact of delay and mobility on feedback, utilizing this information for adaptive feedback scheduling, utilizing finer granularity feedback for dynamic scheduling of multi users in MU-MIMO system and developing HARQ schemes for a distributed MIMO system to improve the end-to-end performance by reducing the total number of retransmissions.

Second, cell search and synchronization is one of the important aspect of RRM since it is required to initiate communication between the two nodes. In this research work, synchronization procedures in D2D are studied and robust detection method is proposed to allow faster timing and frequency synchronization. D2D has been introduced in 3GPP LTE Release 12, with initial focus on public safety use cases. The synchronization signals for D2D are based on downlink synchronization signals. However, specific requirements and constraints are more stringent in D2D due to example much more infrequent transmission of synchronization signals. Therefore, the detection of these signals should be fast, otherwise the D2D communication could not be initiated for a long time. The key outcomes include the development of a robust detection method for PD2DSS that allows to correctly detecting at low SNR values, while maintaining a low implementation complexity. As a result, the synchronization time is reduced for D2D communication.

Third, efficient resource allocation for signaling overhead is a major requirement to integrate most of the advanced technologies in real networks with limited resources in terms of frequency spectrum. Resource allocation related to CA has been investigated in this thesis. CA was introduced in 3GPP LTE Release 10 to combine CCs for larger aggregated bandwidth. More recently, CA has been enhanced in 3GPP LTE Release 13 to combine a large number of CCs for even wider aggregated bandwidth. One of the major issue with this enhancement is the increase in control signaling overhead. The important outcomes of this work has been the investigation of impact on the control signaling and corresponding enhancements to enable efficient allocation for the signaling overhead are investigated. Link level simulations based on 3GPP LTE have been conducted to show gains with the proposed and the accepted enhancements.

Lastly, the aspect of MAC-layer scheduling is dealt in this thesis. MAC-layer scheduling framework is an important component of 3GPP LTE protocol stack to provide the required QoS to the users. Over the last few years, the number of smart devices and internet-based applications on them have drastically increased. This has resulted not only an increase in data traffic and but change in the traffic pattern as well. In this thesis, the focus has been to deal with multi-user multi-QoS traffic flow where multiple users are requesting multiple services with different QoS requirements simultaneously. A novel scheduling framework is proposed to deal with mobile traffic in modern wireless networks. The framework is based on two-dimensional buffer management and it can easily be integrated with any existing scheduling algorithm and improve their legacy performance. In addition, more advanced scheduling algorithm is proposed to fully exploit the benefits of this framework. The main outcomes of this work includes the improvement of existing scheduling algorithms by utilizing this framework and developing new scheduler algorithm to full utilize this framework and show performance gain in terms of throughput, fairness-index and percentage of satisfied GBR users.

Most of the technologies that have been studied in this thesis are still in quite nascent stage in terms of practical deployment and therefore further improvements can be achieved by more efficient deployment in furture networks. The work on the next generation of wireless networks referred as the fifth generation (5G) has already started and technologies such as MU-MIMO, D2D communication and CA are expected to be among the key driving technologies. 5G wireless networks are expected to support 1,000-fold gains in capacity, a 10 Gb/s individual user experience capable of extremely low latency and response times. 5G radio access will be built upon both new radio access technologies (RAT) and evolved existing wireless technologies [35]. As studied in this thesis, multi-antenna transmission including MU-MIMO plays an important role in current generations of mobile communication. It is expected to be even more central in the 5G wireless networks. The 5G radio will employ hundreds of antenna elements to increase antenna aperture beyond what may be possible with current cellular technology. Beamforming will improve the radio environment by limiting interference to small fractions of the entire space around a transmitter and likewise limiting the impact of interference on a receiver. D2D communication including peer-to-peer user-data communication directly between devices and also the use of mobile devices as relays to extend network coverage will be an integral part of 5G era. Direct D2D communication can be used to offload traffic, extend capabilities and enhance the overall efficiency of the wireless-access network. In terms of spectrum usage, mobile communication has relied on spectrum licensed on a per-operator basis within a geographical area. This will remain the foundation for mobile communication in the 5G era, allowing operators to provide high-quality connectivity in a controlled-interference environment. However, per-operator licensing of spectrum will be complemented with the possibility to share spectrum. Such sharing may be between a limited set of operators, or may occur in license-exempt scenarios and CA is seen as the key enabler for efficient sharing of licensed and/or unlicensed spectrum.

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