Université de Toulouse

THÈSE

En vue de l'obtention du

DOCTORAT DE L'UNIVERSITÉ DE TOULOUSE

Délivré par :
Institut National Polytechnique de Toulouse (INP Toulouse)

Discipline ou spécialité :

Réseaux, Télécommunications, Systèmes et Architecture

Présentée et soutenue par :
Geovanny Mauricio ITURRALDE RUIZ

le : mardi 2 octobre 2012

Titre :

Performances des Réseaux LTE

Ecole doctorale :
Mathématiques Informatique Télécommunications (MITT)

Unité de recherche :
IRIT UMR 5505

Directeur(s) de Thèse :
M. André-Luc BEYLOT
Mme. Anne WEI

Rapporteurs :

Mme. Pascale MINET
Mme. Isabelle GUERIN LASSOUS

Membre(s) du jury :
M. André-Luc BEYLOT - Professeur, INPT/ENSEEIHT
Mme. Anne WEI - Professeur, CNAM
Mme. Pascale MINET - Chargé de recherche, HDR, INRIA
Mme. Isabelle GUERIN LASSOUS - Professeur Université Claude Bernard (Lyon 1)
Mme. Tara ALI-YAHIYA - Maître de Conférences, Université Paris Sud
M. Fabrice VALOIS -- Professeur, INSA-Lyon

I would like to dedicate this work to my lovely son... Paulo Gabriel.

Acknowledgements

And I would like to thank Andre-Luc Beylot and Anne Wei, my supervisors, for offering me the opportunity to pursue my doctoral studies at the Institute de Recherche en Informatique de Toulouse (IRIT), for their patience and insightful guidance. My special thanks to Tara Ali-Tahiya for her help, experience, guidance and advice in the resource allocation field. Thanks to the judge members for their hard work and the dedicated time when analysing my thesis.

My special thanks to all my friends, secretaries and office mates for their support at the IRIT laboratory.

Thanks to the Ecuadorian government for financing this thesis by the Secretaria Nacional de Educacion Superior, Ciencia y Tecnologia (SENESCYT).

And finally my deepest gratitude to my parents, for their love, trust and support.

Résumé

Poussé par la demande croissante de services à haut débit sans fil, Long Term Evolution (LTE) a émergé comme une solution prometteuse pour les communications mobiles. Dans plusieurs pays à travers le monde, la mise en œuvre de LTE est en train de se développer. LTE offre une architecture tout-IP qui fournit des débits élevés et permet une prise en charge efficace des applications de type multimédia.

LTE est spécifié par le 3GPP ; cette technologie fournit une architecture capable de mettre en place des mécanismes pour traiter des classes de trafic hétérogènes comme la voix, la vidéo, les transferts de fichier, les courriers électroniques, etc.

Ces classes de flux hétérogènes peuvent être gérées en fonction de la qualité de service requise mais aussi de la qualité des canaux et des conditions environnementales qui peuvent varier considérablement sur une courte échelle de temps.

Les standards du 3GPP ne spécifient pas l'algorithmique de l'allocation des ressources du réseau d'accès, dont l'importance est grande pour garantir performance et qualité de service (QoS).

Dans cette thèse, nous nous focalisons plus spécifiquement sur la QoS de LTE sur la voie descendante. Nous nous concentrons alors sur la gestion des ressources et l'ordonnancement sur l'interface radio des réseaux d'accès.

Dans une première partie, nous nous sommes intéressés à des contextes de macro-cellules. Le premier mécanisme proposé pour l'allocation des ressources combine une méthode de jetons virtuels et des ordonnanceurs opportunistes. Les performances obtenues sont très bonnes mais n'assurent pas une très bonne équité. Notre seconde proposition repose sur la théorie des jeux, et plus spécifiquement sur la valeur de Shapley, pour atteindre un haut niveau d'équité entre les différentes classes de services au détriment de

la qualité de service. Cela nous a poussé, dans un troisième mécanisme, à combiner les deux schémas.

La deuxième partie de la thèse est consacrée aux femto-cellules (ou femtocells) qui offrent des compléments de couverture appréciables. La difficulté consiste alors à étudier et à minimiser les interférences. Notre premier mécanisme d'atténuation des interférences est fondé sur le contrôle de la puissance de transmission. Il fonctionne en utilisant la théorie des jeux non coopératifs. On effectue une négociation constante entre le débit et les interférences pour trouver un niveau optimal de puissance d'émission. Le second mécanisme est centralisé et utilise une approche de division de la bande passante afin d'obliger les femtocells à ne pas utiliser les mêmes sous-bandes évitant ainsi les interférences. Le partage de bande passante et l'allocation sont effectués en utilisant sur la théorie des jeux (valeur de Shapley) et en tenant compte du type d'application. Ce schéma réduit les interférences considérablement.

Tous les mécanismes proposés ont été testés et évalués dans un environnement de simulation en utilisant l'outil LTE-Sim au développement duquel nous avons contribué.

Abstract

Driven by the growing demand for high-speed broadband wireless services, Long term Evolution (LTE) technology has emerged as a competitive alternative to mobile communications solution. In several countries around the world, the implementation of LTE has started. LTE offers an IP-based framework that provides high data rates for multimedia applications. Moreover, based on the 3GPP specifications, the technology provides a set of built in mechanisms to support heterogeneous classes of traffic including data, voice and video, etc. Supporting heterogeneous classes of services means that the traffic is highly diverse and has distinct QoS parameters, channel and environmental conditions may vary dramatically on a short time scale. The 3GPP specifications leave unstandardized the resource management and scheduling mechanisms which are crucial components to guarantee the QoS performance for the services.

In this thesis, we evaluate the performance and QoS in LTE technology. Moreover, our research addresses the resource management and scheduling issues on the wireless interface. In fact, after surveying, classifying and comparing different scheduling mechanisms, we propose three QoS mechanisms for resource allocation in macrocell scenarios focused on real time services and two mechanisms for interference mitigation in femtocell scenarios taking into account the QoS of real time services.

Our first proposed mechanism for resource allocation in macrocell scenarios combines the well known virtual token (or token buckets) method with opportunistic schedulers, our second scheme utilizes game theory, specifically the Shapley value in order to achieve a higher fairness level among classes of services and our third mechanism combines the first and the second proposed schemes.

Our first mechanism for interference mitigation in femtocell scenarios is power control based and works by using non cooperative games. It performs a constant bargain between throughput and SINR to find out the

optimal transmit power level. The second mechanism is centralised, it uses a bandwidth division approach in order to not use the same subbands to avoid interference. The bandwidth division and assignation is performed based on game theory (Shapley value) taking into account the application bitrate . This scheme reduces interference considerably and shows an improvement compared to other bandwidth division schemes.

All proposed mechanism are performed in a LTE simulation environment. several constraints such as throughput, Packet Loss Ratio, delay, fairness index, SINR are used to evaluate the efficiency of our schemes.

Contents

List of Figures

List of Tables

List of Acronyms

ACM/TDM Adaptive Modulation and Coding and Time Division Multiplexing

AMC Adapting Modulation and Coding

ARQ Automatic Repeat reQuest

ARP Allocation and Retention Priority

AVC Advanced Video Coding

BDM Bandwidth Division Mechanisms

BE Best Effort

BS Base Station

BPSK Binary Phase Shift Keying modulation

CBR Constant Bit Rate

CC Component Carrier

CSI Channel State Information

CT Cognitive Mechanisms

CQI Channel Quality Indicator

DL Donwlink

DS-PC Dynamic Self-Power Control

eNb Enhanced Node B

EPS Evolved Packet System

EPC Evolved Packet Core

E-UTRAN Evolved UTRAN

EXP/PF Exponential Proportional Fairness

EXP-RULE Exponential-RULE

FCFS First Come First Serve

FDD Frequency Division Duplexing

FFR Fractional Frequency Reuse

FRF Frequency Reuse Factor

FRM Frequency Reuse Mechanisms

GBR Guaranteed Bit-Rate

GM Graph based Mechanisms

GT Game Theory

HARQ Hybrid Automatic Repeat reQuest

HSS Home Subscriber Server

HDR High Data Rate

HOL Head Of Line

LOG-RULE Logarithmic RULE

LTE Lonf Term Evolution

MAC Medium Access Control

MBR Maximum Bit Rate

MCS Modulation and Coding Scheme

M-LWDF Modified-Largest Weighted Delay First

MME Mobility Management Entity

MMF Max-Min Fair

MIMO Multiple Input Multiple Output

NBS Nash Bargaining Solution

non-GBR non-Guaranteed Bit-Rate

NP Nash Product

OFDM Orthogonal Frequency Division Multiplexing

OFDMA Orthogonal Frequency Division Multiple Access

PCM Power Control based Mechanisms

PDB Packet Delay Budget

PDCCH Physical Downlink Control Channel

PDU Protocol Data Units

PF Proportional Fairness

PHY Physical Layer

PLR Packet Loss Ratio

P-GW Packet-data Network Gateway

P-GW Packet-data Network Gateway

PRB Physical Resource Blocks

QAM Quadrature Amplitude Modulation

QCI QoS Class Identifier

QoS Quality of Service

QPSK Quadrature Phase Shift Keying

RB Resource Block

RLC Radio Link Control

RL Reinforcement Learning

RR Round Robin

SAE System Architecture Evolution

SDU Service Data Units

SINR Signal-to-Interference-plus-Noise Ratio

SC-FDMA Single Carrier Frequency Division Multiple Access

S-GW Serving Gateway

SHV Shapley Value

TBS Transport Block Size

TDD Time Division Duplexing

TB Transport Blocks

TU Transfer Utility

TBM Transmit Beamforming Mechanisms

TTI Transmission Time Interval

UE User Equipement

UL Uplink

UTRAN Universal Terrestrial Radio Access Network

UMTS Universal Mobile Telecommunications System

Introduction

Motivation

In recent years, operators across the world have seen a rapid growth of mobile broadband subscribers. At the same time, the traffic volume per subscriber is also increasing rapidly; in particular, with the introduction of more advanced mobile devices and real time services such as multimedia telephony and mobile TV. The introduction of these new and demanding services such as audio, video streaming, interactive gaming with rapid response patterns has drawn attention toward possible limitation of the capacity and Quality of Service (QoS). Since these services have different performance requirements, for example in terms of bit-rates and packet delays, under the partnership of the 3GPP, LTE (Long Term Evolution) is being introduced to fulfill this ambitious task. LTE is been deployed in Europe, USA and around the world. Thus, nowadays operators have already started to propose LTE technology to subscribers in order to provide high speed data rates.

LTE offers a set of key features: (1) The use of Orthogonal Frequency Division Multiplex (OFDM), (2) time and frequency duplex (TDD and FDD), (3) support of Adaptive Modulation and Coding (AMC), (4) advanced antenna techniques such as Multiple Input Multiple Output (MIMO) and (5) QoS support. In this thesis, we are mainly interested in the feature number five, QoS support. LTE architecture has been developed to serve different classes of services such as video, VoIP, streaming, HTTP etc. However, the 3GPP specifications leave unstandardized the resource management and scheduling mechanism which are crucial components to guarantee QoS.

One essential part for the QoS performance in LTE is the air interface. It is at the air interface where the physical resource allocation is performed. It is extremely important to provide an efficient resource allocation in order to guarantee QoS for downlink and uplink systems. A non-efficient resource allocation might degrade the QoS among several services. Several services such as real time flows, require to be treated taking into account several factors such as packet delays, bitrate, etc.

The question to be asked here is "How to distribute physical resources to an heterogeneous group of services that have heterogeneous requirements"? Since this field has not been completely solved nowadays, the principal motivation for this thesis focuses on this approach. Specifically, we attack the physical resource allocation at the air interface because it is where an important part of the QoS is managed.

In this thesis we evaluate the performance of LTE downlink system in mobile environments. Specifically, we investigate the potential and limitations that LTE possesses to perform real time services and consequently we propose several schemes to improve the QoS. This work mainly addresses the MAC layer considering that resource allocation is carried out at this level. PHY layer is closely linked to this task, so in this thesis PHY layer is not neglected.

This thesis is divided into two main parts. The first part is related to the resource allocation in downlink system in macrocell scenarios focused on real time services. In this part we present several solutions in order to improve the QoS level.

Since operators have started to propose to subscribers femtocells (small base stations to be installed by users at home), the second part of our contributions aims to mitigate interference in femtocell scenarios to reach an enhancement of QoS for real time services. Two schemes are made in contribution to this part of the thesis. The remainder of the thesis is organized as described in next section.

Contributions and Outline

Chapter 1: Overview of LTE

The objective of this chapter is to provide a brief overview of Long Term Evolution technology. Firstly we go through the LTE architecture (EPC and e-UTRAN), we describe the main entities of this architecture as its main functions. Several layers are in charge of the resource distribution performance, the physical layer (PHY), the Medium Access Control (MAC) layer and the Radio Link Control (RLC) layer. Unlike physical layer which is in charge of bit transmission, the Medium Access Control (MAC) layer is responsible for the wisely control of the strong characteristics that physical layer grants such as the optimal resource distribution among users. It is important to remark that resource allocation mechanisms can be performed by using cross-layer methods by interchanging parameters between MAC, PHY and RLC layers [2] [9]. This thesis does not present any cross-layer scheme, therefore in this chapter the layers overview is only limited to the PHY and the MAC layers.

Chapter 2: Overview of Resource Allocation Techniques

In this chapter, we present the state of the art of resource allocation mechanisms for LTE downlink system. An in-depth analysis of existing methods and their characteristics is carried out. Proposed methods have been classified into groups based on their common characteristics. We also analyze the ”pros and cons” of each family of schemes. All this information is taken into account when developing and presenting our schemes in chapter 3.

Chapter 3: Downlink Radio Resource Allocation Strategies

In order to improve the QoS in downlink system, in this chapter we propose three schemes which focus on real time services. The first one adapts a virtual token mechanism to an opportunistic scheduler in order to improve the performance of real time services. In our second contribution, we combine game theory concepts (cooperative games) with opportunistic schemes in order to mitigate the lack of fairness among flows. In our third contribution, we combine our first two mechanisms to achieve an efficient trade-off between fairness and efficiency.

We also evaluate the performance of several well known schedulers utilized in 3G technologies in order to compare them to our proposed solutions.

Parts of this chapter were published in [86] [87] [38] and [90].

Chapter 4: An Overview of Femtocells

In this chapter, we present a quick overview of femtocell architecture. We present a state of the art of femtocells focused on interference mitigation approaches. Several existing proposals are deeply analysed in order to expose the main characteristics of each family of methods.

Chapter 5: Interference Mitigation in Femtocells

In this chapter, we focus on the improvement of QoS in downlink system in femtocell scenarios. We attack the neighboring interference problem by introducing two schemes. Our first contribution proposes to perform a fair sub-band division among femtocell neighbors based on game theory. This scheme is an improvement of the well known four colouring method for interference mitigation. Results show important enhancements of performance. The second proposed scheme performs an interference mitigation based on transmit power control. This scheme is also based on game theory in order to perform a constant bargain between the throughput game and the interference. Numerical results present considerable QoS improvements.

This work has partly been accepted to be published in: [88] and [89]

Chapter 1

An overview of LTE

As LTE technology becomes more widespread, concerns for the Quality of Service (QoS) in the wireless access network and backaul is at the forefront. In this thesis, we focus on the QoS for the wireless access network. However, it is important to provide a brief overview of the general LTE architecture standardized by the 3GPP specifications.

Firstly, we describe the general architecture of LTE. Concepts such as EPS, e-UTRAN are discussed. Secondly, we extend a general overview of the QoS architecture in LTE. In this part, we emphasize on how the QoS is handled. Finally, we present an overview of the LTE air interface. We detail the RLC, MAC and PHY layers which are closely related to the resource allocation performance.

1.1 LTE Architecture

The result of the 3GPP standardization effort is the Evolved Packet System (EPS) that consists of the core network part, the Evolved Packet Core (EPC) and the radio network evolution part, the Evolved UTRAN (E-UTRAN), also known as LTE. The EPC can also be connected to other 3GPP and non-3GPP radio-access networks. As illustrated in Figure 1.1, the EPC consists of some control-plane nodes, called Mobility Management Entity (MME), control Home Subscriber Server (HSS) and two user-plane nodes, called Serving Gateway (S-GW) and Packet-data Network Gateway (P-GW). The LTE radio-access network consists of the base stations, denoted as enhanced NodeB (eNb), that are connected to each other through the X2 interface and to the EPC through the S1 interface. The mobile terminal is denoted as User Equipment (UE).

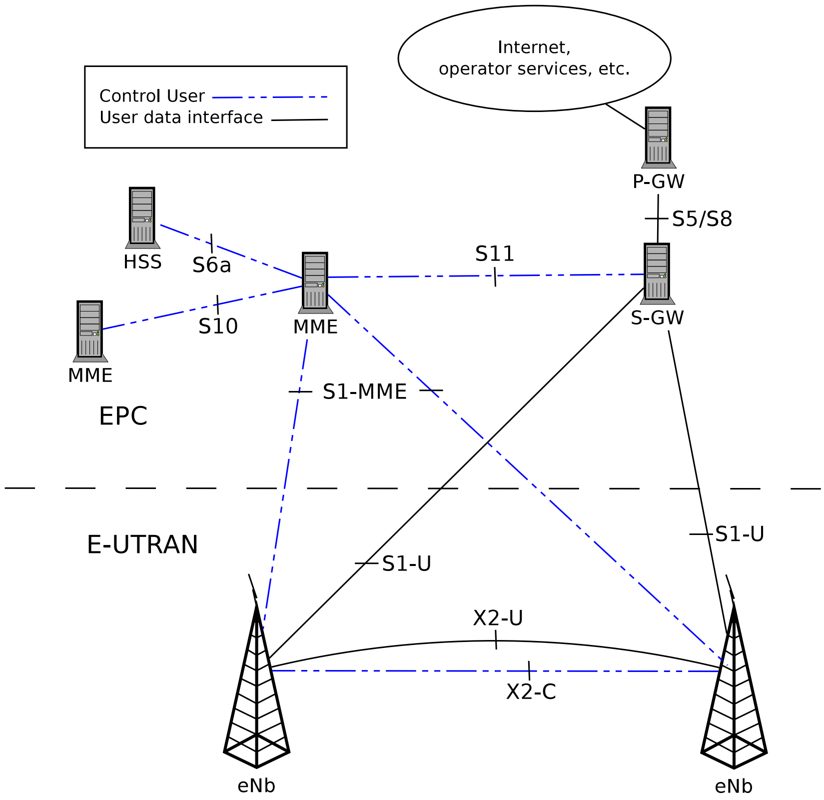

Figure 1.1: Overview of the EPC/LTE architecture

Serving Gateway (S-GW): The S-GW maintains Service Data Flow (SDF) context for the default/dedicated bearers (explained in subsection 1.2.1) established. It is also in charge of the mobility anchor for inter-eNb and inter-3GPP access mobility Packet.

Packet-data Network Gateway (P-GW): Is the entrance and the exit point for data traffic in the EPC. The P-GW performs policy enforcement and packet filtering for each data flow of each subscriber. It maintains the context for each connection of the mobile device, the traffic flow templates for the active services, the QoS profile and the charging characteristics.

Mobility Management Entity (MME): MME is the central management entity for the LTE accesses. It is responsible for the connection of the UE by selecting the gateway through which messages are to be exchanged and a level of resources for the UE in cases of attachment and handover. It also provides authentication and authorization and location tracking using the HSS and intra-3GPP mobility (e.g. between 2G/3G and LTE).

Home Subscriber Server (HSS): The basic HSS function is the control of user subscription data.

Enhanced Node B (eNb): The Enhanced Node B (eNb) hosts the following functions; Radio Resource Management (Radio Bearer Control, Radio Admission Control, Connection Mobility Control, Dynamic allocation of resources to UEs in both uplink and downlink), IP header compression and encryption of user data stream, selection of an MME at UE attachment, routing of user plane data towards SAE Gateway, measurement and measurement reporting configuration for mobility and scheduling. The eNb is in charge of an important QoS task which is the efficient performance of radio resource allocation.

1.2 Quality of Service (QoS)

The QoS in LTE is composed of two main parts, the backhaul part which QoS architecture guarantees the efficient treatment of packet flows by the use of policies. This part focuses on QoS management between the gateways and the eNb. It is at the gateway where the QoS parameters are set up in order to perform an efficient management of packet flows. The QoS management between the eNb and UEs is performed by an entity called the Mac air interface. This entity located at the eNb, is in charge of the final delivery of packet flows to UEs in a wireless environment.

1.2.1 The bearer

The QoS concept in LTE brings out a central element called bearer. A “bearer” identifies packet flows that receive a common QoS treatment between the terminal and the gateway, see Figure 1.2. All packet flows mapped to the same bearer receive the same packet-forwarding treatment (e.g., scheduling policy, queue management policy, rate-shaping policy, link-layer configuration, etc.). There exist two types of bearers: Guaranteed Bit-Rate (GBR) and non-Guaranteed Bit-Rate (non-GBR) [46]. Non-GBR bearers are also known as default bearers, and GBR-bearers are also known as dedicated bearers (Figure 1.3). Bearers are established, deleted and modified at the gateway by an entity called ’Policy Controller’. The Policy Controller makes its decisions based on QoS parameters such as QoS Class Identifier (QCI), Allocation Retention Priority (ARP), Maximum Bit Rate (MBR), Guaranteed Bit Rate (GBR) [26].

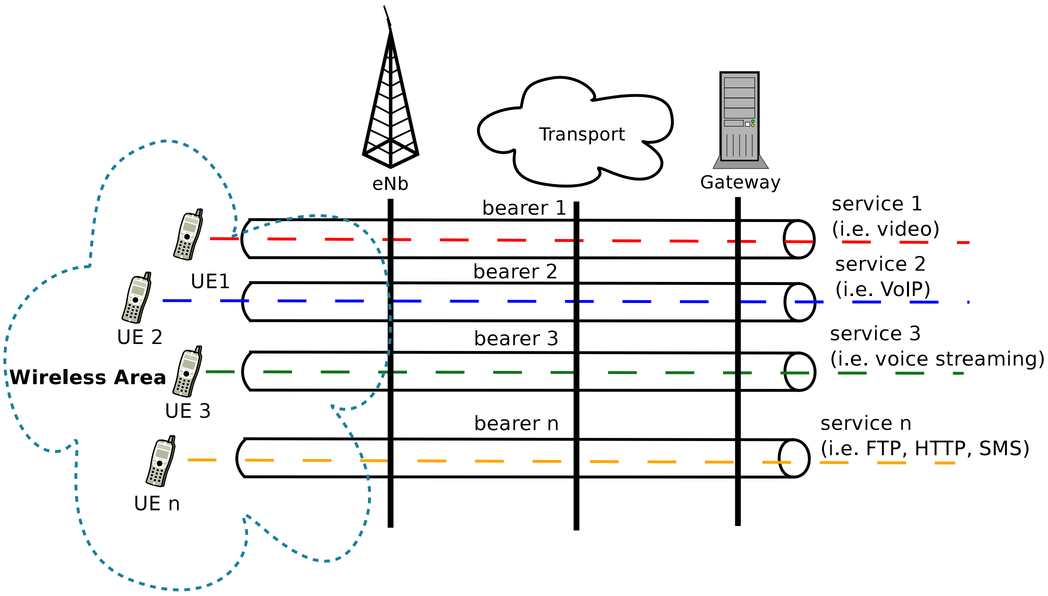

Figure 1.2: The bearer Concept

The QCI is a scalar that is used for the packet-forwarding treatment that the bearer traffic receives edge-to-edge between the terminal and the gateway in terms of bearer type (GBR or non-GBR), priority, packet delay budget, and packet-error-loss rate [9]. ARP is used to decide whether a bearer establishment or modification request can be accepted or must be rejected due to resource limitations. The MBR, is the bit rate that the traffic on the bearer may not exceed, and the GBR is the bit rate that the network guarantees to users [26].

Guaranteed Bit Rate bearers (GBR). A GBR guarantees a minimum bit rate requested by an application. GBR bearers are typically used for applications like Voice over Internet Protocol (VoIP), with an associated GBR value; higher bit rates can be allowed if resources are available. Each GBR bearer is additionally associated with the following bearer level QoS parameters: GBR that denotes the bit rate that can be expected to be provided by a GBR bearer, and the MBR that limits the bit rate that can be expected to be provided by a GBR bearer(e.g. excess traffic may get discarded by a rate shaping function)[26].

Non-Guaranteed Bit Rate bearers (non-GBR). Non-GBR bearers do not guarantee any particular bit rate, and are typically used for applications as web-browsing

[26].

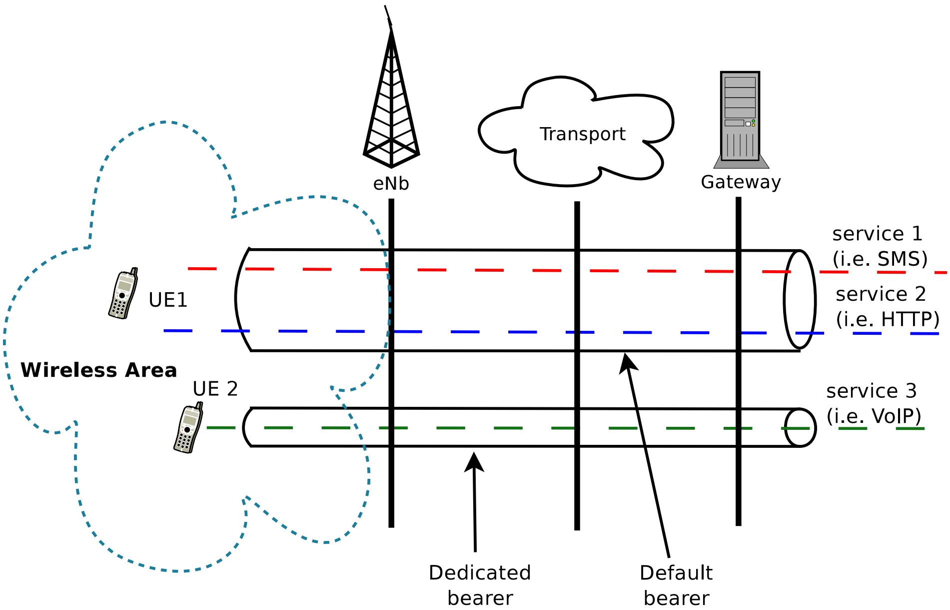

Figure 1.3: Types of bearer

1.3 The Radio Access Network (RAN)

The RAN is a part of LTE architecture between the eNb and the UEs. This part plays an important role in the QoS task because it is where the physical resource allocation to users must be performed efficiently. The eNb performs this task. In this thesis, we focus on this part of the QoS.

1.3.1 The Physical Layer (PHY)

LTE PHY is a highly efficient means of conveying both data and control information between the eNb and UEs. The most important features that PHY layer grants are Orthogonal Frequency Division Multiplexing (OFDM) and the support of FDD and TDD as radio frame structure. OFDM systems break the available bandwidth into many narrower sub-carriers and transmit the data in parallel streams. Because data is transmitted in parallel rather than serially, OFDM symbols are generally much longer than symbols on single carrier systems of equivalent data rate. LTE PHY layer uses OFDMA for downlink system and SC-FDMA for uplink system. Detailed information about PHY layer are presented in the 3GPP specifications in [7] [4].

Sub-channelization in LTE: OFDMA OFDMA allows data to be directed to or from multiple users on a subcarrier-by-subcarrier basis for a specified number of symbol periods. Although the LTE specifications describe both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) to separate UL and DL traffic, market preferences dictate that the majority of deployed systems will be FDD [71].

OFDMA is an excellent choice of multiplexing scheme for the 3GPP LTE downlink. Although it involves added complexity in terms of resource scheduling, it guarantees high performances in terms of efficiency and latency. In OFDMA, users are allocated a specific number of subcarriers for a predetermined amount of time. These are referred to as Physical Resource Blocks (PRBs) in the LTE specifications. PRBs thus have both a time and frequency dimension. Allocation of PRBs is handled by a scheduling function at the eNb.

Link adaptation, Modulation and Coding The Adaptive Modulation and Coding (AMC) is a powerful technique used by 4G technologies such as LTE and WIMAX to strengthen the robustness of the communication to the highly varying channel conditions. This is achieved by employing a robust Modulation and Coding Scheme (MCS) i.e. transmitting at low data rates when the channel is poor and increasing the data rate using a more efficient MCS when the channel conditions are good. The modulation techniques supported by LTE are: BPSK, QPSK, 16 QAM and 64 QAM. All MCS values supported by LTE are stipulated in the 3GPP specifications [3].

Slot and Frame Structure in OFDMA In OFDMA the generic frame structure is used with FDD. Another alternative frame structure is TDD. LTE frames are 10 ms in duration. They are divided into 10 subframes, each subframe being 1.0 ms long. Each subframe is further divided into two slots, each of 0.5 ms duration. Slots consist of either 6 or 7 ODFM symbols, depending on whether the normal or extended cyclic prefix is employed [34].

The total number of available subcarriers depends on the overall transmission bandwidth of the system. The LTE specifications define parameters for system bandwidths from 1.25 MHz to 20 MHz. A PRB is defined as consisting of 12 consecutive subcarriers for one slot (0.5 ms) in duration. A PRB is the smallest element of resource allocation assigned by the base station scheduler. See Figure 1.4

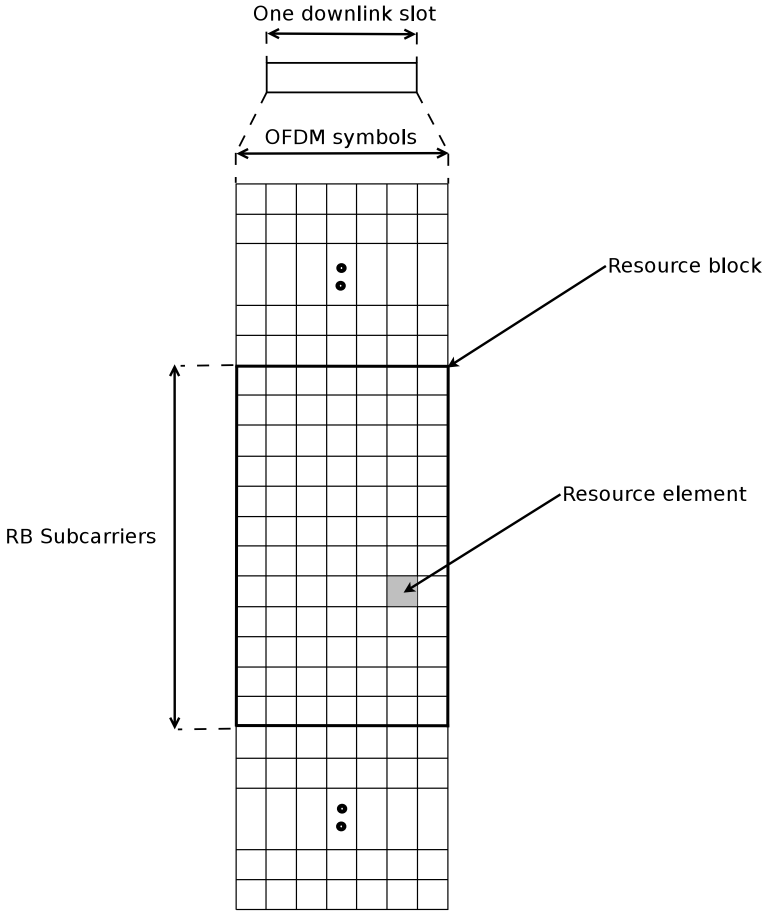

Figure 1.4: Downlink resource grid

1.3.2 The Medium Access Control Layer (MAC)

The Medium Access Control (MAC) layer is responsible for multiplexing and demultiplexing data between the PHY layer and RLC layer. This layer consists of logical channels that are connected to physical channels for transmission of data between the PHY and MAC layers. The main functions of the MAC layer are: scheduling of radio resources between UEs, random access procedure, uplink timing alignment, discontinuous reception, and scheduling information transfer [6] [59]. The MAC layer in LTE provides a medium-independent interface to the PHY layer and is designed to support the PHY layer by focusing on efficient radio resource management. The MAC layer provides data transfer services on logical channels. A set of logical channel types is defined for different kinds of data transfer services as offered by the MAC layer.

1.3.3 The Radio Link Control Layer (RLC)

The RLC layer is used to format and transport traffic between the UE and the eNb. RLC provides three different reliability modes for data transport- Acknowledged Mode (AM), Unacknowledged Mode (UM), or Transparent Mode (TM). The UM mode is suitable for transport of RT services because such services are delay sensitive and cannot wait for retransmissions. The AM mode, on the other hand, is appropriate for NRT services such as file downloads. The TM mode is used when the PDU sizes are known a priori such as for broadcasting system information. The RLC layer also provides in-sequence delivery of Service Data Units (SDUs) to the upper layers and eliminates duplicate SDUs from being delivered to the upper layers. It may also segment the SDUs depending on the radio conditions.

1.3.4 The MAC Air Interface Scheduler

In LTE, the MAC layer at the eNb is fully responsible for scheduling transmissions over the LTE in both the downlink and uplink directions. The entity responsible for this task is called the MAC Scheduler. The MAC Scheduler runs the scheduling algorithms which determine the packets to be sent, when and to/by whom. The MAC Scheduler is responsible for implementing the QoS characteristics assigned to radio bearers. The eNb MAC Scheduler receives inputs from various parameters which are used to perform the decision making in the scheduling algorithms. The output of the MAC Scheduler is a series of resource assignments for a downlink and uplink subframe. Resource assignments are defined in terms of resource blocks. As mentioned earlier, a resource block occupies 1 slot in the time domain and 12 subcarriers in the frequency domain – see Figure 1.4. The resource assignments output by the eNb MAC Scheduler indicate the size of each transport block and what PHY layer resources are to be used in sending it to the UE/eNb via the DL and UL transport channels. The downlink scheduler has the full flexibility to dynamically schedule pending hybrid ARQ retransmissions in the time and frequency domains. During one Transmission Time Interval (TTI), the packet scheduler must decide between sending a new transmission or a pending hybrid ARQ transmission to each scheduled user, since scheduling both to the same user simultaneously is not allowed. Link adaptation provides information to the packet scheduler of the supported modulation and coding for a user depending on the selected set of PRBs. The link adaptation unit primarily bases its decisions on the CQI feedback from the users in the cell and the QoS requirements.

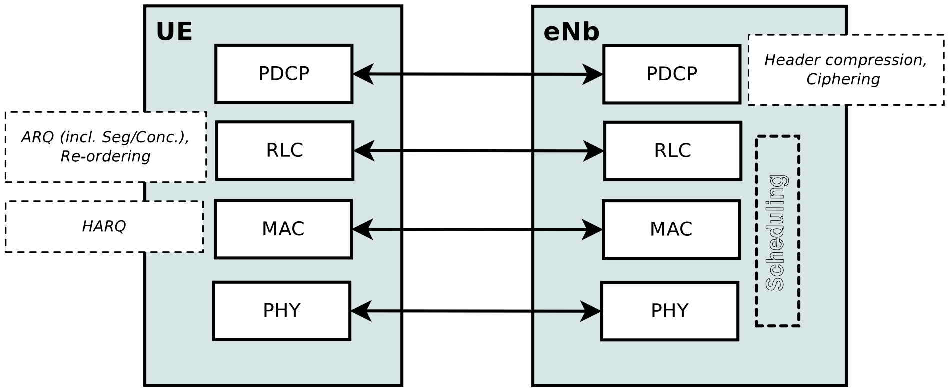

Figure 1.5: User plane protocol stack

1.4 Summary

This chapter presents an overview of LTE. We described the general LTE architecture and the main components of this architecture such as EPC, E-UTRAN, eNb and the general QoS architecture based on 3GPP specifications. Since the target of our thesis is the resource allocation for QoS enhancement, in this chapter we focused on the QoS architecture and the MAC and PHY layers located at the eNb. Regarding the PHY layer we described its downlink frame structure called OFDMA and its sub-channelization. About the MAC layer, we detailed the MAC air interface and its main functions. Since the wireless resource allocation is performed at the MAC scheduler interface, in this chapter we focused on this part to better understand the physical resource allocation and scheduling. In addition, the QoS architecture used by LTE is explained highlighting particular concepts such as bearer. However, a state of the art related to QoS support at MAC level specifically resource allocation techniques will be further discussed in chapter 2.

Chapter 2

Overview of Resource Allocation Techniques

Long Term Evolution technology presents a very challenging multiuser problem: Several User Equipments (UEs) in the same geographic area require high data rates in a finite bandwidth with low latency. Multiple access techniques allow UEs to share the available bandwidth by allocating to each UE a fraction of the total system resources.

The strong motivation beyond the resource allocation algorithms for scheduling is the improvement of system performance by increasing the spectral efficiency at the wireless interface and consequently enhancing the system capacity. Physical channels are constantly exposed to random variations which do not allow a constant bandwidth efficient modulation. In order to mitigate this problem, LTE implements the Adapting Modulation and Coding (AMC) technique.

It is important to bear in mind that not only the spectral efficiency is an essential factor to be maximized by the use of an efficient scheduling algorithm. Other constraints such as fairness, must also be improved. Hence, it is important to find a way to perform an effective trade-off between efficiency and fairness. To develop an efficient scheduler to reach this trade-off, several factors must be taken into account such as: Signal-to-Interference-plus-Noise Ratio (SINR), packet delays, buffer status (queues length and packet delays), type of service, fairness, channel conditions, complexity (time and computing). In this chapter, we present a state of the art of resource allocation proposals in downlink system in LTE. We will discuss the factors which were mentioned earlier and also analyze the strengths and weakness of several proposed resource allocation schemes.

2.1 Resource Allocation Constraints

As mentioned earlier, an efficient scheduling scheme for resource allocation in wireless networks must be built based on several fundamental parameters. Since LTE technology has been proposed to support real time services and high data rates, the following parameters should be taken into account.

Packet Delays. For delay-sensitive multimedia applications like streaming video, bounded packet delays are essential to maintain appropriate quality of service. In an efficient scheduling scheme, the packet delays must be as short as possible according to the standard.

Channel Conditions. The quality of channels could be considered as one of the most important factors in scheduling decision-making in wireless systems. Due to the variable distances between the base station and users, and factors such as shadow fading and multipath, the channel conditions of different users suffer unavoidable fluctuations. Under poor channels conditions, important packet losses are experimented.

Fairness. The concept of "fairness"is amorphous and difficult to define because it can have a very different meaning depending on the setting considered. In the resource allocation field, in some cases fairness implies an equal share of the resource for each flow through it. It is true if and only if, all flows are exactly the same. This means that all of them possess the same characteristics such as size, quality of channel, etc. On the other hand this concept does not work in a heterogeneous group of flows. In this case where flows are different from each other, we define the fairness as the exact amount of resource that a flow deserves to get allocated depending on its characteristics. Since in LTE, flows are different from each other, in this thesis we assume "fairness"as a question about whether users/flows receive an amount of resources that they deserve or not. Moreover, we are interested in quantifying the fairness level when the schedule is not perfectly fair. Specifically in the resource allocation field we define two types of fairness:

1. *Partial Fairness.* We define "partial fairness"as the measure of fairness level in a group where flows belong to the same type i.e. fairness only among VoIP flows for instance. In this example, although all flows belong to the VoIP class, they do not possess the same channel conditions, therefore in this aspect we can say that flows are partially heterogeneous.

2. *Total Fairness.* Unlike partial fairness, we define total fairness as the measure of fairness level in a heterogeneous group. i.e. fairness among different flows such as VoIP, Video and Best Effort. In this example, since flows do not belong to the same group, they do not possess the same bitrate neither the same channel conditions, therefore we can say that flows are completely heterogeneous.

Type of Service. In LTE there exist two main types of services: Real Time (RT) and Non-Real Time (NRT). It is important to define what type of service is going to be provided in order to decide the scheduling priority. For instance, a video conference needs a dynamic resource allocation while an SMS can be delayed without causing any problem.

Complexity. The time complexity quantifies the amount of time taken by an algorithm to run as a function of the size of the input of the problem. Since resource allocation in LTE is performed at each TTI which is 1 ms, an efficient algorithm must provide output results in a time shorter than a TTI. Therefore, an efficient scheduler must have a low complexity for performing this task.

Buffer Status. The buffer status provides information about the amount of pending packets to be served in a queue. Buffer status is highly related to the application bitrate. For instance, in a video application the bitrate could be 242 $Kbps$ and 8.4 $Kbps$ for VoIP service. This can be interpreted as the video queue will be longer than VoIP. In the buffer status we take into account two aspects: the Head-Of-Line (HOL) packet delays and the queue length.

2.2 Scheduling in downlink system

OFDMA is used for downlink in LTE system. The optimum use of transmission granted by OFDMA needs a dynamic management of radio resource allocation. As explained earlier in subsection 1.3.1, a resource unit or slot is composed by a frequency band and a time interval. The bitrate that a UE can obtain after being allocated a Resource Block (RB) depends on several factors such as power transmission, quality of sub-channel, UE geographical position, etc. Resource allocation decisions are made by a central entity called *Scheduler* situated at the eNodeB.

Currently, several schemes proposed as candidates to perform the resource allocation exist. Those schemes possess some characteristics in common, however it is difficult to analyze every scheme so, it is not possible to make an exhaustive overview. Therefore, to better distinguish previous work at this part of the thesis, we group existing solutions in several categories or families of algorithms.

2.2.1 Opportunistic Algorithms

Opportunistic scheduling schemes exploit the time varying nature of the wireless channel to decide which time slot to transmit data for each user or flow. This type of schemes consider opportunistic scheduling in a setting where users' queues are infinitely backlogged (this full buffer setting is typically used to model elastic or best effort flows). They identify channel-aware opportunistic scheduling policies, which maximize the sum throughput (or, more generally, sum of any concave utility function of user throughput) under various types of fairness constraints. Several algorithms have been proposed such as the Proportional Fairness (PF). A variant of opportunistic schedulers which takes into account the packet delays such as Modified-Largest Weighted Delay First (M-LWDF), Exponential Proportional Fairness (EXP/PF) Exponential (EXP-RULE) and Logarithmic RULE (LOG-RULE) have been introduced in order to improve the performance of non elastic flows.

2.2.1.1 Proportional Fairness (PF)

Proportional Fairness algorithm [49], which is implemented in High Data Rate (HDR) networks such as Universal Mobile Telecommunications System (UMTS), was introduced to compromise between a fair data rate for each user and the total data rate. PF is a very suitable scheduling option for non-real time traffic. It assigns radio resources taking into account both the experienced channel quality and the past user throughput. The goal is to maximize the total network throughput and to guarantee fairness among flows. The PF scheduler is represented as follows

$$j = \frac{\mu_i(t)}{\bar{\mu_i}} \tag{2.1}$$

where $\mu_i(t)$ denotes the data rate corresponding to the channel state of the user i at time slot t, $\bar{\mu_i}$ is the mean data rate supported by the channel.

Several researchers have also examined the fairness aspect of the proportional fair algorithm [69] [25] [51]. It has been shown that, with users experiencing heterogeneous channel quality, the differences in variances of the channel quality can result in unfairness using the proportional fair algorithm [15].

PF is one of the most common schedulers used in 3G wireless networks which shows a high performance. The fact that PF performs a desired performance in 3G Networks does not mean that it could be the main candidate to perform resource allocation in 4G Networks. It must be taken into account that the essence of 4G Networks are multimedia services. Multimedia flows which are also called non elastic flows, have an important dependence of delays because they are performed in real time. Unfortunately PF does not take into account Head Of Line (HOL) and packet delays in its mechanism during resource allocation. PF scheduler has been tested under OFDMA LTE systems in [49][66]. This algorithm presents good performance for non-real time flows but it lacks high performance when performing real time services.

2.2.1.2 Exponential Proportional Fairness (EXP/PF)

Exponential Proportional Fairness is an algorithm that was developed to support multimedia applications in an Adaptive Modulation and Coding and Time Division Multiplexing (ACM/TDM) system, this means that a user can belong to a real time service or to a non-real time service [75]. This algorithm has been designed to increase the priority of real time flows with respect to non-real time ones.

At time slot t, the EXP/PF rule chooses user j for transmission as follows

$$j = \max_i a_i \frac{\mu_i(t)}{\bar{\mu_i}} \exp(\frac{a_i W_i(t) - \overline{aW}}{1 + \sqrt{\overline{aW}}}) \tag{2.2}$$

where $\mu_i(t)$ denotes the data rate corresponding to the channel state of the user i at time slot t, $\bar{\mu_i}$ is the mean data rate supported by the channel, $W_i(t)$ is the HOL packet delay and $a_i > 0, i = 1, ..., N$, are weights, which define the required level of QoS. The term $\overline{aW}$ is defined as

$$\overline{aW} = \frac{1}{N} \sum_i a_i W_i(t) \tag{2.3}$$

When the HOL packet delays for all the users do not differ a lot, the exponential term is close to 1 and the EXP/PF rule performs as the PF rule. If for one of the users the HOL delay becomes very large, the exponential term overrides the channel state-related term, and the user gets a priority.

2.2.2 Delay based Algorithms

Delay Based packet schedulers base their decision-making on packet delays and Head of Line (HOL) values. This kind of algorithms have been created to perform non-elastic flows i.e. video streaming, VoIP. When a packet flow exceeds its HOL delay value it is stamped at the queue as expired, therefore it will be removed. These losses degrade the quality of service specially when performing non elastic flows. Several delay based schedulers have been proposed to perform this type of services [81] [21]. The M-LWDF scheduler is a delay based scheduler and also an opportunistic scheduler.

2.2.2.1 Maximum-Largest Weighted Delay First (M-LWDF)

M-LWDF is an algorithm designed to support multiple real time data users in CDMA-HDR systems[92]. It supports multiple data flows with different QoS requirements. This algorithm takes into account instantaneous channel variations and delays in the case of video service for instance.

The M-LWDF scheduling rule tries to balance the weighted delays of packets and utilizes the knowledge about the channel state efficiently. At time slot t, it chooses user j for transmission as follows

$$j = \max_i a_i \frac{\mu_i(t)}{\bar{\mu}_i} W_i(t) \tag{2.4}$$

where all the corresponding parameters are the same as in subsubsection 2.2.1.2 (EXP/PF rule) According to [91], a rule for choosing a_i, which works in practice, is $a_i = -\log(\delta_i)T_i$. Here T_i is the largest delay that user i can tolerate and δ_i is the largest probability with which the delay requirement can be violated.

This algorithm focus its performance on real time services, the core of its decision-making mechanism is the packet delays and HOL values. On the other hand, this algorithm is not a good option when performing non-real time services because when serving elastic flows the packet delay does not play an important role.

2.2.3 Throughput optimal Algorithms

Throughput optimal schedulers have as characteristic decision-making policies based on queues states in order to maximize utility functions of user throughput under rate constraints. This kind of schemes find a trade-off between elastic and non elastic flows in order to choose the service rate for each flow. Based on the type of service, the resources are allocated to flows depending on the queue length, however the scheduling decision is reduced to PF (based on user's channel conditions) when queue lengths of all users are equal or fairly close. The complexity level of throughput optimal schedulers is relatively low.

2.2.3.1 EXP Rule

The exponential rule has been proposed to serve high data rates requirements. [79] The Exp rule is represented as follows:

$$j = \max_i \exp\left(\frac{a_i W_i(t)}{1 + \sqrt{\overline{W}}}\right) \frac{\mu_i(t)}{\bar{\mu_i}} \tag{2.5}$$

where $\mu_i(t)$ denotes the data rate corresponding to the channel state of the user i at time slot t, $\bar{\mu_i}$ is the mean data rate supported by the channel, this is the proportional fair rule [49]. $a_i = 6/d_i$ where d_i is the maximal delay target of the th user's flow. For $a_i = 6/d_i$, the following values 5 and 10 show good results according to [57]. $W_i(t)$ is the HOL packet delay.

2.2.3.2 Max-Weight

The Max-Weight scheduler basically makes its scheduling decision based on queue lengths (or packet delays) [78]. The Max-Weight is represented as follows:

$$j = \max_i q_i \frac{\mu_i(t)}{\bar{\mu_i}} \tag{2.6}$$

Where $\mu_i(t)$ and $\bar{\mu_i}$ are the same parameters explained earlier in EXP-RULE. The value of q_i represents the length queue which can be replaced by W_i as also explained in Exp rule.

2.2.3.3 Log Rule

The log rule has been proposed in [13]. The log rule is represented as follows.

$$j = \max_i \log(1 + a_i q_i) \frac{\mu_i(t)}{\bar{\mu_i}} \tag{2.7}$$

Where $\mu_i(t)$ and $\bar{\mu_i}$ are the same parameters already explained in Exp rule. The value of q_i represents the length queue which can be replaced by W_i as also explained in Exp rule. $a_i = 5/d_i$ where d_i is the maximal delay target of the th user's flow [57]. $W_i(t)$ is the HOL packet delay.

2.2.4 Fair Algorithms

Fair algorithms is a family of schedulers that perform the resource allocation decision focusing on fairness. In section 2.1, we defined two approaches of fairness for this subject, partial fairness and general fairness. The results granted by fair algorithms lack throughput efficiency. Several works have focused the resource allocation in LTE downlink system on the fairness factor. Several algorithms misunderstand the concept of fairness by assuming that "fairness means equality". Other proposed schemes use mathematical tools such as game theory to reach fairness.

2.2.4.1 Round Robin (RR)

A classic strategy for resource allocation in wireless network is the Round Robin (RR) scheduler. This scheduler allocates the same quantity of resources to all UEs. Given that, fairness has been an issue to be solved in several algorithms, the RR algorithm was developed to address the problem. RR meets the fairness by allocating an equal share of packet transmission time to each user. However, throughput performance degrades significantly as the algorithm does not rely on the reported instantaneous downlink SINR values when determining the number of bits to be transmitted. For several reasons the RR scheduler could not be totally qualified as fair. This could be explained by the fact that not all users are in the same position with regards to the base station, therefore the quality of channel will not be the same which means that each user cannot be guaranteed the same bitrate. Not all users are asking for the same type of services i.e. VoIP, Video, HTTP and SMS. Each service has its own QoS constraints such as expected bitrate and packet sizes. Nevertheless the resource allocation performance of this algorithm has been tested in OFDMA systems and compared to other schedulers such as PF [35] [43]. Taking into account that LTE focuses its QoS on real time services, RR scheduler is not a smart choice to perform the resource allocation because it lacks of efficiency in serving non elastic flows.

2.2.4.2 Max-Min Fair (MMF)

The resource allocation by MMF is a mechanism which performs an iteratively resource distribution among users in order to increase the global bitrate granted to each user progressively and fairly. Whenever a user was allocated completely the required bitrate, the algorithm stops assigning resources to this user and it starts to allocate resources to the next user until satisfying all its bitrate requirements. The algorithm stops when all users are completely allocated or when all resources were completely distributed.

Max-Min criterion has been considered for channel allocation in multiuser OFDM systems [77]. However, by using this criterion, it is not easy to take into account the notion that users might have different requirements. Moreover, since the Max-Min approach deals with the worst case scenario, it penalizes users with better channels and reduces the system efficiency. Strictly speaking, all UEs get allocated the same bitrate, this grants a big advantage to UEs which have feeble requirements because their small required bitrates are always completely satisfied. On the other hand, the UEs with high required bitrates are not always satisfied, usually the assigned bitrate is not enough to perform the desired QoS level. The concept of fairness carried out by this algorithm is not optimal because it does not take into consideration the requirement level of each UEs. Therefore this algorithm could be hardly an efficient choice for resource allocation in LTE.

2.2.4.3 Game theory based Algorithms

In the last five years, researchers started to propose scheduling algorithms based on game theory in order to improve the fairness level among UEs. Game theory is an analytical mechanism frequently used for modeling interactive decision-making. Game theory models are usually appropriate in analyzing resource managing issues where user performance could be described, as these users compete for resources. Game theory is mostly used in the resource allocation field to answer the following question: "How to perform a fair resource distribution among players?", in most of the cases players are users. Game theory is frequently divided into two categories: cooperative and non-cooperative. Cooperative game theory is used as a mechanism to solve problems such as how to distribute resources among players (users in this thesis) in a coalition [100]. Since the system efficiency and fairness are vital in any resource allocation problem, cooperative game theory is suitable to find out the trade-offb etween an efficient and a fair resource allocation. Systems optimized by opportunistic algorithms by maximizing the spectrum utilization are frequently exposed to starvation issues where users get disproportional allocated resources. Simply put, game theory is mostly employed in the analysis and design of fair resource allocation mechanisms.

The Nash Bargaining Solution (NBS) is frequently used in several works. The NBS is a game theory concept proposed by John F. Nash [62]. This method is mainly regarded as non-zero two-person game which involves two individuals who have the opportunity to collaborate for mutual benefit in more than one way. Resource allocation by NBS has been tested under OFDMA in several previous works [94] [40] [98]. Also, there are several works based on NBS in order to improve resource allocation in LTE networks [84]. Although game theory based solutions grants good results for fairness, few authors have considered the complexity level that NBS carries as the main problem to deal with.

When using game theory, the complexity is an extremely important issue which cannot be neglected. In the field of resource allocation, there could be interesting solutions handled by game theory which theoretically could be well supported but in practice it may not be feasible. The problem focuses on the complexity since the complexity increases with the number of players increase. The classical procedures for computing the algorithmic complexity are based in the enumeration of all coalitions. Thus, if the input size of the problem is n, then the function which measures the worst case running time for computing the indices is $O(2^n)$. The complexity of the equilibrium of Nash for 2-person games and for n-person games has been addressed in several works. The generalized NBS is the maximizer of the Generalized Nash Product for the two-user case. There are many aspects of games that might make the Nash problem hard to solve. An in-depth study has been introduced by Daskalakis, Goldberg and Papadimitriou in [31], where the authors prove that finding Nash equilibriums is indeed hard with games for four players and more. Finding a Nash-equilibrium in a game between two players could be easier for several reasons. First, the zero-sum version can be solved in polynomial time by linear programming. Secondly, it admits a polynomial size rational number solution [24] while games between three or more players may only have solutions all in irrational numbers. Briefly, game theory based algorithms possess a strong efficacy, but they lack efficiency. The central issue regarding the high complexity problem in n-players games when authors set users as players, the algorithm becomes unfeasible. However, game theory could be combined to any smart scheme in order to perform a resource allocation in LTE networks only under several conditions such as low time complexity and high bitrate efficiency.

2.2.5 Multiclass Algorithms

Multiclass based algorithms take into account the flows classes to perform the scheduling decision-making and efficient results for all classes. RT and NRT services are fundamental parameters for this type of algorithms. Before making the resource allocation decision, this kind of schemes first checks the type of service and then they perform the RB assignation. These algorithms are built to prioritize RT flows without neglecting NRT ones. Those approaches are the most close to LTE requirements, however aspects such as fairness do not reach the optimal level. Several proposed algorithms are [83] [96] [16][27].

2.2.6 Real time QoS guaranteed Algorithms

This kind of algorithms aim to guarantee a minimal QoS level among services. The performance of a minimal QoS is focused on real time services such as video streaming or online gaming. These type of algorithms focus their attention only on sensitive traffic and they consider that NRT services such as HTTP, FTP, SMS etc do not deserve any priority above non elastic services. Several proposed algorithms are [29] [58].

2.3 Summary

In Table 2.2, we can appreciate the main characteristics shown by the most important schedulers analyzed in this chapter. In Table 2.1, we present the analysed algorithms classified into families by taking into account its common characteristics.

Table 2.1: Classification of Algorithms by Families

Algorithm	*Reference*	*Family*
PF	[49]	Opportunistic
EXP PF	[75]	Opportunistic
MLWDF	[92]	Delay Based
Max-Weight	[78]	Throughput Optimal
Log RULE	[13]	Throughput Optimal
EXP RULE	[79]	Throughput Optimal
RR	[35]	Fairness Based
MMF	[77]	Fairness Based
Qian's Alg.	[83]	Multicast Alg.
Ai's Alg.	[96]	Multicast Alg.
Guan's Alg	[29]	QoS Guaranteed
Adibah's Alg.	[58]	QoS Guaranteed
Vastikas Alg.	[84]	Fairness Based
Han's Alg.	[40]	Fairness Based
Zhang's Alg.	[98]	Fairness Based
FLS	[27]	Multicast Alg.
Sharifian's alg	[81]	Delay Based
Park's alg	[21]	Delay Based

Algorithms which do not take into account packet delays, are not appropriate schemes to satisfy LTE requirements. Also as previously explained, the general fairness is not at all a strong quality in OFDMA due to the heterogeneous nature of LTE services.

Table 2.2: Comparison of different Algorithms

Algorithm	*Reference*	*Buffer Status*	*Channel Condit.*	*Partial Fairness*	*General Fairness*	*Low Complexity*	*Multi-service*
PF	[49]		✓	✓		✓	
MLWDF	[92]	✓	✓	✓		✓	
EXP PF	[75]	✓	✓	✓		✓	✓
Max-Weight	[78]	✓	✓			✓	✓
Log RULE	[13]	✓	✓	✓		✓	✓
EXP RULE	[79]	✓	✓			✓	✓
RR	[35]			✓		✓	
MMF	[77]			✓		✓	
Qian's Alg.	[83]	✓	✓			✓	✓
Ai's Alg.	[96]		✓			✓	✓
Guan's Alg	[29]		✓	✓		✓	
Adibah's Alg.	[58]	✓	✓			✓	
Vastikas Alg.	[84]		✓	✓		✓	
Han's Alg.	[40]		✓		✓		
Zhang's Alg.	[98]		✓		✓		
FLS	[27]	✓	✓	✓		✓	✓
Sharifian's alg	[81]	✓	✓			✓	
Park's alg	[21]	✓	✓			✓	✓

The use of game theory is a smart and efficient option to build a fair algorithm. Due to the high fairness level granted by these algorithms a fair minimum allocation for every UE or flow is assured. However game theory based algorithms present some constraints to be solved. Thus, they could be hardly adapted to LTE requirements due to several reasons. The first one is the complexity. The execution time must be as short as possible since resource allocation in LTE is performed at each TTI (1 ms). In most of proposed schemes, game theory based algorithms have focused on fairness for non-real time services which is an important point to be solved in LTE but seriously bearing in mind that the most important services are the real time ones.

Opportunistic and throughput optimal scheduling based on multiuser diversity allocates each subcarrier to the user that has the highest channel gain on that subcarrier. Despite total capacity maximization, those scheduling causes users with poor channel quality fail to access the channel most of the time and hence degrades their service satisfaction. Those schedulers lack of general fairness. Opportunistic schedulers try to combine partial fairness and high bitrate performances, however an optimum trade-off has not been reached. PF is a good candidate to schedule non-real time services but it presents a strong weakness for real time services since PF does not take into account packet delays during its decision-making. On the other hand schedulers such as M-LWDF, EXP/PF and EXP-RULE are a better choice for real time services.

Multiclass algorithms are closer to satisfy the LTE requirements than others. Those schedulers possess the main characteristics as shown in Table 2.2. However general fairness is not satisfied.

In the next chapter, we propose several radio resource allocation strategies taking into account the most important features presented by the different families of schedulers such as game theory based and opportunistic algorithms.

Chapter 3

Downlink Radio Resource Allocation Strategies

Providing Quality of Service (QoS), in particular meeting the data rate and packet delay constraints of real-time data users, is one of the requirements in high-speed data networks such as LTE. This requirement is particularly challenging in networks that serve RT flows. Indeed, the quality of a wireless channel is typically different for different users, and randomly changes in time on both slow and fast time scales. In addition, wireless link capacity is usually a scarce resource that needs to be used efficiently. Therefore, it is important to find efficient ways of supporting QoS for real-time data (e.g., live audio, video streams) over wireless channels (i.e., supporting as many users as possible with the desired QoS).

In chapter 2, we discussed the importance of resource allocation in LTE networks. An extensive state of the art regarding resource allocation is presented. Proposed methods were classified based on their main characteristics. An in-depth analysis showed that none of them is suitable for the resource allocation task in LTE because none of them assures the optimum balance between the two types of fairness previously described in section 2.1 and bitrate efficiency. Partial fairness and bitrate efficiency characteristics were found in opportunistic schedulers. On the other hand the general fairness characteristic was found in game theory based algorithms as shown in Table 2.2 and in subsubsection 2.2.4.3.

The main objective of this chapter is to provide several solutions for the resource allocation problem by taking into account all the constraints presented in section 2.1 in order to build a good scheduler. Those constraints are packet delays, channel conditions, fairness (we defined two types of fairness; partial fairness and general fairness), low complexity, multi-service and buffer status (packet delays and queue's length). Three scheduling schemes were proposed. The first one focuses on serving RT services requirements by using a virtual token mechanism which is a well known method used to force schedulers to perform the decision making bearing in mind the queue sizes. The second one aims to perform an optimal distribution also focusing on RT services without neglecting NRT services by using game theory [80]. And finally the third one is a combination of the first two proposed methods.

3.1 Proposed Resource Allocation Strategies

3.1.1 Resource Allocation by Using Virtual Token Mechanism in LTE Networks

3.1.1.1 Problem Formulation and Justification

Opportunistic Algorithms such as PF, M-LWDF or EXP-RULE and (its variations EXP/PF) are mostly used in 3G technologies for resource allocation. As mentioned earlier QoS in LTE is mainly focused on RT services, therefore it is clear that schedulers must target packet delays in order to have an efficient QoS (i.e EXP-RULE and M-LWDF). However, the HOL and packet delays metrics are not enough to focus the scheduling priority on RT services. We consider that the required bitrate and the delay are important constraints to take into account when performing the scheduling task. Those are useful parameters to help the scheduling decision making. There exists a method that takes advantage of this constraint called Virtual Token (VT) mechanism (also called token bucket mechanism) [79]. By using this method we aim to modify the opportunistic scheduler EXP-RULE in order to balance the scheduling decision to RT services.

3.1.1.2 Scheduling Proposed Scheme

In broad outline, we consider the problem of scheduling transmissions of multiple data users sharing the same wireless channel so as to satisfy delay or throughput constraints of all, or as many as possible flows.

It is essential that queue state information, such as queue length and packet delay, which is a reflection of traffic burstiness, be utilized in scheduling packets. On the other hand, since the queue state information is tightly connected with QoS, wisely controlling queues is one of the most effective ways for QoS provisioning. As it is described earlier, M-LWDF and EXP-RULE make scheduling decisions based on the actual packet delays.

However, we propose to modify these algorithms by combining them with a Virtual Token (VT) mechanism in order to take not only the delay into consideration but also to provide a certain minimum throughput to flows. VT possesses a quality that grants the flexibility of controlling the services priority when scheduling. By combining VT mechanism to opportunistic schedulers it is possible to calibrate the priority for RT services or NRT services. This token queue mechanism has been proposed in [91] in order to enhance RT services in High Data Rate (HDR) systems. This mechanism has been adapted only to M-LWDF, therefore in this section we perform this method in LTE networks by combining it not only with M-LWDF, we also combine it with EXP-RULE in order to find the best performance [86].

A virtual token queue is associated to each flow, into which tokens arrive at constant rate r_i, the desired guaranteed minimum throughput of flow i. Let us define $V_i(t)$ as the delay of the head of line token in the flow i token queue. Note that we do not need to maintain the token delays. As the arrival rates of tokens are constant,

$$V_i(t) = \frac{Q_i(t)}{r_i} \tag{3.1}$$

where $Q_i(t)$ is the token queue length (a counter value at time t). The value for r_i is 1 in our simulation scenario, like this, the same desired minimum throughput is set to all flows.

Then, we use the M-LWDF and EXP-RULE rules with $W_i(t)$ being replaced by $V_i(t)$ respectively.

$$j = \max_i a_i \frac{\mu_i(t)}{\bar{\mu_i}} V_i(t) \tag{3.2}$$

$$j = \max_i \exp\left(\frac{a_i V_i(t)}{1+\sqrt{\overline{\overline{W}}}}\right)\frac{\mu_i(t)}{\bar{\mu_i}} \tag{3.3}$$

After the service of a real queue, the number of tokens in the correspondent token queue is reduced by the actual amount of transmitted data as shown in Figure 3.1.

By using this method we force any opportunistic algorithm (EXP-RULE in our case) to take into account the queue length buffer status to perform the decision making. To enlarge the RT service priority in a scheduling decision making, it is necessary to take into account the packet delays and the queues length, therefore, since that EXP-RULE takes into account the packets delays already, we chose this virtual token mechanism to complement this performance by bearing in mind buffer status.

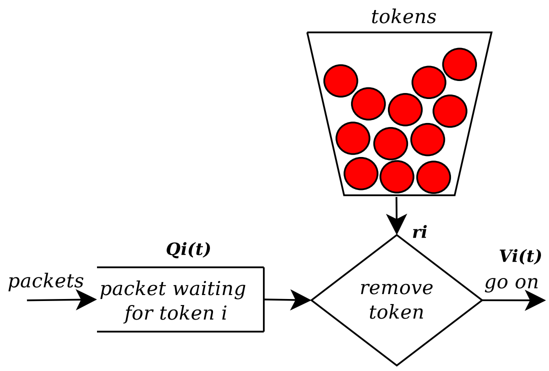

Figure 3.1: Virtual token mechanism

3.1.1.3 Simulation Scenario

In this thesis, we set a simulation scenario based on realistic approaches. In this chapter all the simulations are performed by following the same scenario, they share the same parameters and only one simulator called LTE-Sim is used. The physical models are taken from 3GPP specifications. The LTE propagation loss model is composed by 4 different models (shadowing, multipath, penetration loss and path loss)[7].

3.1.1.4 The Simulator: LTE-Sim

LTE-Sim is an open source simulation platform destined to simulate LTE scenarios. LTE-Sim has been conceived to simulate uplink and downlink scheduling strategies in multi-cell/multi-users environments taking into account user mobility, radio resource optimization, frequency reuse techniques, AMC module, and other aspects very relevant for industrial and scientific communities to test enhanced techniques for improving 4G cellular networks such as new physical functionalities, innovative network protocols and architectures, high performance scheduling strategies and so on. LTE-Sim is freely available under the GPLv3 license [17]. LTE-Sim can simulate several types of services such as BE, VoIP, video and CBR. More services can be added if necessary. This is an important factor for modelling multi-service scenarios which is indispensable in LTE. The MAC and PHY layers are well structured, they are modeled by following 3GPP specifications. The characteristics that LTE-Sim presents have been compared to other simulation platforms such as NS3 [32] [67] and OMNET [68]. NS3 possesses only a basic implementation of LTE architecture, concept of bearers and basic physical models, however the MAC layer is not very well implemented and PHY layer lacks of standardized 3GPP TBS and MCS values. OMNET has implemented only the PHY layer of LTE architecture, it also shows a lack of services models. Since LTE-Sim seems to be the most complete simulator to perform this task, we chose it as the main tool for this research.

Although nowadays LTE-Sim seems to be the most complete tool to simulate LTE scenarios, Several aspects such as the post processing of simulator output trace were not included in the first releases. We contributed to this project with the post processing part, some bugs corrections and 3GPP specifications updates.

3.1.1.5 Simulation Parameters

All simulations in this chapter share the same scenario with only one macro cell. Users are constantly moving at a speed of 3 *kmph* in random directions (random walk). The parameters of the simulation are shown in Table 3.1.

We set up our simulation scenario for all our algorithms as follows: there are 40% of users using video flows, 40% of users using VoIP flows and the remaining 20% are using CBR flows.

In this thesis, we mainly focus on RT services; however, to analyze the obtained results it is necessary to compare the behavior of RT against NRT services. To do so we consider video and VoIP flows as RT services and CBR flows as NRT services. Since modelling NRT services (i.e. HTTP, SMS, P2P) is extremely hard, we use CBR traffic as a parasite flow which sends packets all the time. Besides, to model NRT flows a simulator which supports TCP is necessary, the current version of LTE-Sim only supports UDP.

3.1.1.6 Simulation Traffic Model

A video service with 242 *kbps* source video data rate is used in the simulation, this traffic is a trace based application that sends packets based on realistic video trace files which are available in [1]. For VoIP flows G.729 voice flow are generated by the VoIP application. In particular, the voice flow has been modeled with an ON/OFF model, where the ON period is exponentially distributed with mean value of 3 *s*, and the OFF period has a truncated exponential probability density function with an upper limit of 6.9 *s* and an average value of 3 *s* [22]. During the ON period, the source sends 20 *bytes* sized packets every 20 *ms* (i.e., the source data rate is 8.4 *kbps*), while during the OFF period the rate is zero because the presence of a Voice Activity Detector is assumed. The CBR application generates packets with a constant bitrate with a packet size and inter-arrival packet time.

Table 3.1: LTE downlink simulation parameters

Parameters	Values
Simulation duration	150 s
Flows duration	120 s
Frame structure	FDD
Radius	1 km
Bandwidth	10 MHz
Slot duration	0.5 ms
Scheduling time (TTI)	1 ms
Number of RBs	50
Max delay	0.1 s
Video bitrate	242 $kbps$
VoIp bitrate	8.4 $kbps$
NRT bitrate	20 $kbps$
Pathloss	$128 : 1 + 37 : 6 \log(d)$ d = distance UE - eNodeB (km)
Multipath	Jakes model
PenetrationLoss	10 dB
Shadowing	log-normal distribution (mean = 0dB, stand dev = 8dB)

3.1.1.7 Simulation Metrics

In furtherance of carrying out an evaluation of the simulation results, several metrics are used in this work. When evaluating the QoS, it is important to focus the performance of schedulers on bitrate, packet losses, delays, fairness etc. Let us explain the used metrics as follows:

Average Throughput per user. This metric represents the average rate of successful message delivery over physical channel. It is calculated by dividing the size of a transmitted packets by the time it takes to transfer the packets per each user. We chose this metric to examine the degradation of throughput when the number users increases.

Packet Loss Ratio (PLR). This metric aims to measure the percentage of packets of data traveling across a physical channel which fail to reach their destination. Also there exist packet losses caused by buffer overflows.

Delay. Delay measures the elapsed time between packets departing and packets destination reach. It is at the queues where packets spend time causing undesirable delays, packet delays must be as short as possible to perform a desirable QoS level.

Fairness Index. In order to obtain an index related to the fairness level we use the Jain's fairness index method [20].

$$FI = \frac{(\sum x_i)^2}{N \cdot \sum {x^2}_i} \tag{3.4}$$

where x_i is the throughput allocated to user i among N competing flows.

3.1.1.8 Numerical Results

EXP-RULE and M-LWDF schedulers have been chosen and respectively modified to use a virtual token mechanism to improve their performance when using multimedia services such as video and VoIP. To make an evaluation of results the following notation is used: "PF "represents the proportional fair algorithm (Equation 2.1), "M-LWDF"represents the classic M-LWDF algorithm (Equation 2.4), "EXP-RULE "represents the classic EXP-RULE (Equation 2.2), "M-LWDF-VT "represents the modified M-LWDF which use the virtual token mechanism (Equation 3.2), and "EXP-RULE-VT "represents the modified EXP-RULE by using virtual token mechanism (Equation 3.3).

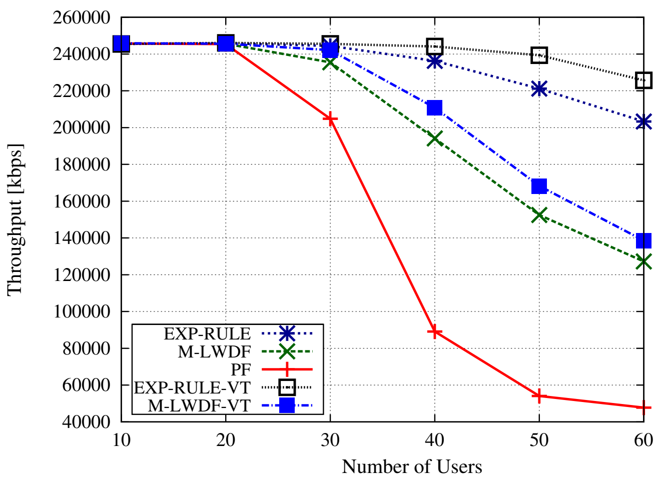

Figure 3.2: Average throughput per video flow (EXP-RULE-VT)

In this analysis, a percentage value is used to compare modified algorithms results to the results of non-modified algorithms.

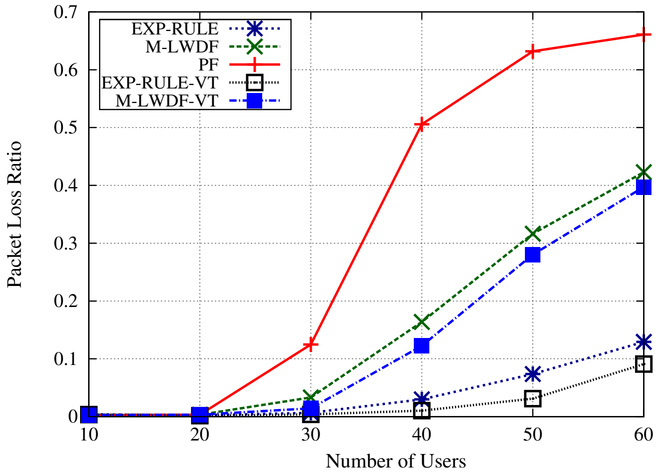

Figure 3.3: Packet loss ratio for video flows (EXP-RULE-VT)

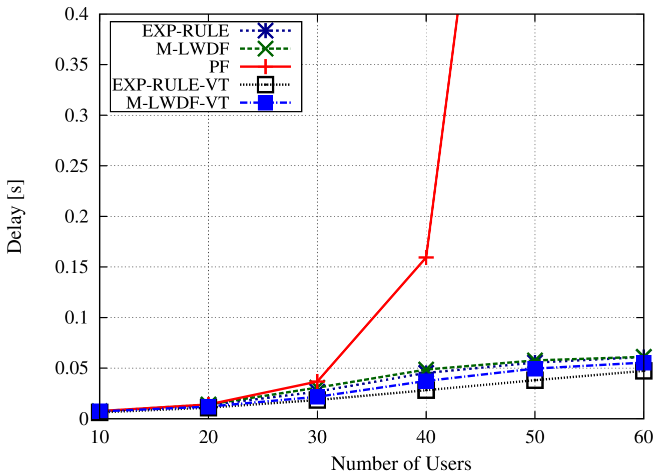

Figure 3.4: Delay for video flows (EXP-RULE-VT)

Throughput. For video flows, the aggregate throughput increases considerably by 35.1% for 60 users when EXP-RULE-VT is used, compared to the non-modified EXP-RULE. An explanation for this increase is that by using a Virtual Token Mechanism, video flows will always have the largest virtual token queue, which justify the considerable priority that they get as we can see in Figure 3.2. M-LWDF-VT shows a better throughput performance than M-LWDF, increasing by 11%. The worst results are obtained by PF.

For VoIP flows there is not a significant variation of throughput between modified algorithms as we can see in Figure 3.4. Since we use an ON/OFF model, no packet

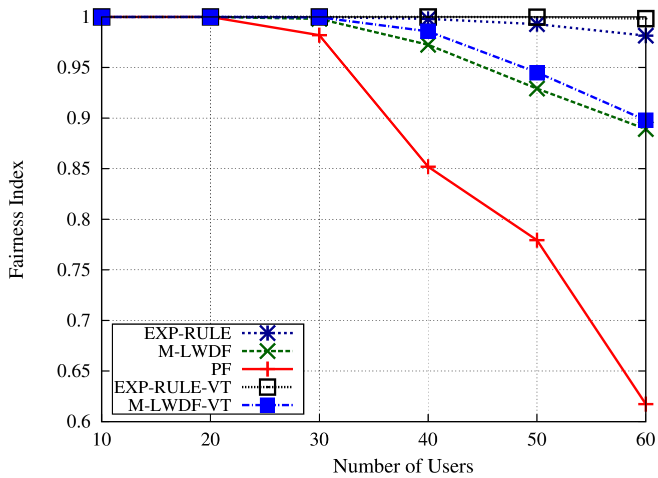

Figure 3.5: Fairness Index for video flows (EXP-RULE-VT)

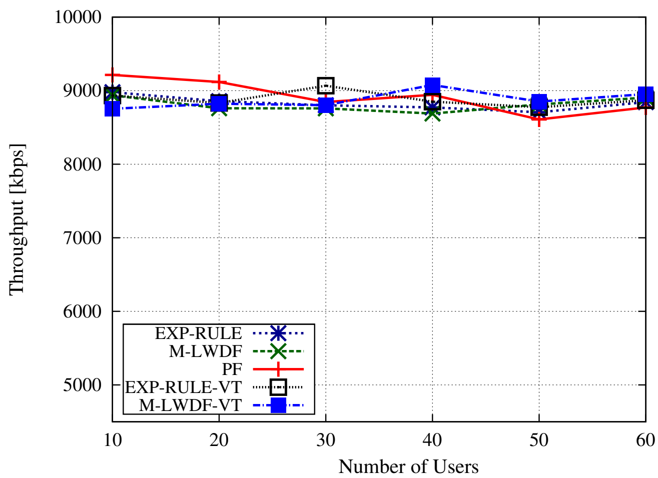

Figure 3.6: Average throughput per VoIP flows (EXP-RULE-VT)

arrives at the virtual queue when the state is set to OFF. This explains why there is almost no variation in throughput gain. However VT mechanism performs the expected throughput when the cell is loaded by 60 users.

For NRT flows M-LWDF shows the most optimal results. Throughput is maintained even when the cell is totally loaded by 60 users. PF also performs good results. On the other hand, the algorithms that use VT mechanism perform the worst results. EXP-RULE-VT shows a poor performance due to a sharp decrease of throughput. The most likely explanation is that NRT queue is the shortest one, the scheduler grants priority to larger queues such as video for instance, therefore there might be considerable packet

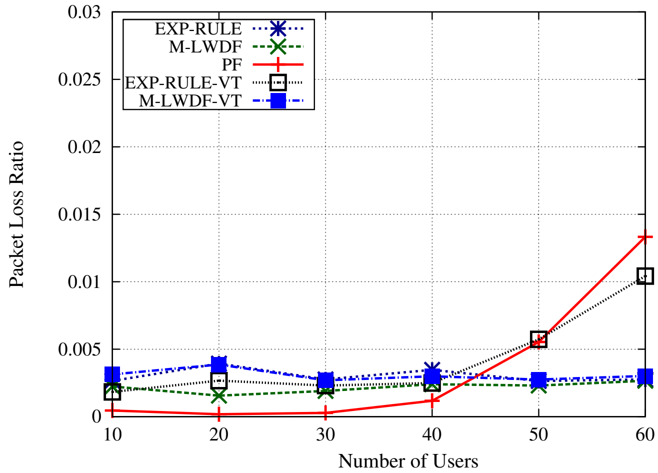

Figure 3.7: Packet loss ratio for VoIP flows (EXP-RULE-VT)

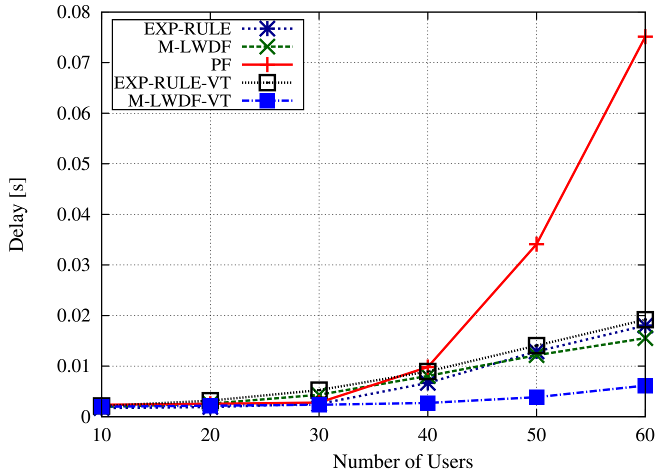

Figure 3.8: Delay for VoIP flows (EXP-RULE-VT)

losses caused by buffer overflows. See Figure 3.10

Packet Loss Ratio. For video flows, the packet loss ratio decreases considerably by 61.6% when using EXP-RULE-VT compared to the classical EXP-RULE as shown in Figure 3.3. Since video flows use the highest bitrate, video queue is the first to be served, so packet losses caused by buffer overflows is reduced. The worst performance is presented by PF. This is explained by the fact that PF does not take into account packet delays. M-LWDF-VT shows a decrease of PLR by 10%. Video service support a PLR under 1%. In our scenario only 23 users reach a PLR under this threshold.

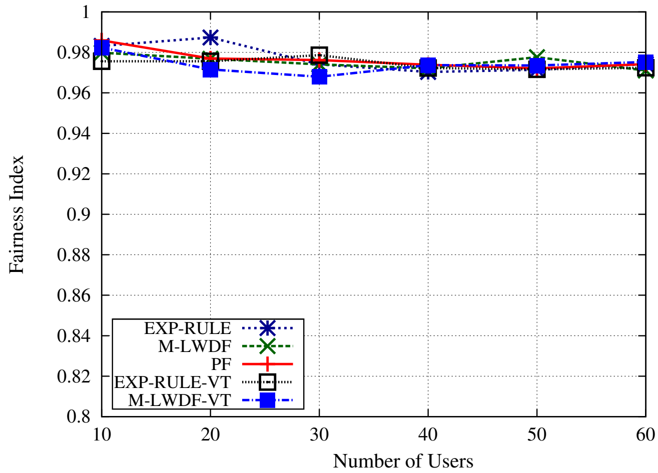

Figure 3.9: Fairness Index for VoIP flows (EXP-RULE-VT)

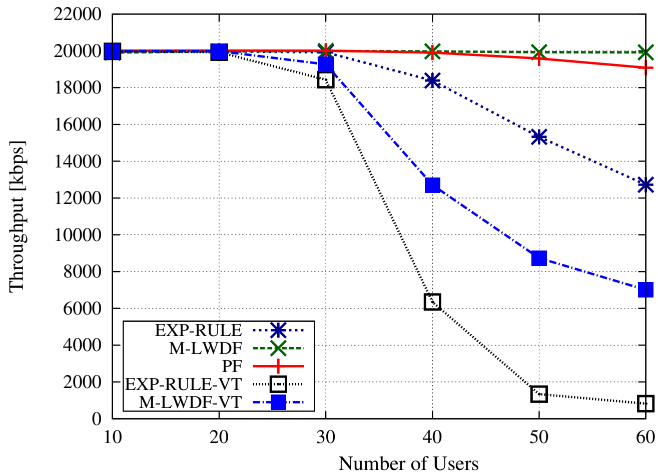

Figure 3.10: Average throughput per NRT flow (EXP-RULE-VT)

For VoIP flows the accepted PLR is under 3%. In our scenario all schedulers show acceptable packet loss rates under 3%. When the cell is loaded by 60 users only PF shows a PLR above 1% as shown in Figure 3.7.

For NRT flows the best PLR performance is shown by M-LWDF whose PLR is under 1% when the cell is loaded by 60 users. PF also shows an acceptable PLR when the cell is loaded up to 50 users. EXP-RULE shows a PLR under 3% when the cell is loaded up to 31 users. EXP-RULE-VT and M-LWDF-VT show a sharp increase of packet loss ratio. This can be explained by the fact that in our scenario VT mechanism has been set to 1 which represents the value of r in Equation 3.1. It means that NRT

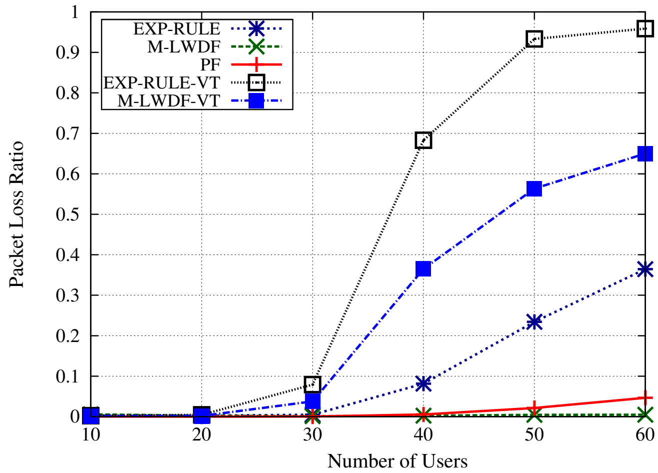

Figure 3.11: Packet loss ratio for NRT flows (EXP-RULE-VT)

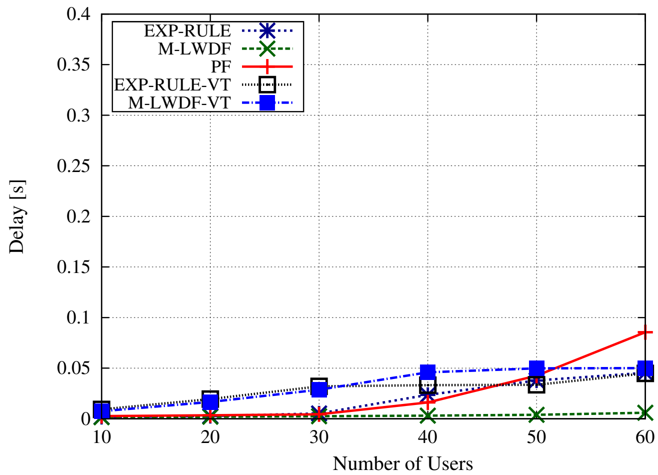

Figure 3.12: Delay for NRT flows (EXP-RULE-VT)

queue will be the shortest one, therefore NRT flows will perform high packet losses caused by buffer overflows. However, it should also be noted that LTE-Sim works under UDP traffic, so considering that FTP is normally implemented under TCP, the PLR rate could be lower than shown in Figure 3.11 due to the TCP retransmission control.

Delay. Video delays are illustrated in Figure 3.4. The best performance is shown by EXP-RULE-VT with its delay under 0.05 s. The other schedulers are under 0.07 s except PF which presents the worst performance.

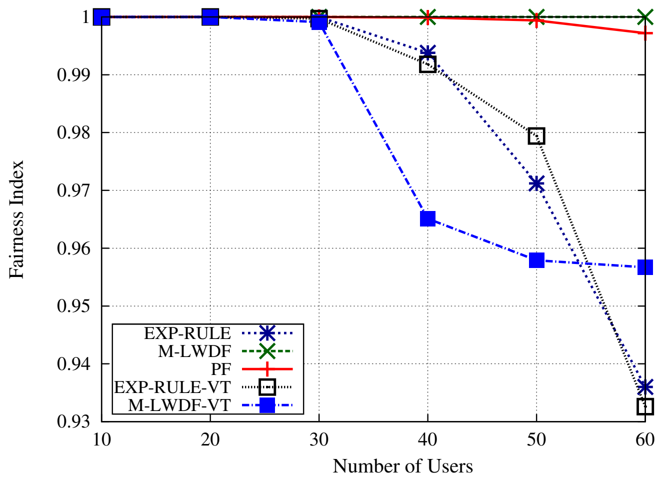

Figure 3.13: Fairness Index for NRT flows (EXP-RULE-VT)

VoIP delays are shown in Figure 3.8. The shorter delays are performed by M-LWDF-VT (under 0.007 s when the cell is loaded by 60 users). The other schedulers show similar packet delays, all of them under 0.02 s, except PF (0.08 s) when the cell is loaded by 60 users.

NRT delays are shown in Figure 3.12. The shorter delays is shown by M-LWDF. These results complements the results obtained in throughput and PLR figures. We earlier on assumed that the poor throughput performance is caused by packet losses. We also assumed that packet losses is caused by buffer overflows. Now regarding Figure 3.12, our assumptions about high buffer overflows are confirmed because the packet delays are in the average range in physical layer transmission.

Fairness Index. The fairness index for video flows is shown in Figure 3.5. The best results are performed by EXP-RULE-VT and EXP-RULE that reach a fairness index above 95%. The worst results are performed by PF that reaches a fairness index of 61%.

For VoIP flows, Figure 3.9 shows the fairness index. Since the VoIP flows are created by an ON/OFF method the curves show ups and downs. All algorithms show a fairness index performance between 97% and 99%.

For NRT flows, Figure 3.13 the highest fairness indexes are presented by M-LWDF and PF that reach above the 99%. The worst fairness index levels are showed by M-LWDF-VT and EXP-RULE-VT that reach a level between 93% and 94%.

As we can see in this section, the use of virtual token mechanism improves the performance of RT flows such as video and VoIP. On the other hand its performance for NRT flows is relatively poor. Both algorithms EXP-RULE-VT and M-LWDF-VT show the best performance for Video and VoIP flows in terms of throughput, PLR, delay and fairness index. These schedulers show considerable packet losses due to buffer overflows in NRT flows. To handle this problem, it is necessary to assign to r in Equation 3.1 a different value for each flow in order to reach an equilibrium. However, this task is not that simple because it is necessary to perform several tests with several values for r in order to find the optimist one.

3.1.2 Resource Allocation by Using Cooperative Game Theory

3.1.2.1 Problem Formulation and Justification

Resource Allocation in LTE using only opportunistic algorithms does not guarantee the desired general fairness level. In the previous section, we have shown the performance of several opportunistic schedulers under LTE constraints. Despite the fact that the VT method has been adapted to schedulers that consider HoL packet delays, there still exist no optimal trade-off between fairness and throughput efficiency. The virtual token method presented earlie combined with EXP-RULE showed a high performance for RT flows but the performance for NRT flows is poor. Although our proposed method reached an important improvement for resource allocation performing it still lacks of general fairness. This means that the fairness level among flows classes (i.e. video, VoIP, BE) needs to be improved.

In this scheme, we aim to provide the scheduling mechanism the general fairness characteristic. An optimal scheduler must not only focus on RT services, it also has to serve NRT services. The partial fairness performed by opportunistic schedulers does not take into account the type of service. To achieve this goal, it is necessary to use any method for fairness reaching therefore we chose game theory. The need of fairness approaches brings us out to involve this research to the use of game theory. Until recently the mathematical standard of fairness for specific problems (i.e. the cake cutting problem) is modelled with game theory. Game theory possesses special properties such as bargaining [62], proportional fair division [80], voting systems and general equilibrium which are interesting concepts to be adapted to the main difficult task in resource allocation which is the decision making in order to build a smart and efficient scheduler [80][63][62].

Therefore, the problem could be formulated as: How to improve the fairness level of opportunistic schedulers while maintaining a high bitrate efficiency performance? How to reach an optimal trade-off between flow classes?

3.1.2.2 Scheduling Proposed Scheme

In subsubsection 2.2.1.1, we remarked the lack of general fairness carried out by the PF algorithm. The fairness definition of PF is only based on users channel quality; we consider that this parameter is not enough to evaluate a multi service fairness level. Therefore, in order to improve the fairness constraint we take this concept as a higher level of performance where we also consider other aspects such as the number of flows that belong to each flow class and the bitrate required for each class to perform an efficient service. An efficient method for performing this task is the bankrupcty games which is part of game theory and whose main method is the Shapley Value (SHV) [80]. Bankruptcy games focus on a distribution problem involving the allocation of a given amount of a perfectly divisible good among a group of agents. The focus is on the case where the amount is insufficient to satisfy all their demands.

Based on a standard bankruptcy game, our proposed resource allocation algorithm for a downlink system is composed by two levels, see [87]. On the first level a fair resource distribution among classes using Shapley value method is performed. On the second level, having the proportion of resource destined to each class (video, VoIP, CBR, etc) a resource allocation is performed using EXP-RULE, respecting the amount of resource that Shapley value assigned to each class as can be seen in Figure 3.14.

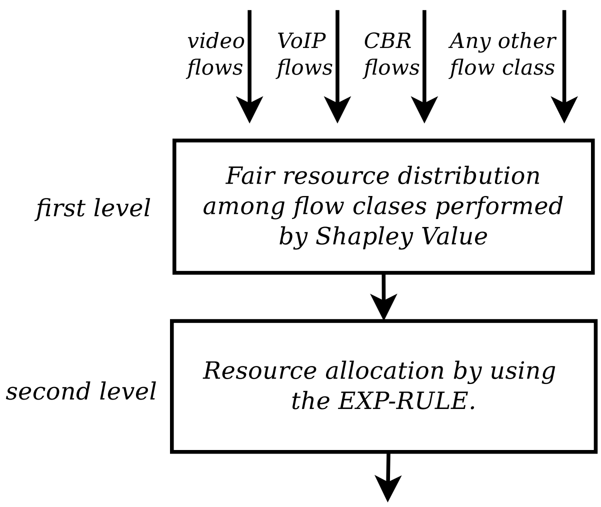

Figure 3.14: Two level resource allocation method based on game theory

High Level At this level a Transfer Utility (TU) game is carried on. The Shapley Value (SHV) is used as method for fairness assuring. SHV is a Game Theory concept proposed by Lloyd Shapley [80] which proposes the fairest allocation of collectively gained profits between the several collaborative players. The basic criterion is to find the relative importance of every player regarding the cooperative activities. In mathematics SHV is considered as a fairness standard.

$$\phi_i(v) = \sum_{S \subseteq N} \frac{(|S|-1)!(n-|S|)!}{n!}(v(S) - v(S\backslash\{i\})) \tag{3.5}$$

Details about this equation can be found in [80]. In our proposed scheme the main task of Shapley value is to perform a fair division of resource blocks among flow classes (i.e. video, NRT, VoIP). This division must be performed taking into account constraints such as the number of users that belong to each flow class and the bitrate that each flow class requires (i.e. video=128 $Kbps$, VoIP=8.4 $Kbps$).

Consider the following scenario to explain our resource allocation model.

Let us define three classes $A = video$, $B = VoIP$ and $D = NRT$ as players in our scenario $N = \{A, B, D\}$. Consider $C = 32Mbps$ (50 Resource Blocks per TTI). The bandwidth required by a single flow of each class is $b = (242, 8.4, 20)kbps$. The allocation is dynamic and depends on simultaneous flows quantity $K = (k_A, k_B, k_D)$. Thus, our bandwidth game is modeled as $(N; vc_g)$ where $|N| = 3$ and $vc_g(S) = max\{C - \sum_{i \in N \backslash S} g_i, 0\}$, with $v(N) = C$. Developing the characteristic functions we have:

$$\begin{aligned}
v(1) &= max\{32000 - (8.4k_B + 20k_D), 0\} \\
v(2) &= max\{32000 - (242k_A + 20k_D), 0\} \\
v(3) &= max\{32000 - (242k_A + 8.4k_B), 0\} \\
v(1,2) &= max\{32000 - 20k_D, 0\} \\
v(1,3) &= max\{32000 - 8k_B, 0\} \\
v(2,3) &= max\{32000 - 242k_A, 0\} \\
v(1,2,3) &= 32000
\end{aligned}$$

Thus, we go through to Shapley value as can be seen in Equation 3.5 to compute the resources related to each class depending on K.

Low Level We also call this level the second fairness level. On the high level our scheme performs a global resource apportioning based on flow classes, bitrate flows requirements and quantity of flows in each flow class which assures a high fairness level. Now in the low level we perform the EXP/RULE mentioned earlier in subsubsection 2.2.1.2. EXP-RULE has been chosen to perform this task based on its high performance for RT flows shown in last section. Each flow class performs the EXP-RULE scheduler to allocate resources to its flows depending on their quality of channels and delays. To summarize, on the high level our algorithm assures that each flow class will get allocated, and in the low level the flows that have the most high packet delay and the best quality of channel will get allocated.

3.1.2.3 Numerical Results

In this work, the fairness characteristic granted by the Shapley Value is used to apportion resources among classes before using the EXP-RULE algorithm. Algorithms like PF, M-LWDF and the classical EXP-RULE are also performed in our scenario in order to help to carry out the performance evaluation, comparing their results with our proposed scheduling scheme. We call our proposed scheduling scheme "EXP-RULE-SH ". The simulation scenario is the same as described in subsubsection 3.1.1.3.

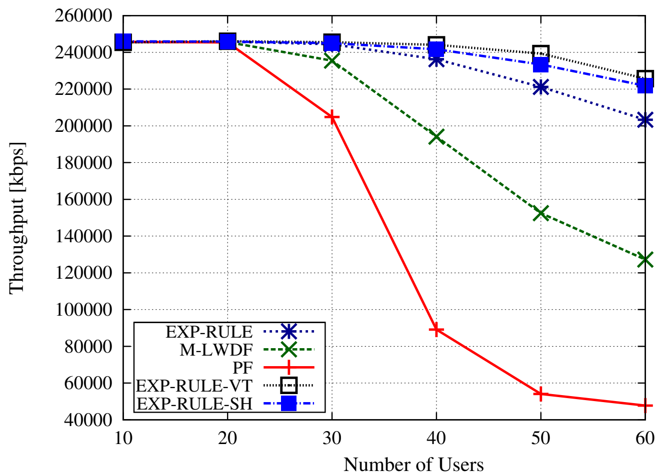

Figure 3.15: Average throughput per video flow (EXP-RULE-SH)

The classical EXP-RULE algorithm, serves the packets having the best scheduling metric, no matter the type of service that packets belong. Therefore, there could be the case where a given flow class, would not be served during a given TTI. Now using Shapley value before performing the resource allocation, EXP-RULE is not bounded only by allocating resources to flows whose packets have the best scheduling metric but also to all flow classes without any exception at each TTI. This implies a higher fairness level among flows, throughput gain for each flow, PLR decrease, and a lower delay. In

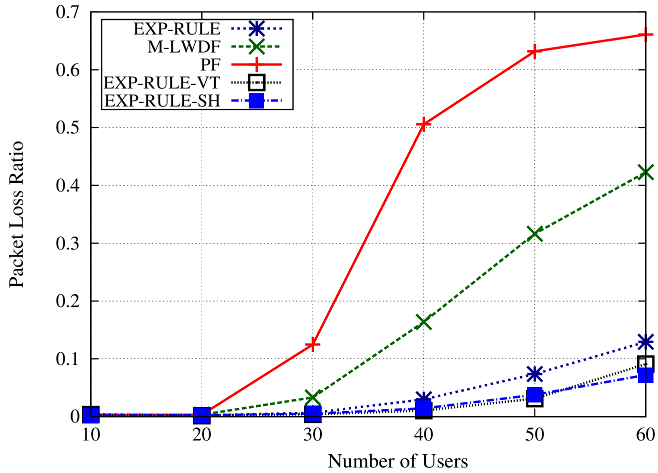

Figure 3.16: Packet loss ratio for video flows (EXP-RULE-SH)

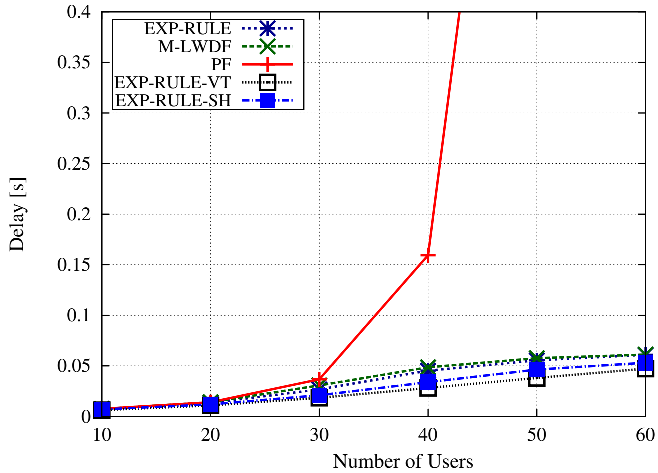

Figure 3.17: Delay for video flows (EXP-RULE-SH)

consequence, our proposed algorithm improves the classical EXP-RULE scheduler as follows:

Throughput. For video flows as shown in Figure 3.15, there is a throughput gain up to 25% when using EXP-RULE-SH compared to EXP-RULE when the cell is loaded up to 60 users. However EXP-RULE-SH does not show a better performance than EXP-RULE-VT. Both schedulers perform a satisfactory video throughput up to 55 users, it means 15 users more than EXP-RULE.

For VoIP flows as seen in Figure 3.19, all algorithms show similar results. All

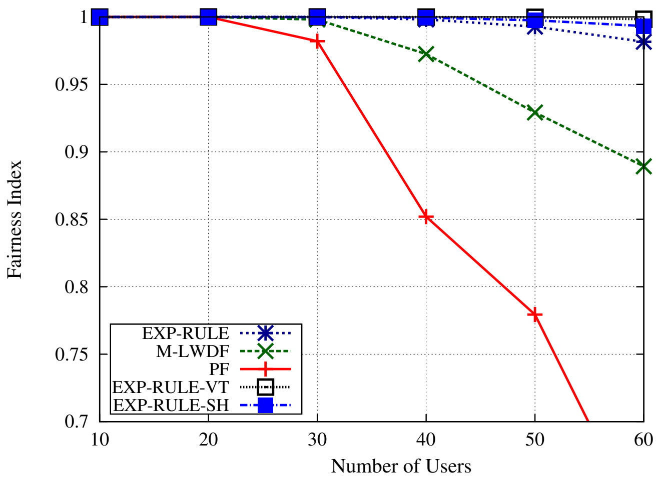

Figure 3.18: Fairness Index for video flows (EXP-RULE-SH)

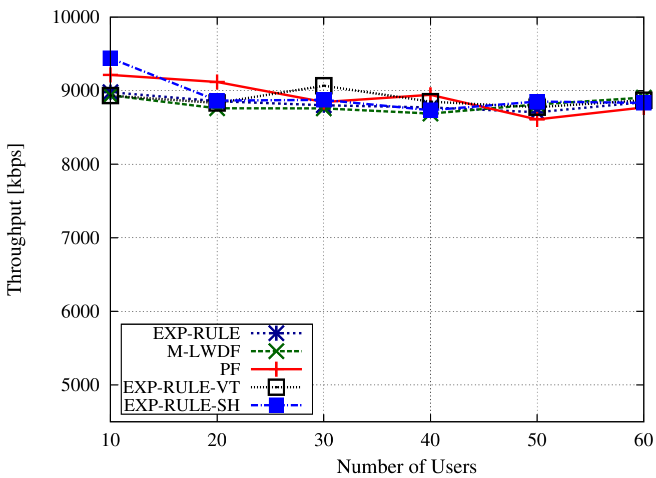

Figure 3.19: Average throughput per VoIP flows (EXP-RULE-SH)

algorithms show the desired throughput when the cell is totally loaded up to 60 users.

For NRT flows as shown in Figure 3.23, throughput increases up to 30% when using EXP-RULE-SH compared to EXP-RULE when the cell is loaded by 60 users. However the best performance is found in M-LWDF and PF schedulers. The worst results are performed by EXP-RULE-VT. EXP-RULE-SH maintains the required throughput when the cell is loaded up to 42 users.

Packet Loss Ratio. For video flows the PLR decreases by 30% when using EXP-RULE-SH compared to EXP-RULE when the cell is totally loaded by 60 users. As

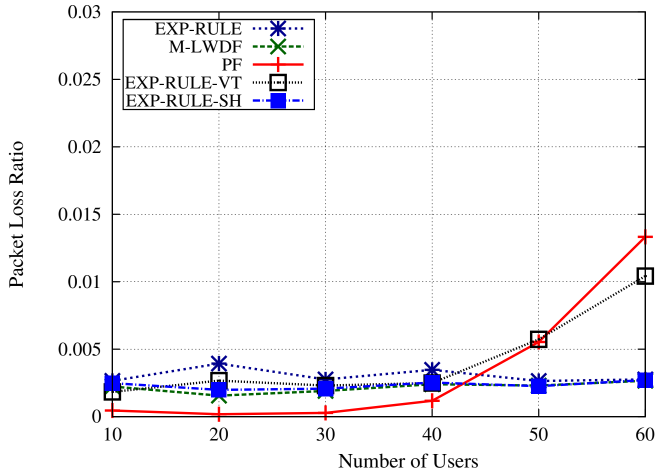

Figure 3.20: Packet loss ratio for VoIP flows (EXP-RULE-SH)

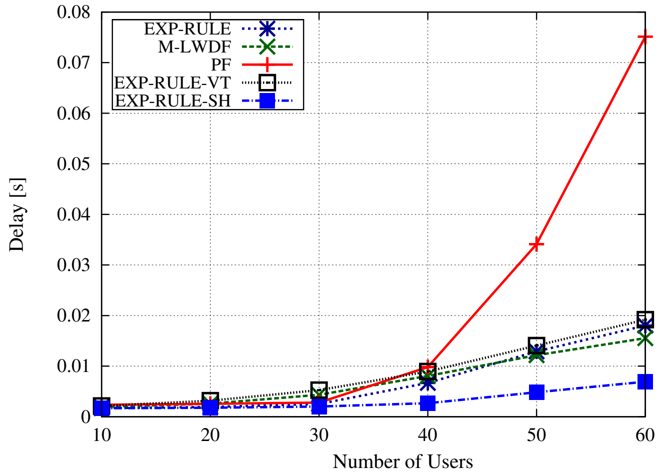

Figure 3.21: Delay for VoIP flows (EXP-RULE-SH)

shown in Figure 3.16, EXP-RULE-SH performs similar results than EXP-RULE-VT. Only 23 users show a PLR up to 1%.

For VoIP flows Figure 3.20, EXP-RULE-SH shows the best performance. The worst results are performed by PF and EXP-RULE-VT, however they are under the limit level (3%). Although all schedulers perform PLR under 1.5%, EXP-RULE-SH shows a lower PLR than EXP-RULE-VT.

For NRT flows as shown in Figure 3.24, the best performances are found in PF and M-LWDF. EXP-RULE-SH shows a lower PLR compared to EXP-RULE. It is worth noting that NRT flows does not show high PLR levels caused by buffer overflows

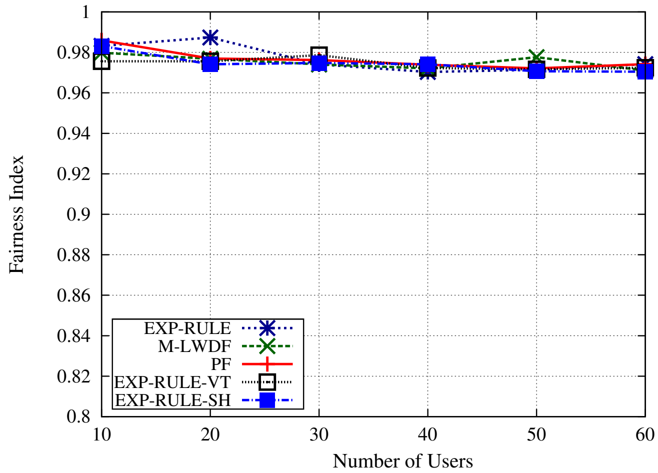

Figure 3.22: Fairness Index for VoIP flows (EXP-RULE-SH)

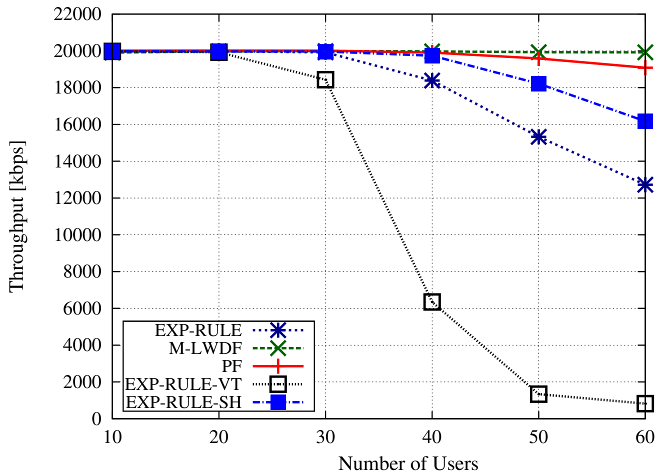

Figure 3.23: Average throughput per NRT flow (EXP-RULE-SH)

compared to EXP-RULE-VT. However, its performance does not support a desirable QoS when the cell is loaded by more than 40 users.

Delay. Delay for video flows is shown in Figure 3.17. EXP-RULE-SH performs shorter delays than EXP-RULE. However it is EXP-RULE-VT scheduler which shows shorter delays.

Delay for VoIP flows is shown in Figure 3.21. The shorter delays are performed by EXP-RULE-SH.

Delay for NRT flows is shown in Figure 3.25. The shorter delay is still shown by

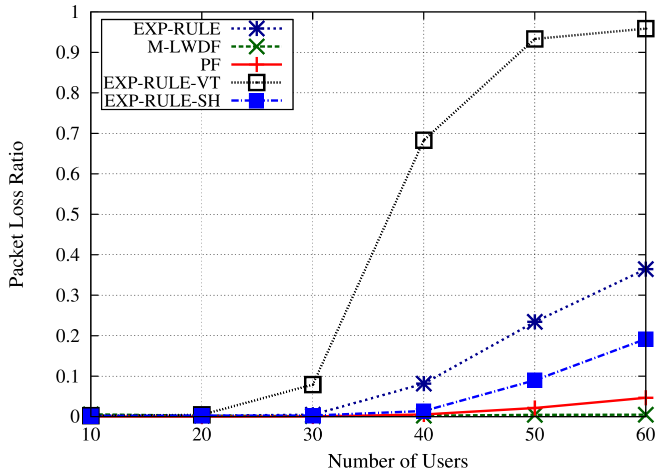

Figure 3.24: Packet loss ratio for NRT flows (EXP-RULE-SH)

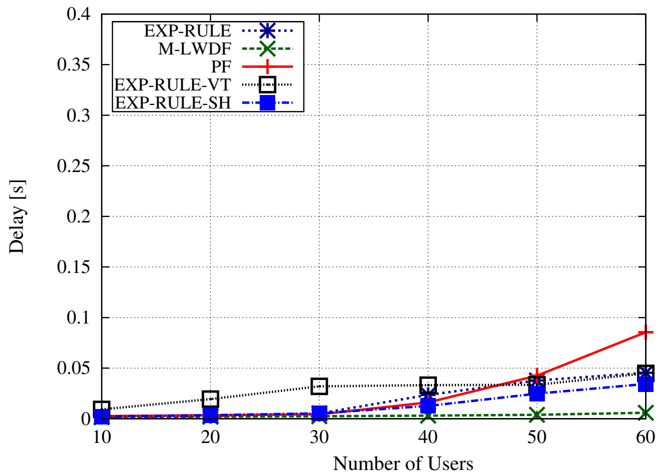

Figure 3.25: Delay for NRT flows (EXP-RULE-SH)

M-LWDF, however EXP-RULE-SH shows shorter delays than other schedulers (except than M-LWDF).

Fairness Index. Fairness index for video flows is shown in Figure 3.18. EXP-RULE-SH shows a fairness index increase up to 2.1% compared to EXP-RULE when the cell is loaded by 60 users. The best fairness index is obtained by EXP-RULE-VT and EXP-RULE-SH, however EXP-RULE-VT shows a higher fairness index than EXP-RULE-SH.

Fairness index for VoIP flows is shown in Figure 3.22. All schedulers show a fairness

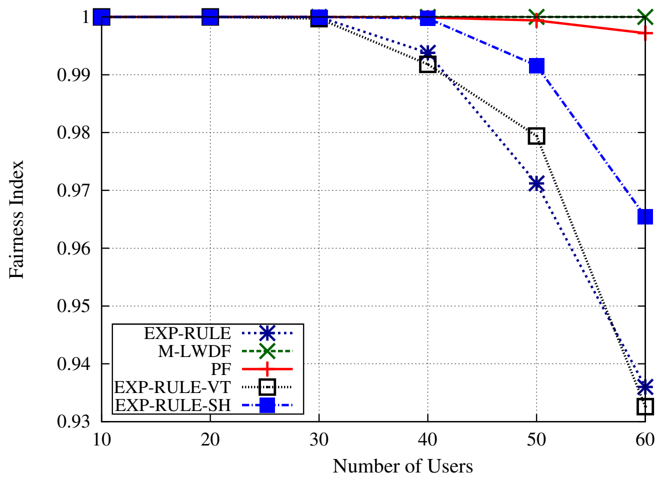

Figure 3.26: Fairness Index for NRT flows (EXP-RULE-SH)

level between 97% and 99%.

Fairness index for VoIP flows is shown in Figure 3.26. the best results are performed by M-LWDF and PF. However EXP-RULE-SH performs a higher fairness index than EXP-RULE and EXP-RULE-VT. It reaches a fairness level of 96.5% when the cell is loaded by 60 users.

Previously, by implementing the VT mechanism we found out that it presents good improvements such as throughput, fairness index, PLR, delay for RT services. However it showed a lack of general fairness, CRB flows do not give optimal results when using VT mechanism.

The use of Shapley value mitigates the general fairness issue. EXP-RULE-SH shows a similar performance than EXP-RULE-VT for RT services such as video and VoIP. The performance for NRT flows is improved by EXP-RULE-SH, however it is M-LWDF and PF schedulers that reach the best performance. A special characteristic carried out by this scheme is the fact that all flow classes are getting allocated at each TTI which forces this algorithm to reach general fairness. This algorithm does not take into account queues length, so in the next proposed method we introduce another algorithm that combines this one with the virtual token method. One possible issue that could cause a small problem is the complexity level when using a high quantity of flow classes at the same time.

3.1.3 Resource Allocation by Using Cooperative Game Theory and Virtual Token Mechanism

3.1.3.1 Problem Formulation and Justification

We previously introduced two different methods in order to improve the resource allocation performance. The first one focuses on the use of buffer status (queues length) by using virtual token mechanism, the second one reaches a general fairness improvement by the use of game theory. In this chapter in order to improve the resource allocation in LTE networks we combine the two previously proposed methods. Those two methods show good results, obviously each one focuses on different characteristics, the first one improves the throughput efficiency and the second one enhances the general fairness. It is important to emphasize that an efficient scheduler must perform an efficient trade-off between those two essential aspects which in our view is the most meaningful characteristic to be taken into account. Therefore in furtherance of this meaningful characteristic we propose a third scheme which combines our two proposed schemes, see [90].

3.1.3.2 Scheduling Proposed Scheme

In subsubsection 3.1.2.2, we introduced a fair algorithm whose main structure is based on game theory. This scheme combines the fairness concept carried on by the Shapley value with an opportunistic scheduler focused on RT services such as EXP-RULE. This scheme presents a good improvement related to the fairness index among flow classes.

On the other hand in subsubsection 3.1.1.2, we proposed to use the well known virtual token mechanism by modifying the EXP-RULE algorithm in order to improve the performance of RT services. By simulation we showed that virtual token method reaches good results for high bitrate flows.

In order to combine both main characteristics of fairness and throughput efficiency we propose to combine the schemes introduced earlier. Based on a standard bankruptcy game, the proposed resource allocation algorithm for a downlink system is composed by two levels. On the first level, a fair resource distribution among classes using Shapley value method is performed. On the second level, having the proportion of resource destined to each class (video, VoIP, NRT, etc) a resource allocation is performed using a EXP-RULE respectively modified by using a virtual token mechanism.

Two levels algorithm As we can see in Figure 3.27 this scheme is also performed in two levels. The first level a game theory bargain is performed exactly as presented

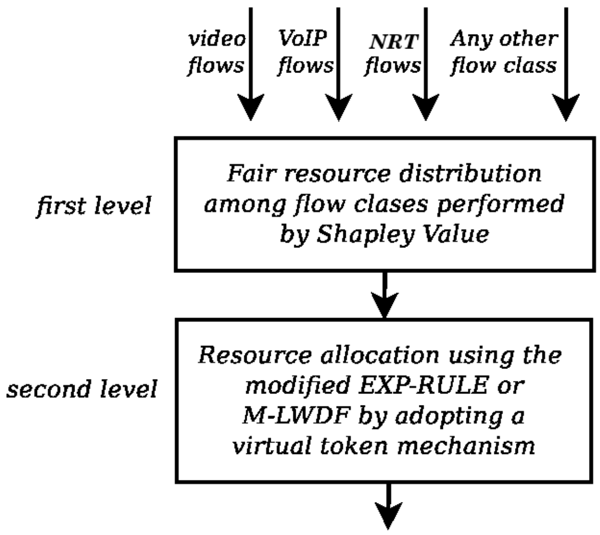

Figure 3.27: Two level resource allocation method based on game theory and virtual tokens mechanism

in section 3.1.2.2. The low level is also called the second fairness level. On the high level our scheme performs a global resource apportioning based on flow classes, bitrate flows requirements and quantity of flows in each flow class which assures a high fairness level. Now in the low level we perform the EXP-RULE modified to use a virtual token mechanism as mentioned earlier in subsubsection 3.1.1.2. EXP-RULE has been chosen to perform this task based on its high performance for RT flows shown in last section. Each flow class performs the EXP-RULE scheduler to allocate resources to its flows depending on their quality of channels. To summarize, on the high level our algorithm assures that each flow class will get allocated, and in the low level the flows which possess the most high packet delay and the best quality of channel will get allocated.

3.1.3.3 Numerical Results

In this work, the fairness characteristic granted by the Shapley Value is used to apportion resources among classes before using the opportunistic scheme composed by EXP-RULE algorithm and a VT mechanism. In this scenario in order to help carry out the performance evaluation, the non modified EXP-RULE, M-LWDF, the EXP-RULE modified by a VT mechanism, and the EXP-RULE combined to the Shapley Value are performed in order to compare their results with our proposed scheduling scheme. We call our proposed scheduling scheme "EXP-RULE-VT-SH ". The simulation scenario is the same as described in subsubsection 3.1.1.3.

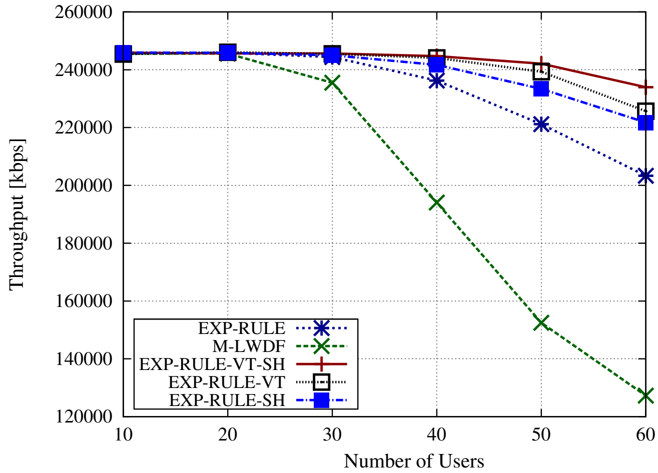

Figure 3.28: Average throughput per video flow (EXP-RULE-VT-SH)

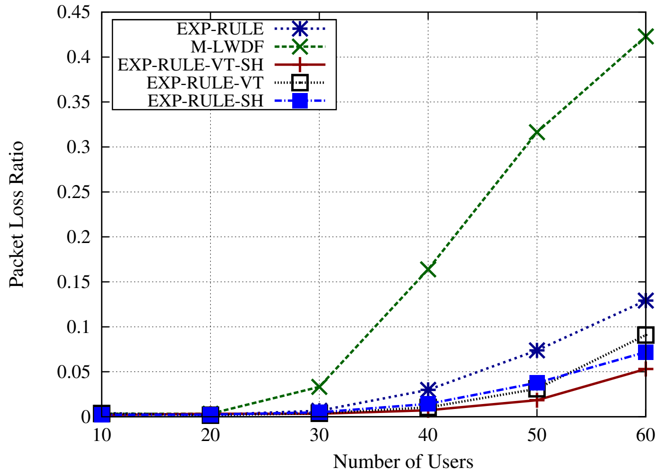

Figure 3.29: Packet loss ratio for video flows (EXP-RULE-VT-SH)

The classical EXP-RULE algorithm, serves packets having the best scheduling metric based on opportunistic parameters, no matter the type of service that packets belong. However, there could be the case where a given flow class, would not be served during a given TTI. Now using Shapley value before the allocation, EXP-RULE is bounded only by allocating resources to flows having packets with best scheduling metric, but also to all flow classes without any exception at each TTI. This implies more fairness among flows, throughput gain for each flow, PLR decrease, and a lower delay. In consequence, our proposed algorithms improves the classical EXP-RULE scheduler as follows:

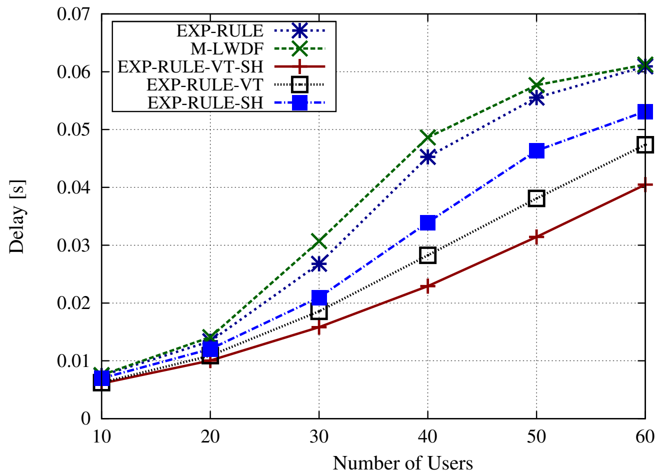

Figure 3.30: Delay for video flows (EXP-RULE-VT-SH)

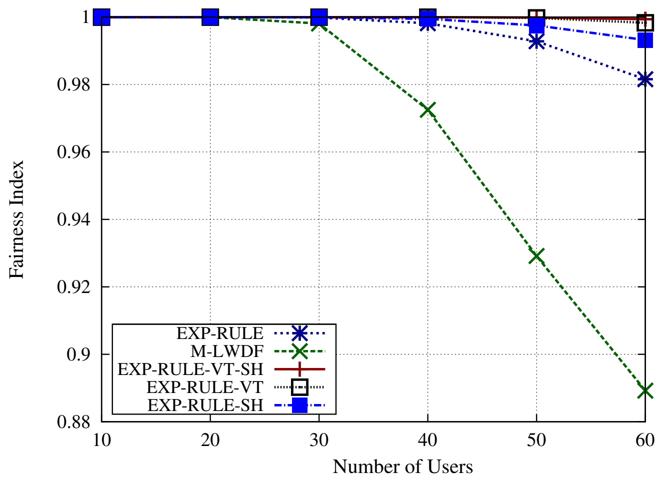

Figure 3.31: Fairness Index for video flows (EXP-RULE-VT-SH)

Throughput. Average throughput per video flow is shown in Figure 3.28. EXP-RULE-VT-SH shows a better throughput performance compared to EXP-RULE-VT and EXP-RULE-SH. EXP-RULE-VT-SH maintains the throughput when the cell is loaded by 60 users whereas that EXP-RULE supports only 40 users. By adopting the view that HOL is removed of EXP-RULE when it is modified by the VT mechanism, we can justify this throughput increase by the high bitrate needed for video flows, video flows have a higher quantity of tokens. On the other hand the Shapley value guarantees resource allocation at each TTI for each flow class. By combining both methods we can guarantee a minimum bitrate to flows that eventually have a very low quantity of

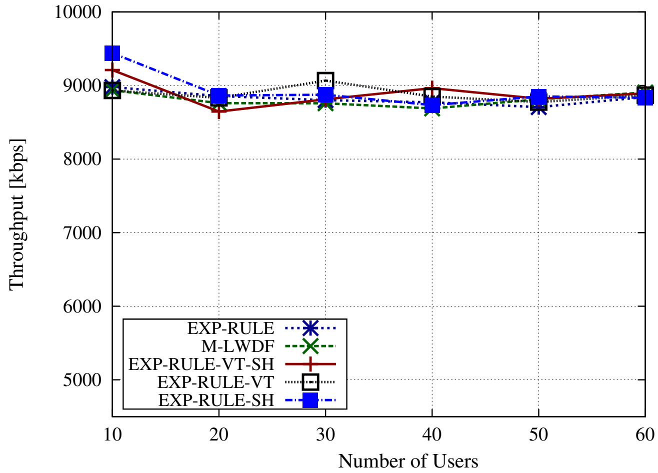

Figure 3.32: Average throughput per VoIP flow (EXP-RULE-VT-SH)

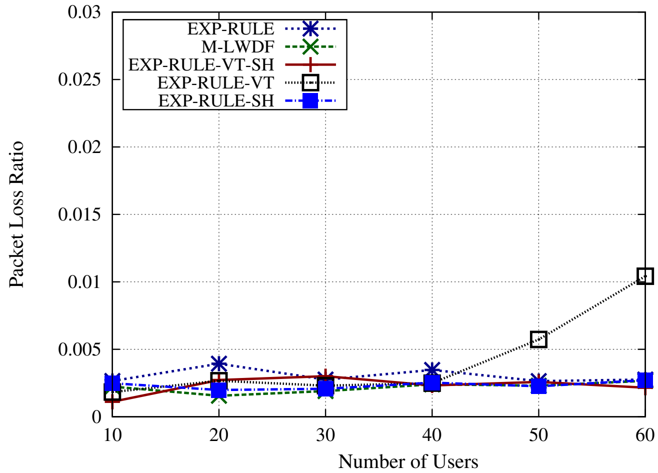

Figure 3.33: Packet loss ratio for VoIP flows (EXP-RULE-VT-SH)

tokens which is the weakness of VT method.

Average throughput per VoIP flow is shown in Figure 3.32. EXP-RULE-VT-SH also performs an efficient throughput level as all tested schedulers do. The throughput is maintained when the cell is loaded by 60 users.

Average throughput per NRT flow is shown in Figure 3.36. EXP-RULE-VT-SH shows a poor performance when serving NRT flows. Although the Shapley value guarantees a minimal resource allocation for NRT flows at each TTI, the use of virtual tokens still causes buffer overflows. The best performance is shown by M-LWDF.

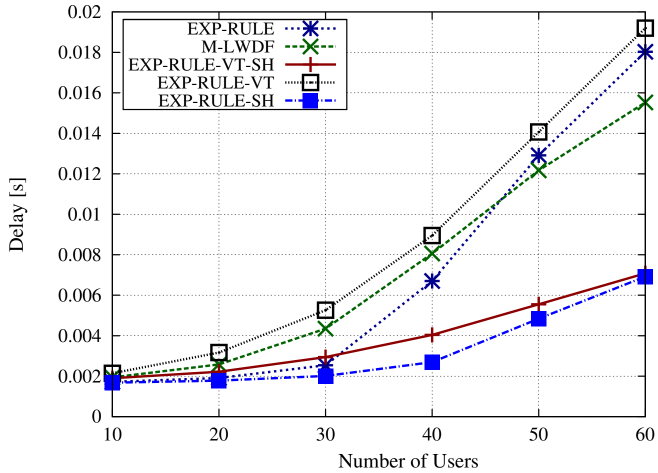

Figure 3.34: Delay for VoIP flows (EXP-RULE-VT-SH)

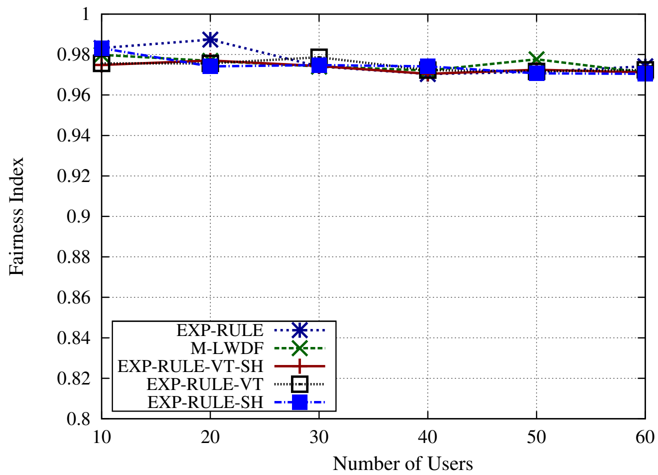

Figure 3.35: Fairness Index for VoIP flows (EXP-RULE-VT-SH)

Packet Loss Ratio. Packet loss ratio for video flows is shown in Figure 3.29. EXP-RULE-VT-SH shows the best performance compared to the two proposed algorithms. EXP-RULE-VT-SH performs a PLR under 1% when the cell is loaded up to 43 users.

Packet loss ratio for VoIP flows is shown in Figure 3.33. EXP-RULE-VT-SH performs a PLR lower than 0.3% like the other schedulers when the cell is loaded by 60 users. The only exception is EXP-RULE-VT that performs a PLR lower than 1%.

Packet loss ratio for NRT flows is shown in Figure 3.37. EXP-RULE-VT-SH and EXP-RULE-VT show the worst performance. Although PLR decreases when EXP-RULE-VT-SH compared to EXP-RULE-VT, results are not as expected. We can as-

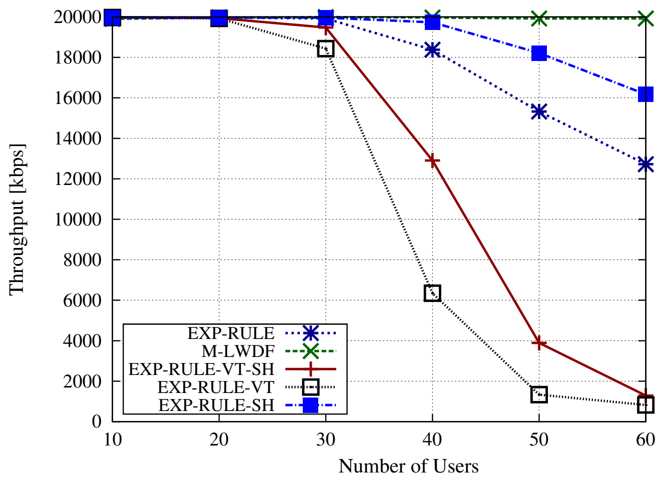

Figure 3.36: Average throughput per NRT flow (EXP-RULE-VT-SH)

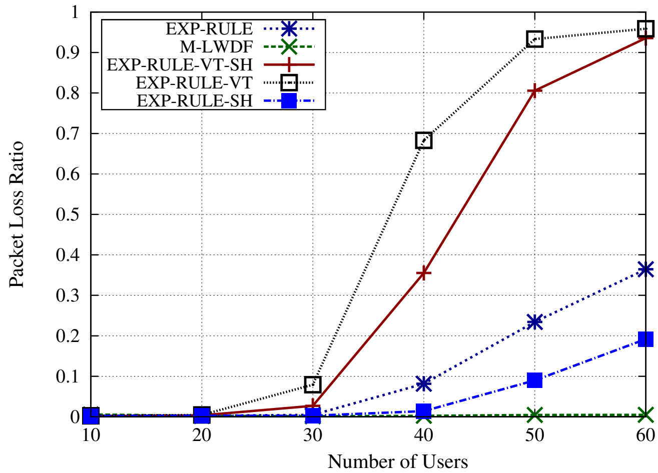

Figure 3.37: Packet loss ratio for NRT flows (EXP-RULE-VT-SH)

sume that there are still packet losses caused by overflows. It is still the M-LWDF scheduler that performs the lower PLR.

Delay. Delay for video flows is shown in Figure 3.30. EXP-RULE-SH-VT performs the shortest delays. This figure complements the information granted by throughput and PLR constraints which confirm an efficient performance for video flows.

Delay for VoIP flows is shown in Figure 3.34. The shortest delay is performed by EXP-RULE-SH, however EXP-RULE-VT-SH shows a similar performance. The longest delay is performed by EXP-RULE-VT.

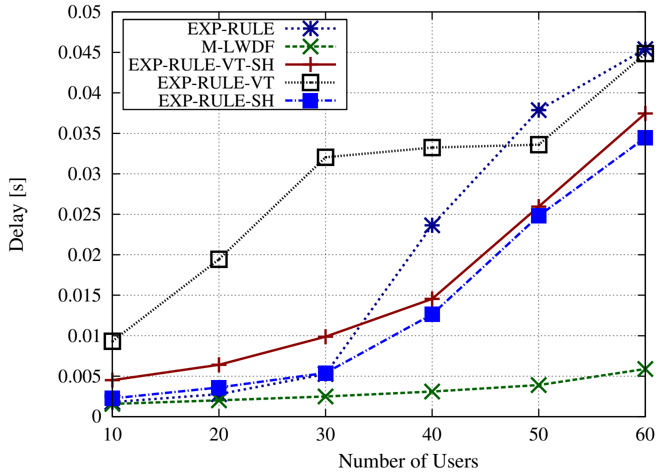

Figure 3.38: Delay for NRT flows (EXP-RULE-VT-SH)

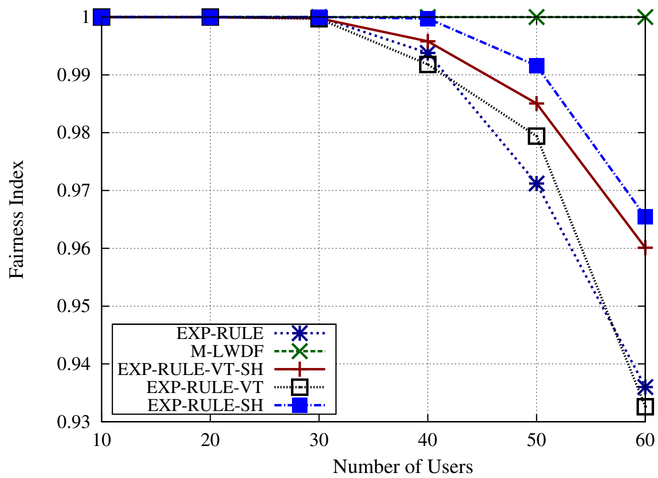

Figure 3.39: Fairness Index for NRT flows (EXP-RULE-VT-SH)

Delay for NRT flows is shown in Figure 3.38. The shortest delay is still performed by M-LWDF, however EXP-RULE-VT-SH performs shorter delays than EXP-RULE-VT.

Fairness Index. Fairness Index for video flows is shown in Figure 3.31. EXP-RULE-VT-SH shows the best performance, it reaches the 99.9% when the cell is loaded by 60 users. Another efficient fairness index is performed by EXP-RULE-VT. On the other hand, the worst results are shown by M-LWDF that reaches a fairness index of 89%.

Fairness index for VoIP flows is shown in Figure 3.22. All schedulers show a fairness level between 97% and 99%.

Fairness index for VoIP flows is shown in Figure 3.26. The best results is performed by M-LWDF. However EXP-RULE-VT-SH performs a higher fairness index.

The goal of this proposed method is to build an algorithm capable of performing a high bitrate efficiency and also a desirable fairness level. We combined the two first proposed schemes. The expected result has been accomplished for RT flows. Our proposed scheme achieves a high improvement of QoS performance for RT services. It partially mitigates the performance problem for NRT flows but it is not enough. A special characteristic carried out by this scheme is the fact that all flow classes are getting allocated at each TTI which forces this algorithm to reach general fairness. However there is still no efficient performance for NRT flows due to buffer overflows. The difference between this algorithm and the previous one is that this scheme does take into account the queues length buffer status, consequently the RT services performance has been improved. However, the complexity level when using a high quantity of flow classes at the same time is still an issue to be solved.

3.2 Summary

Along this chapter, three resource allocation schemes have been introduced. The first one aims to improve the actual opportunistic algorithms by combining a VT mechanism to the opportunistic scheduler EXP-RULE. This mechanism takes into account the buffer status (queue length), consequently the throughput efficiency level for RT services is highly enhanced. However, this algorithm is unfair in a multi service level, the scheduling priority is granted preferentially to RT services while NRT services are forced to wait for allocation. Since NRT flows have a longer waiting time before being allocated, they experience buffer overflows and consequently packet losses. The importance of throughput obviously cannot be argued, on the other hand the importance of fairness must be carefully analyzed, specially in wireless systems where users possess particular conditions.

With regard to this fairness issue, we introduced a second scheme based on game theory. We justify the use of game theory by the fact that it is currently used in other several fields such as economic science for instance to exploit its qualities such as fairness, bargaining, distribution etc. On the second algorithm we employed game theory to introduce a general fairness characteristic as a QoS parameter for the scheduling decision. As we can notice in Table 2.2, most of the algorithms do not take into account the general fairness factor, therefore our second proposed algorithm addresses its goal to fairness. As it was expected, this algorithm enhances the fairness level in resource allocation, however its bitrate efficiency for RT flows is not higher than the one reached by the VT method. On the other hand, although the throughput performance for NRT flows is better than that of the VT mechanism based algorithms, results are not that efficient as expected.

Finally, we introduced a third scheme which emphasizes on throughput efficiency and fairness. This algorithm improves our second algorithm by combining it to the virtual tokens one. Again results show an enhanced performance as envisaged, with this algorithm we reach to perform an efficient trade-off between fairness and throughput efficiency for RT flows. However, NRT flows do still experience buffer overflows, and consequently packet losses. We can discern the different parameters taken into account in our algorithms in Table 3.2.

In this chapter we have introduced three schedulers, none of them perform efficient results for NRT flows. It is M-LWDF and the PF algorithms that perform efficient results for NRT flows. A possible solution is using two types of scheduling at each TTI, one of the presented in this chapter for RT services and another one such as M-LWDF or PF for NRT services.

Table 3.2: Comparison of our Proposed Algorithms

Algorithm	*Reference*	*Packet delays*	*Channel Condit.*	*Partial Fairness*	*General Fairness*	*Low Complexity*	*Multi-service*	*Queue's length*
EXP-RULE-VT	[86]	✓	✓	✓		✓	✓	✓
EXP-RULE-SH	[87]	✓	✓	✓	✓	✓	✓	
EXP-RULE-SH-VT	[90]	✓	✓	✓	✓	✓	✓	✓

Concluding this section we can say that by dividing the whole scheme into some layers, the resource allocation task can be simplified by the fact that each layer is responsible in granting a specific characteristic. In wireless systems, the opportunistic scheduling grants a partial fairness to users which bases its main decision on the quality of channels. Opportunistic schedulers reach high throughput efficiency but they present a lack of general fairness. In order to keep a general fairness level, our algorithms use game theory approaches in a different layer or level. When adapting a game theory to a smart opportunistic scheduler, the fairness level increases without decreasing the bitrate efficiency. Therefore it is also reasonable to conclude that dividing the algorithm in layers or levels, an effective trade-off is reached without having complex processes. There are obvious limitations when using this scheme, specially in the game theory level which is related to the complexity which must be carefully taken into account.

From the next chapter, we start the second part of this thesis, the QoS in femtocell scenarios. We present an overview of femtocell architecture and a state of the art of interference mitigation mechanisms for femtocell scenarios.

Chapter 4

An Overview of Femtocells

In mobile telecommunications technologies a critical problem to deal with, is the macrocell limitation for serving users who are geographically situated in low signal reception places. As seen in previous chapters, in LTE macrocell scenarios users who possess the best channel conditions get a higher QoS level, consequently bad channel conditions users get the lower QoS level. In order to mitigate this issue and strongly improve the QoS level for users who are located distant of the eNb, femtocell architecture has been adopted by the 3GPP specifications in [2]. Femtocells are small base stations also called Home eNodeB (HeNb) which are installed by users and data is sent through a broadband over the Internet. The main purpose of femtocell architecture is to provide a private mobile coverage inside buildings with free radio resources on the outdoor network. Femtocell architecture improves the bitrate for users whose positions are far from the eNb, however, there exist several issues that avoid high QoS performance, one of these issues is the neighbours interference. This chapter presents a brief introduction to femtocell architecture and the state of the art related to interference mitigation schemes in femtocell scenarios.

4.1 Overview of Femtocells architecture in LTE

In LTE architecture, the QoS management is handled by the eNb by controlling the resource allocation performance. The eNb experiences hard resource allocation problems due to users' geographical positions. When a user is close to the eNb it will experience a very good QoS. On the other hand, when a user is located in a very poor signal coverage place, its performance might not be as expected specially when using non elastic services due to a packet loss.

In the LTE specifications [2], a femtocell architecture is proposed to strongly improve the QoS of next generation wireless technology. Due to macrocell limitations to serve users that are geographically situated in bad signal reception places, femtocell architecture aims to provide a high quality of service to users that are not being efficiently served by the eNb. Femtocells base stations in the LTE standard are called HeNb (Home EnodeB). The main goal of HeNbs is to provide a private mobile coverage inside buildings with free radio resources on the outdoor network, consequently increasing the total capacity of the mobile system by avoiding several wall penetration losses. Furthermore, the radio technology used in indoor scenarios is the same as the one used in outdoors scenarios. Although femtocells grant users a better quality of signal, the resource allocation performance is subject to neighbouring interference.

The main interference issues in femtocell scenarios are essentially focused on macro-femto interference and femto-femto interference. According to handover process between macrocells and femtocells, access control mechanisms, open-access and closed-access are identified. In open-access femtocells, macro-users are allowed to be handed over to the corresponding femto base station. In closed-access the femto base station only grants access to a particular set of authorized users. It is the closed-access system that causes the most harmful interference. Macro-femto interference can be well explained in a scenario where macro-users utilize the same sub-band than some femto-user at the same time. The consequence of this particular issue is the loss of transmission caused by this interference to the femto-user.

Femto-femto interference is caused by neighbouring issues. The geographical distribution of buildings does not follow any standard, therefore HeNbs will be positioned in a random manner. This causes home cell edge interference between apartments and offices in small coverage areas. A user using a high data rate service (i.e., video) in his/her room will experiment strong interference issues in the case that the neighbour HeNb is installed on the other side of the wall. Unlike the macrocell, femtocell can be installed by users in their own premises (i.e., in a random manner), making it difficult to handle the femto-femto interference problem.

4.1.1 Femtocell Architecture

In section 1.1 low layers such as the physical and MAC were described. The functions supported by the HeNb are the same as those supported by an eNb. HeNb possesses the same protocol stack as a macrocell, therefore given that the low layers were already presented, the femtocell architecture is presented in Figure 4.1

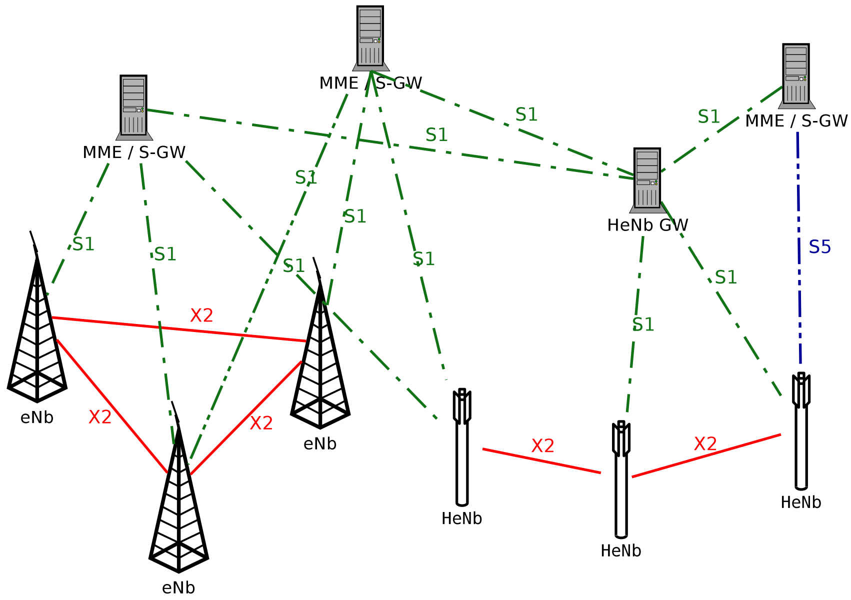

Figure 4.1: Femtocell Architecture

HeNbs communicate with gateways (MME/S-GW and HeNb GW) by using the S1 interface. Nowadays the last version of the specification supports direct X2-connectivity between HeNbs, independent of whether any of the involved HeNbs is connected to a HeNb GW. There is no supported connectivity between eNb and HeNb. HeNb GW almost always will handle a HeNb neighborhood.

4.1.2 Understanding the femtocell interference impact

Interference in wireless systems is a factor which alters, modifies, or disrupts a signal as it travels along a channel between a source and a receiver. Interference hampers coverage and capacity, and limits the effectiveness of transmissions. Interference causes packet losses, retransmissions and delays, therefore it degrades the QoS in wireless systems. In order to have a high network performance, interference must be minimized.

As previously mentioned, there is a huge difference related to interference mitigation between macrocell and femtocell scenarios. In Figure 4.2, we can see an approach of macrocell interference scenario. It is important to bear in mind that geographical macrocell positions are assigned by macrocell operators by following technical plannings including macrocell transmit power, distance between macrocells and the expected number of users. As we can see in Figure 4.2 users exposed to interferences are those who are positioned in macrocell common edges representing few part of total number of users.

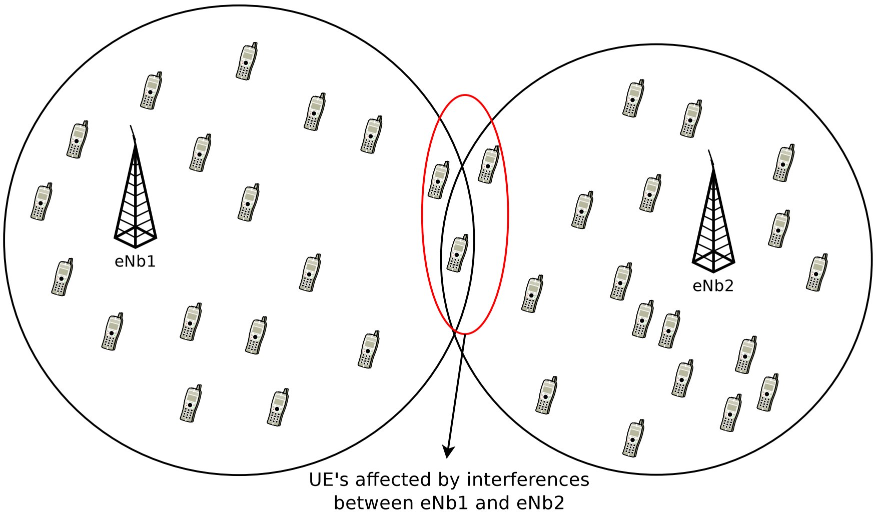

Figure 4.2: Macrocell Interference Scenario

Now in Figure 4.3 we can observe the femtocell interference scenario. Since femtocell scenario differs from macrocell scenario, the interference mitigation scheme must take into account factors such as:

1. In a femtocell the number of users is approximately reduced on range from 1 to 3, so the impact of QoS degradation due to interferences could reach the 100% of users.

2. The distance between femtocell cannot be controlled due to the fact that users themselves install the femtocell at home randomly.

3. In a macrocell scenario the transmit power is controlled by operators, the decision is made based on cell positions which facilitates the interference mitigation. The 3GPP specifications indicate the signaling accomplishment over the X2 interface between base stations in order to use interference mitigation mechanisms [5]. Femtocell standard does not specify any transmit power control scheme, the transmit power is set as fix which causes interference when neighbours randomly install the femtocells close to each other.

4. Unlike macrocells, femtocell surfaces are relatively smaller, consequently the pathloss models are different.

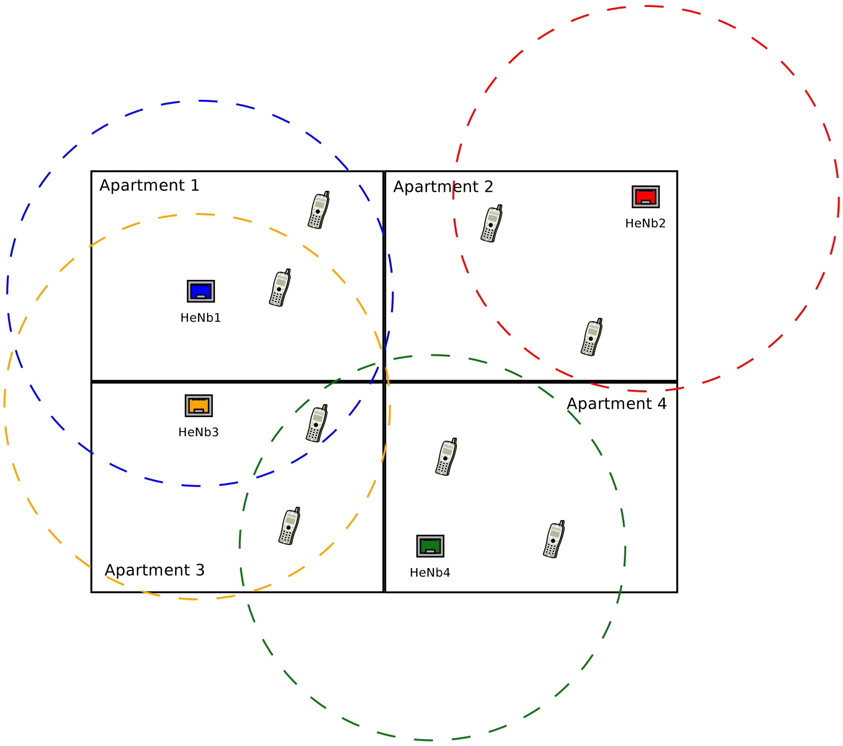

Figure 4.3: Femtocell Interference Scenario

When mitigating interference in femtocell scenarios it is important to know the types of interference in order to choose an optimal method.

4.2 Overview of Interference Mitigation in Femtocell Scenarios

Unlike macrocell interference mitigation techniques, interference mitigation in femtocell scenarios has not been completely deployed. In macrocell several techniques such as transmit power control, Static Fractional Frequency Reuse (FFR), spatial techniques, etc. have been introduced [85] [5]. Unfortunately due to several factors, as explained earlier macrocell techniques cannot be used in femtocell scenarios. However, several authors have attempted to adapt macrocell techniques to femtocell scenarios.

4.2.1 Interference levels

To better understand the related work about interference mitigation, we firstly classify the interference experienced by users in two levels; co-tier and cross-tier.

Co-tier Interference. Co-tier interference occurs among network elements that belong to the same tier in the network. In case of a femtocell network, co-tier interference occurs between neighbouring femtocells. For example, a femtocell base station acts as a source of downlink co-tier interference to the neighbouring femtocell UEs. However, in OFDMA systems, the co-tier interference occurs only when the aggressor (or the source of interference) and the victim use the same sub-channels.

Cross-tier Interference. This type of interference occurs among network elements that belong to the different tiers of the network, i.e., interference between femtocells and macrocells. For example, the serving macrocell base station and femtocells cause downlink cross-tier interference to the femtocell UEs and nearby macrocell UEs, respectively. Again, in OFDMA-based femtocell networks, cross-tier interference occurs only when the same sub-channels are used by the aggressor and the victim.

4.2.2 Interference Mitigation Topologies

In order to coordinate the interference mitigation, we classify the interference mitigation methods in centralized and distributed schemes. However, in this thesis, the self-configured schemes are considered part of distributed schemes.

Centralized Schemes. A centralized scheme for interference mitigation performs its coordination and decision making at a central entity. Since the central entity needs to know at every moment femtocells information, this kind of schemes require an optimal level of signaling performance. In this context, femtocells need to send feedback to the central entity several parameters such as number of users, quality of channels and even type of services. When the femtocell density is low, centralized schemes present high performances and are considered as efficient solutions. On the other hand when the femtocell density increases in several cases the computational complexity also increases becoming a trouble to deal with. A strong candidate to be the "central entity"is the HeNb GW because it interconnects femtocells and by the S1 interface as shown in Figure 4.2.

Distributed Schemes. Unlike centralized schemes, distributed schemes do not need a central entity in the decision-making. In a distributed scheme each femtocell sends information to femtocell neighbours, therefore the decision making is performed at each femtocell by following a general standardized scheme taking into account the same parameters such as number of users, quality of channels and even type of services etc. The problem in distributed schemes comes up when the femtocell density becomes high.

Self-Configuration Schemes. In self-configured schemes femtocell manages their interference mitigation mechanisms without interchanging messages between neighbours. Only basic information is used to perform the decision making. This technique is mostly used in co-tier interference.

4.2.3 Interference Mitigation Mechanisms

In this part of the thesis, we aim to present a brief state of the art of interference mitigation mechanisms. We analyze the several proposed techniques and we classify them in groups in order to highlight their common characteristics. Each mechanism is carried out by considering several features such as interference mitigation topologies (as seen in subsection 4.2.2) and interference levels (as seen in subsection 4.2.1).

4.2.3.1 Bandwidth Division Mechanisms (BDM)

This family of mechanisms works by dividing the total bandwidth among femtocells in order to use the different sub-bands. This type of interference mitigation mechanism can be applied in co-tier and cross-tier interference. Schemes based on bandwidth division can be considered as an efficient solution. However, this kind of schemes requires mechanisms to decide the amount of bandwidth to be assigned to each HeNb/eNb.

Graph based Mechanisms (GM) Graph based solutions are proposed to mitigate interference issues in macrocell networks. The core of this method is to divide the whole bandwidth into sub-bands. Each bandwidth chunk is assigned among base stations in order to avoid base stations to use the same sub-bands, hence mitigating the interference.

The problem of interference mitigation can be formulated as an interference graph in which UEs correspond to the nodes and relevant interference relations between UEs correspond to the respective edges. To minimize interference, connected UEs should not be allocated the same set of resources. Such a problem is directly related to the graph coloring problem in which each color corresponds to a disjoint set of frequency resources. The goal is for each node in a graph to be assigned a color in a way that no connected nodes are assigned the same color. Graph that approaches such as graph coloring methods [41] [54] [12] [50] are mostly implemented at MAC layer. Graph coloring algorithms cannot guarantee the originally intended bitrate. When using this method, each HeNb can only use a fraction of the total bandwidth (1/4 of the total bandwidth in the worst case). On the other hand the SINR value is high which means no interference among femto neighbours. However, graph based coloring methods have a few critical problems:

- It may fail to achieve the target data rate, because the graph is generated based on a partial sub-band allocation model. This could be a considerable issue to deal with, specially in the case where services are non-elastic which is the core of LTE.
- The sub-band division and distribution shall be performed by a central entity. This leads to a high time complexity in a dense HeNb deployment.

Frequency Reuse based Mechanisms (FRM) This type of schemes allows femtocells to access the resources that are not being used by macro users. The basic mechanism of this method divides the entire frequency spectrum into several sub-bands. Afterwards, each sub-band is assigned to each macrocell or sub-area of the macrocell. Since the resource for eNb and HeNb is not overlapped, interference between eNb and HeNb can be mitigated.

In [48], the authors propose frequency reuse schemes allowing the femtocells (which have a lower priority than macro users) to access the resources that are not being used by the macro users around them. In this paper, the proposed scheme has a reuse factor of 1 and has been considered with a focus on reinforcement learning and an equal priority between macro and femto users.

In [44], the authors propose a frequency sharing mechanism that uses frequency reuse coupled with pilot sensing to reduce cross-tier/co-channel interference between macrocell and femtocells. In this scheme, Fractional Frequency Reuse (FFR) of 3 or above is applied to the macrocell. When a HeNb is turned on, it senses the pilot signals from the eNb and discards the sub-band with the largest received signal power, and thus uses the rest of the frequency sub-bands resulting in an increased SINR for macrocell UEs. The overall network throughput is enhanced by adopting high-order modulation schemes.

In [39], another interference management scheme for LTE femtocells is presented based on FFR. The scheme avoids downlink cross-tier interference by assigning sub-bands from the entire allocated frequency band to the HeNbs that are not being used in the macrocell sub-area. In the proposed scheme, the macrocell is divided into centre zone (corresponding to 63% of the total macrocell coverage area) and edge region including three sectors per each region.

In [53], an adaptive FFR scheme is presented to minimize downlink interference caused by the HeNbs in the vicinities of a macrocell. The proposed scheme adopts FFR radio resource hopping or orthogonal FFR radio resource allocation based on the density (e.g., high or low) and location information (e.g., inner region or outer region) of the HeNbs. The location information of the HeNbs may be obtained and maintained within the network through using registered physical address associated with the broadband IP (Internet Protocol) address that a HeNb uses. The proposed scheme only deals with the cross-tier interference posed by the HeNbs located (inner region) near the eNb. If the HeNb is situated in a high dense inner region, then orthogonal sub-channels are adopted by the HeNbs. Otherwise, the HeNb selects a subchannel arbitrarily, utilizes it for a certain period of time, and then hops to other sub-channels. The proposed scheme reduces downlink cross-tier interference.

In [64], the authors consider the use of Fractional Frequency Reuse (FFR) to mitigate inter-femtocell interference in multi-femtocell environments. They consider the use of FFR that adjusts the Frequency Reuse Factor (FRF) according to the operating environment. The femto gateway analyzes the effect of mutual interference among femtocells by means of interference graph modelling with the aid of femtocell location information. Based on the mutual interference information, it classifies femtocells into a number of groups according to the amount of interference to others. Then it determines the minimum number of orthogonal subchannels for each group to provide target performance near the cell boundary. After the allocation of subchannels to femtocells in each group, the transmit power of each femtocell is adjusted in a distributed manner.

4.2.3.2 Power Control based Mechanisms (PCM)

One solution to avoid the interference neighbour problem is self-power control mechanisms, i.e., femtocell first measures the signal power of the nearest macro BS and adjusts its transmission power to a suitable level. PCM are used in co-tier and cross-tier interference mitigation levels that generally focus on reducing transmission power of HeNbs. PCM are advantageous in that the eNb and HeNbs can use the entire bandwidth with interference coordination. Dynamic or adjustable power setting, which is preferred over fixed HeNb/eNb power setting, can be performed either in proactive or in reactive manner. The main factor to attack in PCM is the method to use in order to set the transmit power level. High transmit power level may perform the desirable results in a scenario where no femto neighbours can cause interference which means a femtocell deployment area with low femtocell density. However, the transmit power of the femtocells can be adjusted to provide desirable SINR level with femto users near the indoor cell edge. The desired transmit power can be determined by measuring the interference between any other femto user and any femtocells. Power control methods for radio resource management are tools often used in cellular systems to mitigate interference [74] [64] [42] [11] [60] [61]. If they are not applied, the users who are located far from a base station will be jammed by users in much closer positions. For example, in closed access femtocells, the users who are located far from the HeNb and being asked to raise their power level, might produce high levels of interference to neighbouring femtocells or even to the macrocell users.

Since the decrease of transmit power causes a decrease of interference, it is considered as a potential solution for interference mitigation, however, there are some issues to be taken into account.

- The interference problem can be solved by adjusting the transmit power but the communication quality might be degraded due to the power reduction. This means, a low transmit power reduces the interference level, but the bitrate transmission is also reduced. The Modulation and Coding Scheme (MCS) and Transport Block Size (TBS) are computed based on the user's Signal-to-Interference-plus-Noise Ratio (SINR) level, therefore the problem focuses on how to manage the power transmission level setting in order to reduce the interference but maintaining an efficient bitrate.
- If a femto transmit power is set too low, the macrocell transmit power could pick up femto users and turn them into macro users, specially when power based handovers algorithms are used.

Most literature works base their power control mechanism choice on measuring SINR [74] [47]. Another tool for transmit power level controlling is game theory. A distributed power control mechanism by using non cooperative game approach in [37] where players are femtocells. In [37], a distributed power control allocation problem is formulated for downlink transmission of OFDMA-based. The problem is modelled as a non-cooperative game, where the throughput of each station in the network is maximized under power constraints. In this game, the macro users are referred as the leaders and the femto users are considered to be the followers.

The problem with these kind of schemes is the complexity and the signaling among femtocells.

At this point, we completely agree with the fact that transmit power control reduces interference. However, most of the current works focus on determining the dynamic range of the downlink transmission power of femtocells, rather than an analytical framework and detailed power control schemes. Several PCM are combined with other types of mechanisms described in this chapter, this kind of hybrid mechanism shows good results.

4.2.3.3 Transmit Beamforming Mechanisms (TBM)

Transmit beamforming mechanisms arise as an effective way to improve system performance when (low-rate) control signaling links can be established between UEs and femtocells. In TBM, an active UE first estimates the channel gains that it observes from each femtocell transmit antenna, and then forms a feedback message that is transported via the uplink control channel. Based on this feedback information, the femtocell decides on the beamforming weight that should be applied for transmission.

TBM mechanisms mostly focus on the downlink of a closed-access femtocell system, where each femtocell is equipped with 2 transmit antennas, and each femtocell UE can establish a signaling link to its serving and its (strongest interfering) neighbouring femtocell. Based on the reported information, femtocells apply different beamforming weights in order to improve the rate performance of that femtocell UE that is in the most disadvantageous situation. More details about this method can be found in [10].

Several schemes for interference mitigation by using TBM mechanism have been proposed. Hybrid schemes are also considered as effective, for instance in [47], authors consider the use of transmit power control and beamforming for femtocells with the use of imperfect Channel State Information (CSI) to provide the desired SINR to femto users near the femtocell edge while minimizing the interference among the serving femto users and adjacent macro users. A TBM mechanism with nulling is proposed in [93] to increase the SINR of cell-edge users. The scheduling decisions of interfering base stations are sent through a special uplink sounding mechanism. The beamforming weights (precoding matrix) are calculated to form nulls to the cell-edge users which belong other base stations during data transmission so that the interference is reduced. Authors in [23] adapt this mechanism to femtocell scenarios, in order to reduce the interference at the macro UE from the femtocells, the macro UE can be treated as a cell edge user. Hence, TBM with nulling can be applied at the femtocells in order to mitigate the interference at a macro UE. In [65], the authors considered coordinated user scheduling combined with transmit beamforming to mitigate the interference among adjacent femtocells. Exploiting the CSI of users in adjacent femtocells, the proposed scheduler schedules users in a coordinated manner with the use of transmit beamforming. In [52], the authors uses a TBM mechanism to mitigate cross-tier interference by using orthogonal random beamforming with a beam subset selection strategy at the macrocell as a way of maximizing the achievable throughput and improving both macrocell and femtocell user immunity to cross-tier interference.

4.2.3.4 Cognitive Mechanisms (CM)

Cognitive approaches adapted by radio resources work by monitoring the wireless environment and inform the resource allocation controller about local and temporal spectrum availability and quality. Thus, opportunistic access points can dynamically select available channels and adapt transmission parameters to avoid harmful interference between contending users. Cognitive mechanisms are mostly used for co-tier interference mitigation.

In [95], an efficient downlink co-tier interference management scheme for an OFDMA-based LTE system is proposed where the path-loss information is shared among HeNb neighbours. In addition, adjacent HeNbs share the information related to the usage of LTE Component Carriers (CC), achieved based on carrier aggregation technique leading to a sub-channel, in a distributed manner. The exchange of information between HeNbs may be done via femtocell gateway (HeNb GW) or over-the-air (OTA) method. The HeNb GW is considered to be an intermediate node between HeNbs and mobile core network that manages the inter-HeNb coordination messages via S1 connection. On the other hand, the OTA method includes a direct link between HeNb and eNb.

In the proposed scheme, when a HeNb is turned on, it identifies the adjacent neighbours and obtains the knowledge of the CCs used by the neighbours. The main idea of the scheme is that, each HeNb estimates the co-tier interference based on the path-loss information, capitalizes the knowledge of the usage of CCs by the neighbours, and accesses the spectrum intelligently to minimize interference. The selection of CC is done in such a way that, each HeNb selects the CC which is not used by the neighbour or the CC that is occupied by the furthest neighbour or the CC that is occupied by the least number of neighbours (in a chronological order as mentioned).

In [19], the authors propose a cognitive based method called CRRM to mitigate interference. The proposed CRRM for the femto-network enables the autonomous interference mitigation, which provides the scalability for a dense network deployment without any impacts on the legacy Macro-network operations. This method provides statistical delay guarantees, which enables a smooth transmission of the real-time voice traffic and achieves a fully radio resource utilization. As a result, the proposed CRRM can be smoothly applied to 3GPP LTE-A and WiMAX femto-networks to serve urgent multimedia needs.

In [55], the authors use a cognitive radio mechanism to mitigate cross-tier interference in downlink system. This hybrid scheme combines a power control, cognitive and game theory approaches to present a cognitive access control scheme of cognitive femtocells. This scheme also uses game theory to enhance system throughput which in turn enhances the QoS for macro and femto users and power control to partially mitigate interference. Results show an improvement of QoS level.

In [45], the authors introduce a hybrid mechanism which combines cognitive characteristics with game theory to mitigate interference in UMTS LTE technologies. The proposed scheme works in a distributed manner. This article first demonstrates the insufficiency of traditional coexistence solutions in the LTE context and then proposes co-tier and cross-tier interference solutions by using game theory mechanisms such us the Nash Bargaining Solution (NBS) and the Nash Equilibrium.

4.2.4 Optimization Mathematical Tools

In last subsection, we make a general description of several families of mechanisms used for interference mitigation in femtocell scenarios in co-tier and cross-tier level. However, those mechanisms require several approaches to improve them by combining them with some mathematical tools.

4.2.4.1 Reinforcement Learning (RL)

Reinforcement learning dates back to the early days of cybernetics and work in statistics, psychology, neuroscience, and computer science. Reinforcement learning is a mathematical tool for modelling interactions between agents, providing them with the capability of learning in order to enable them to act in an optimized manner. The basic idea behind reinforcement learning is quite simple: an agent learns by trials-and-errors. The agent learns that its actions and decisions have consequences upon the surrounding environment, consequences which need to be quantified such that appropriate conclusions can be drawn.

Applying reinforcement learning algorithms for femtocells has been studied in the literature. One of the main parameters of reinforcement learning is the state of the environment. In [28], the state is given by two indicators: the interference on the macro users and the power allocated by the femtocell in each resource, while in [14] the state is selected as being composed of three indicators: the interference on the macro users, the number of other femtocells that use the same resources and the number of macro users that are moving around to the femtocell.

In [73], a different approach has been proposed. It works by taking into account factors such as the QoS level achieved by the femtocell (indicating if the femtocell has reached the required QoS for the femto users it serves), and information concerning the QoS level of the macro users represented by the interference created by the femtocell on them. The algorithm described in [73] can be applied for femtocells when deciding which portion of the spectrum resources to use such that a low impact on the macro layer is experienced. Thus, the femtocells play the role of the agents described in the reinforcement learning algorithm. This scheme deals with femto-macro interference management for systems based on OFDMA, such as LTE.

In [56], the authors introduce two distributed mechanisms for interference mitigation, inspired by evolutionary game theory and machine learning to support the coexistence of a macrocell network underlaid with self-organized femtocell networks. In the first approach, stand-alone femtocells choose their strategies, observe the behavior of other players, and make the best decision based on their instantaneous payoff, as well as the average payoff of all other femtocells. The interactions are formulated among selfish femtocells using evolutionary games in order to make the system to converge to an equilibrium. In contrast, in the RL, information exchange among femtocells is no longer possible and hence each femtocell adapts its strategy and gradually learns by interacting with its environment (i.e., neighbouring interferers) through trials-and-errors.

In [33] another interesting hybrid algorithm is proposed. This algorithm combines game theory and reinforcement learning to reach an optimal co-existence between macrocell and femtocell. Femtocells exchange information through a central controller, adapt their strategies based on their instantaneous payoffs and average payoffs of the femtocell population. When information exchange among femtocells is no longer possible, each femtocell gradually learns by interacting with its local environment through trials-and-errors, and adapt its strategies based on its learning approach.

4.2.4.2 Game Theory (GT)

Game theory is a mathematical tool used in fields such as economy, telecommunications, biology, etc to perform efficient decisions based on fairness. This kind of approaches is reached by bargaining or cooperative process or selfish decisions. The most important entities in game theory are called "players". Leading to the so called cooperative games, players can interact between them in cooperative manners (for instance the Shapley value) [80], non cooperative manners called non cooperative games such as NBS [63].

This technique has been utilized in several interference mitigation schemes in order enhance the mitigation process [45] [33] [56] [55]. Game theory is an extensive field which possesses a diversity of schemes to be adapted to several types of scenarios.

4.2.4.3 Genetic Algorithms (GA)

GA is a method that uses genetics as its archetype for problem solving. GA is based on the survival of the best individual in a population. Genetic algorithms belong to the larger class of evolutionary algorithms, which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover. [82].

Several authors have proposed mechanisms for interference mitigation in macrocell scenarios by using optimization techniques like genetic algorithms [30] [70].

In [72] the authors propose a multi-objective heuristic based on a genetic algorithm for a centralized self-optimizing network containing a group of UMTS femtocells. In order to optimize the network coverage in terms of handled load, coverage gaps, and overlaps, the algorithm provides a dynamic update of the downlink pilot powers of the deployed femtocells. The results demonstrate that the algorithm can efficiently optimize the coverage based on the current statistics of the global traffic distribution and the levels of interference between neighbouring femtocells.

4.3 Summary

In this chapter we presented a state of the art of interference mitigation in femtocell scenarios. Several approaches have been studied. Each approach presents several algorithms that share common characteristics, however not all algorithms are expected to totally mitigate the interference problem. Several algorithms only focus on co-tier interference, others on cross-tier. The main problem to bear in mind when building an interference mitigation scheme is the femtocell density deployment. Several algorithms can effectively mitigate interference in a low density but they do not take into account that femtocells density increases constantly which causes an increase of complexity. In Table 4.1, we present a summary of the main characteristics of each proposed interference coordination scheme.

Among all mechanisms reviewed in this chapter, the main characteristics of each algorithm are highlighted. Few schemes work under a centralized entity, specially for managing cross-tier interference. The main issues to deal with in a centralized mechanism is the complexity (caused by the increase of femtocell density) and signaling. Distributed schemes allow each femtocell to perform the decision making, based on information obtained from femto neighbours. The problem with this schemes is that femtocell depends on the type of information sent by femto neighbours. To achieve a good communication between HeNbs, signaling protocols must be well specified. Communication between the macrocell and femtocell could suffer high complexity issues when there exist a high femtocell density. However, most of proposed schemes use distributed mechanism.

An optimal scheme to mitigate interference must maintain the QoS guarantees offered by LTE. The target is to reduce the packet losses. Graph based mechanisms divide the total bandwidth among femtocells in order to force femtocells to use the different subchannels in order to avoid interference. This could be considered as a smart solution, however the performance of real-time services must be studied. Delay sensitive services such as video and VoIP need a high bitrate, so the fact that those services will use only a chunk of the total bandwidth must be analyzed. On the other hand, in femtocell scenarios the pathloss is lower than macrocell scenarios, so we can assume that losses caused by penetration walls will not happen.

Power control mechanisms work by setting their transmit power is an effective technique that could be adapted to small surfaces scenarios such as femtocell scenarios. This technique can be used in a distributed manner or even in a self configuring mechanism. By reducing the unnecessary transmit power of HeNbs interference is also reduced.

The key of this method is about the mechanism to use to control the transmit power level in order to fix it optimally. A factor to be taken into account is the eNb transmit power level (which is set as fixed) that could dull this mechanism applied in HeNbs. Power control based mechanism can be combined to other mechanisms for controlling the power level setting and the eNb transmit power issue.

Reinforcement learning mechanisms for interference mitigation is a method that aims to constantly improve the network performance by learning from trials-and-errors. The problem with this kind of methods is the time and computational complexity. The time decision interval must be set based on the computing time that this kind of methods requires. Also it is important to remark that it is not optimal to perform RT services in the trial-time, because if the trial becomes an error the RT service performance will suffer a QoS degradation.

Table 4.1: Comparison of different Interference schemes

Algorithm	*Reference*	*Centralized*	*Distributed*	*Co-tier*	*Cross-tier*	*Low Complex.*	*QoS guarant.*
Li's Alg.	[41]	✓		✓	✓		✓
Uygungelen's Alg.	[12]	✓		✓		✓	
Kim's alg	[50]		✓	✓		✓	✓
Xiangfang's Alg.	[74]	✓	✓	✓	✓		✓
Lee's Alg.	[64]		✓	✓	✓	✓	
Arulselvan's Alg.	[42]		✓	✓	✓	✓	✓
Jo-1's Alg.	[60]		✓		✓	✓	
Jo-2's Alg.	[61]		✓		✓	✓	
Chandrasekhar's Alg.	[18]		✓	✓	✓	✓	✓
Zhioua's Alg.	[36]		✓	✓	✓	✓	
Stefan's Alg.	[73]		✓		✓		✓
Taeyoung's Alg.	[48]	✓		✓	✓		
Oh's Alg.	[47]		✓	✓	✓		
Guruacharya's Alg.	[37]		✓	✓	✓		
Zhang's Alg.	[95]		✓	✓		✓	✓
Tae-Hwan's Alg.	[44]		✓	✓		✓	
Poongup's Alg.	[39]		✓	✓		✓	
Juang's Alg.	[53]		✓	✓		✓	
Yun's Alg.	[97]		✓	✓	✓		
Dowhuszko's Alg.	[10]		✓	✓		✓	
Jiang's Alg.	[23]	✓			✓		
Heui-Chang's Alg.	[65]		✓	✓		✓	
Park's Alg.	[52]	✓	✓	✓	✓	✓	
Shao-Yu's Alg.	[19]		✓	✓	✓		✓
Qian's Alg.	[55]		✓	✓	✓		✓
Attar's Alg.	[45]		✓		✓		✓
Nazir's Alg.	[56]		✓		✓	✓	✓
Bharucha's Alg.	[11]	✓			✓	✓	
Bennis-2's Alg.	[33]	✓	✓	✓	✓		✓
Galindo's Alg.	[28]		✓		✓		✓
Bennis-2's Alg.	[14]		✓	✓	✓		✓

Frequency reuse mechanisms divide the total bandwidth into sub-bands to consequently assign a part of bandwidth to eNb and the rest of sub-bands to HeNb. This method avoids cross-tier interference, but does not guarantee a complete co-tier interference mitigation. Another factor to take into account is “How to optimally assign the bandwidth to eNb and HeNbs”? To make this decision efficiently it is necessary to use stochastic methods i.e. game theory, but it would lead to the complexity problem again.

Cognitive radio based mechanisms are an interesting solution which works by sharing channel state information among femtocells. This kind of schemes works in a distributed manner and needs an efficient signaling protocol via gateways or wireless, whose problem still is related to complexity caused by femtocell density deployment. Most works propose this scheme to mitigate co-tier interference, however some hybrids which combine this technique with transmit power control and/or game theory are proposed.

Beamforming mechanisms seem to be an effective choice to mitigate interference in a co-tier level. To take into account the eNb in the interference scheme, beamforming methods must be combined to others.

It is important to remark that the techniques presented above may be ineffective in practice. As mentioned earlier, this is due to dense femtocells deployment with consequent large population of interferers expected by operators. However, the femtocell deployment requires a new paradigm because of two main reasons. First, femtocell users can benefit from a high quality downlink signal enabled by short range communications characterizing femtocell deployments. Second, only few users locally compete for a large amount of frequency resource in a femtocell. Therefore, a femtocell benefits from a huge amount of spectral/power resource. In our vision, there is a need for designing a novel approach to reduce interference, improve the spectrum usage and communication robustness in face of undesired interference, and to limit power consumption.

In the next chapter we propose two schemes to improve the QoS in femtocell scenarios by mitigating femtocell interference.

Chapter 5

Interference Mitigation in Femtocell Scenarios

In the precedent chapter, an overview of femtocell architecture and interference mitigation for femtocell scenarios was presented. We analyzed several proposed methods and their characteristics to mitigate interference issues. In this thesis we focus our attention on QoS improvement. Aware that most of works proposed in chapter 4 aim to reduce interference, however, it is important to bear in mind that none of those propositions use QoS constraints such as PLR, throughput gain, delay, etc to analyze the QoS level.

In this chapter we propose two methods to mitigate interfere in femtocell scenarios.

A limitation when mitigating interference in femtocell scenarios is the signaling topology (as see in Figure 4.1). In order to avoid the signaling complexity which is found in centralized and distributed schemes, we proposed the first algorithm which belongs to the power control family. This scheme proposes a self-configured algorithm that performs a game theory bargain based on interference channel levels to reach an optimal transmit power setting. This mechanism is performed at the PHY layer.

In section 4.2.3.1, we observed the graph based mechanisms for interference mitigation as an interesting solution. However, we consider that this kind of mechanisms can be improved by using optimization technique such as game theory. In order to bear in mind the class of service performed by each HeNb, we propose a second scheme which is centralized. This mechanism can be considered as an improved based graph mechanism. This method is hybrid and uses the Shapley value to improve the well known four colouring method by performing the bandwidth distribution among femtocells based on the type of services that it serves.

Our first scheme can mainly be used to mitigate interference when the femtocells density is high, on the other hand our second scheme can be used when the femtocells density is relatively low.

To measure the performance of our both proposed schemes, we use constraints such as PLR, throughput, delay and SINR.

5.1 Proposed Interference Mitigation Strategies

5.1.1 Interference Mitigation by Dynamic Self-Power Control in Femtocell Scenarios

5.1.1.1 Problem Formulation and Justification

Interference mitigation by transmit power control methods has several advantages to highlight making this technique a smart choice. Dynamic power control approaches achieve high bitrate levels in a low density femtocell scenario. On the other hand when the femtocell density deployment becomes high, the PCM can reduce losses caused by interference. The issue to tackle in this transmit power control concerns how to set the transmit power level optimally and efficiently. If the transmit power is set too high it will cause interference among femtocell neighbours, on the other hand if the transmit power level is set too low, the bitrate decreases. Therefore an efficient trade-off between interference and bitrate must be reached in order to choose the optimal transmit power level. We propose to use a game theory approach based on a constant bargaining to perform this task.

5.1.1.2 Network definition and Interference Computing

When a user asks for resources in a femtocell scenario, it is important to consider several important points.

The well known proposed solutions for interference mitigation in a macrocell scenario might not be useful in a femtocell scenario due to an important parameter that is the distance between the user and the base station (macro or femto). In a macro cell scenario users are often distributed in large surfaces such as 1000,2000, or 3000 m^2 but in a femtocell scenario the users are distributed in very small surfaces from 25 to 30 m^2. Note that in a macrocell scenario the interference problem affects the cell-edge users, but in a femtocell scenario due to its small surface there are no cell-edge users, therefore interference affects all users.

A well known method to mitigate interference is by reducing transmission power but it must be taken into account that the transmission power reduction also produces throughput decrease.

Let us explain this point as follows. Let us define a LTE femtocell network as a set of:

femtocells $F = \{f_1, f_2, ..., f_n\}$

femtocell users $U = \{u_1, u_2, ..., u_m\}$

Sub-bands $S = \{s_1, s_2, ..., s_l\}$

Consider the 3GPP pathloss model pl between a user u and a femtocell f represented with this formula [76].

$$pl_{u,f} = 127 + (30 * \log(d)) \tag{5.1}$$

Where d is the distance between the user and the base station.

To perform a total bandwidth distribution among all users, it is necessary to divide the total bandwidth into sub-bands. Also the total transmission power TxP must be divided by the number of sub-bands in order to get the sub-band transmission power $\delta_{u,f}$

$$\delta_{u,f} = 10 \log_{10} \left(\frac{10^{\frac{TxP-30}{10}}}{nsb} \right) \tag{5.2}$$

Where $nsb = |S|$ represents the number of sub-bands.

Using (Equation 5.1) and (Equation 5.2) the interference γ_u for user u is computed as follows:

$$\gamma_u = \sum_{f_1}^{f_n} (\delta_{u,f} - pl_{u,f}) \tag{5.3}$$

In order to obtain the noise-plus-interference we first compute the noise in db as follows:

$$noise_{db} = nf + np + 10 \log_{10}(schb) - 30 = -148.95 \tag{5.4}$$

Where $nf = 2.5dbm$ is the noise figure, $np = -174dbm$ is the noise power, and $schb = 180kHz$ is the subchannel bandwidth.

In order to compute the measured $SINR$ value $mSinr$.

$$mSinr = \delta - 10 \log_{10}(10^{\lambda} + \gamma) \tag{5.5}$$

Table 5.1: LTE MCS (Modulation and Coding Schemes)

MCS	Modulation	Code Rate	SINR [db]
MCS1	QPSK	1/12	-4.63
MCS2	QPSK	1/9	-2.6
MCS3	QPSK	1/6	-0.12
MCS4	QPSK	1/3	2.26
MCS5	QPSK	1/2	4.73
MCS6	QPSK	3/5	7.53
MCS7	16QAM	1/3	8.67
MCS8	16QAM	1/2	11.32
MCS9	16QAM	3/5	14.24
MCS10	64QAM	1/2	15.21
MCS11	64QAM	1/2	18.63
MCS12	64QAM	3/5	21.32
MCS13	64QAM	3/4	23.47
MCS14	64QAM	5/6	28.49
MCS15	64QAM	11/12	34.6

Where $\lambda = \frac{noise_{db}}{10}$

$$SINR = \frac{\sum_{s_1}^{s_l} mSinr}{nsb} \tag{5.6}$$

Now having the $SINR$ value, it is possible to compute the MCS value as shown in Table 5.1 and consequently computing the Transport Block Size (TBS) following the 3GPP specification TS 36.213 - Table 7.1.7.2.1-1. Those MCS values are constantly reported to the base station(eNb or HeNb).

5.1.1.3 Analysis

In this work, we focus our attention on transmission power control due to its importance on SINR values computed as shown in last section. Due to the coverage surface that femtocells serve (3GPP 5X5 m), the interference level depends closely on the transmission power level. In a case where a femtocell has no femto neighbours a fix transmission power set on the highest level becomes a privilege for the owner because the quality of signal will be good in a large coverage area.

Now let us explain the scenario where there exist close femto neighbours asking for resources at the same time as it can happen in a metropolis building. If two or more femtocells set their transmission power values to the highest level in a specific case where user (belonging to different femtocells) ask for resources, each femtocell will assign all their sub-bands to its users. This will cause interference and this interference will prevent an optimal packet transmission performance.

Considering that if femto owners decide to set the transmission power level to the lowest threshold value, the interference level will decrease, but coverage signal quality and MSC values will decrease as well. If MSC values are small TBS values will be small too, therefore throughput gain will not get a high level which is not an optimal solution when transmission packets belong to real-time flows.

Now the key idea of this study is focused on setting the transmission power value as a dynamic variable which changes depending on the scenario changes. As mentioned earlier, each user computes its SINR estimation and reports its MSC values to the HeNb. Each HeNb will decide the value of transmission power depending on the users position, in order to maintain the power value as low as possible but without affecting the throughput gain. At this level our algorithm proposes a game theory bargain between *SINR* and *throughput* gain as players.

5.1.1.4 2-person bargaining game

Non-cooperative games are part of game theory. Non-cooperative games are based on the absence of coalitions where it is assumed that each participant acts independently without communication or collaboration with any others. In [63] J. Nash presented a two-person zero-sum game concept which aims to find an equilibrium point.

The most important factor of our proposed algorithm is the 2-person game bargaining where players are *Throughput* and *SINR* as early mentioned. Players compete for transmission power value as seen in Figure 5.1. In order to increase its level, *SINR* will propose to set the power as low as possible and on the other hand *Throughput* will propose to set the transmission power value as high as possible to increase its level as we can see on the 1st move - Figure 5.1. Our algorithm performs a bargaining between those two players at the HeNb in order to find an optimum trade-off between them. The target of this method is focused on avoiding femtocells to transmit with too much power than users require. To better explain this point let us assume a scenario where femtocells transmit with a high power level. There is a user located quite close to the HeNb, therefore it will perform a good QoS level due to the high femto transmit power. It must be taken into account that this user could get the same good QoS level by setting the femtocell transmit power level a little lower. If the femtocell transmit power level is lower, it will cause low interference to the neighbours.

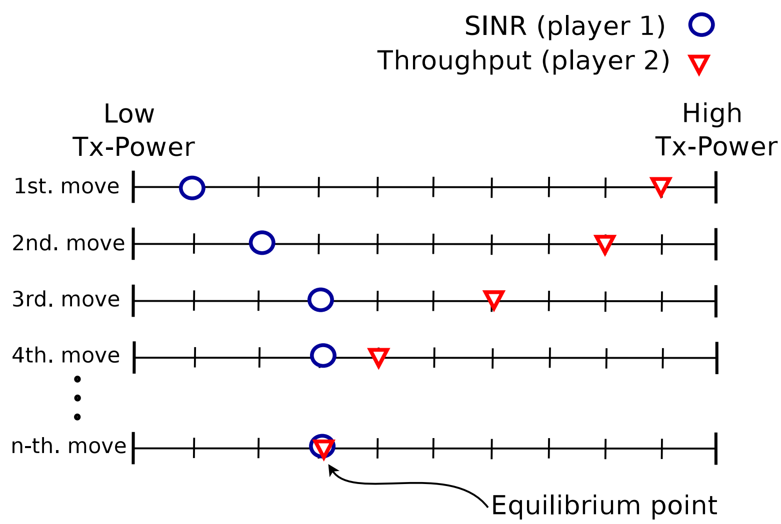

Figure 5.1: 2-person game for power level control

5.1.1.5 Proposed Algorithm

In order to build an algorithm for the interference mitigation, we take into account all formulas described earlier in subsubsection 5.1.1.2 and the 2 person bargaining game described in subsubsection 5.1.1.4. All this process is carried out by performing the steps described in Algorithm 1.

5.1.1.6 Simulation Scenario

The tool used for this task is LTE-Sim, previously described in subsubsection 3.1.1.3. Also in this scenario the same simulation traffic model is used for video flows and VoIP flows but the only difference is the video bitrate. The simulation metrics are also the same as previously shown, with the difference that in this chapter we also take into account the SINR level.

Femtocell Scenario To perform our resource allocation model, our femtocell scenario is set as follows. We use a single cell with several femtocells distributed in a building. The number of femtocells which are neighbours relatively close start from 1 until 10, increasing in one unit in order to increase the interference level. For the first proposed scheme, there is only one user at each femtocell which utilizes all the femtocell resource blocks. We have tested one scenario where all femtocells serve video flows, and another one using VoIP flows. The 3GPP 5x5 standard for femtocell is used to model the indoor scenario [8]. This work is focused only on femto-femto interference

Algorithm 1 Proposed Algorithm

$tx\_pow_{min} \leftarrow pow_{min}$ {set the HeNb min trans power}
$tx\_pow_{max} \leftarrow pow_{max}$ {set the HeNb max trans power}
$tx\_power \leftarrow tx\_pow_{max}$ {This process will be repeated in a period of 10 TTIs }
$Compute\_Pathloss()$; {According Eq. (5.1)}
$Compute\_SINR()$; {According Eq. (5.6)}
$Compute\_MSC()$;
$Compute\_TBS()$;
{Starting bargaining }
$player\_1 \leftarrow SINR$
$player\_2 \leftarrow Throughput$ {Computed at the HeNb using the received TBS in the last period }
$tx\_pow_{com} \leftarrow perform\_Game(player1, player2)$;
if $tx\_pow_{com} < tx\_power$ **then**
  $tx\_power \leftarrow tx\_power - 1$
else
  $tx\_power \leftarrow tx\_power + 1$
end if

mitigation therefore macrocell interference is not taken into account in both scenarios. Users are constantly moving at speed of 1 *kmph* in random walking mobility model. The LTE propagation loss model for femtocell is specified in [8] [7].

Simulation Parameters All simulations in this chapter share the same scenario, with small exceptions. In each scenario a macro cell is set. Simulation parameters are shown in Table 5.2.

5.1.1.7 Numerical Results

We prove the efficiency of our algorithm by presenting the simulation results. All figures present two curves, the red curve represents the scenario where the transmission power value is fixed to 23 *dbm* (It is important to remark that in [99] authors suggest to set the transmit power between 10 to 20 *dbm*, however the great majority of publications set the transmit power to 23 *dbm*). The blue curve represents our proposed method which we call Dynamic Self-Power Control (DS-PC) where power is dynamically changing depending on our algorithm results.

Throughput. Figure 5.2 and Figure 5.4 show the average throughput per video and VoIP flows respectively. There is not a significant decrease of throughput when using

Table 5.2: LTE downlink simulation parameters

Parameters	Values
Simulation duration	60 s
Frame structure	FDD
Apartement size	100 m^2
Bandwidth (1st Approach)	10 MHz
Bandwidth (2nd Approach)	15 MHz
Slot duration	0.5 ms
Scheduling time (TTI)	1 ms
Scheduler	EXP-RULE
Number of RBs(1st Approach)	50
Number of RBs(2nd Approach)	75
Max delay	0.1 s
video bit-rate	128 $kbps$
VoIP bit-rate	8.4 $kbps$
Number of femtocells	$1, 2, 3, ..., 8 or 10$
Users per femtocell (2nd. Approach)	2
Users per femtocell (1st. Approach)	1
Pathloss	$PL = 127 + 30\log(d)$
Multipath	Ped-A
PenetrationLoss	0 dB
Shadowing	log-normal distribution (mean = 0dB, standard deviation = 8dB)

DS-PC method compared to the fixed power (23 dbm). As we can see, 23 dbm causes a high interference degrading the throughput, consequently avoiding a good QoS level even when 2 femtocells transmit at the same time. On the other hand when using DS-PC method we keep maintaining the throughput up to 2 femtocells assigning resources for video flows at the same time. For VoIP flows DS-PC method maintains the desirable throughput up to four femtocells transmitting at the same time.

Packet Loss Ratio. Figure 5.3 and Figure 5.5 show the PLR of video and VoIP flows respectively. Both figures show a decrease of PLR. Although the PLR decreases considerably in both cases it is important to highlight that the PLR value is greater than 3% (which is the supported percentage for VoIP flows), and 1% (which is the supported percentage for Video flows).

SINR. Figure 5.6 represents the interference level (SINR values) against throughput gain for video flows. As we can see the interference decreases when using our method

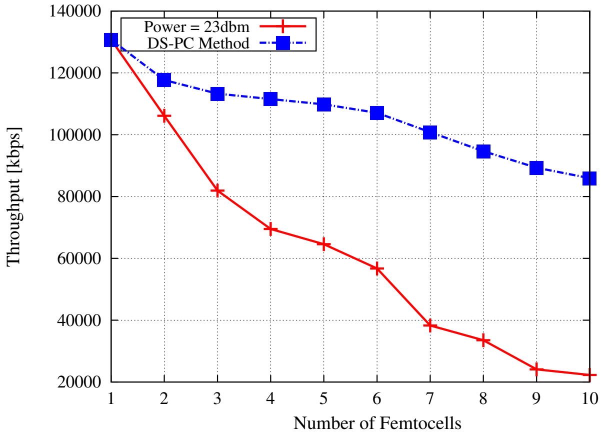

Figure 5.2: Throughput average per video flow - transmit power method

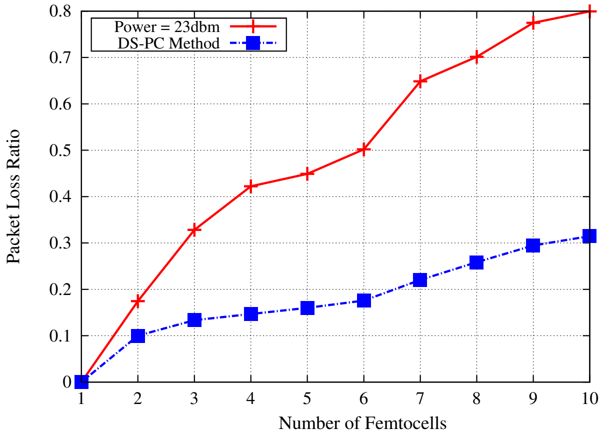

Figure 5.3: packet Loss ratio for video flows - transmit power method

compared to the static power.

This proposed method has focused attention on interference mitigation by controlling the transmit power in femtocell scenario in LTE downlink system. We defined three performance metrics namely, throughput, PLR, and SINR.

Although femtocell architecture proposes an interesting alternative to improve the QoS, it could be degraded by interferences. By simulations we have shown the impact negatively caused by interferences. We draw attention to the fact that, the QoS suffers a degradation of capacity when the transmit power is not set to an optimum level specially in femtocell scenarios where signal coverage surfaces are small. Our proposed method based on transmit power control seems to be a smart alternative which aims to

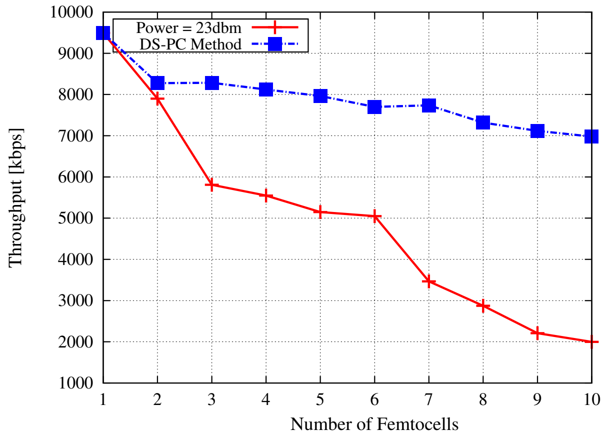

Figure 5.4: Throughput average per VoIP flow - transmit power method

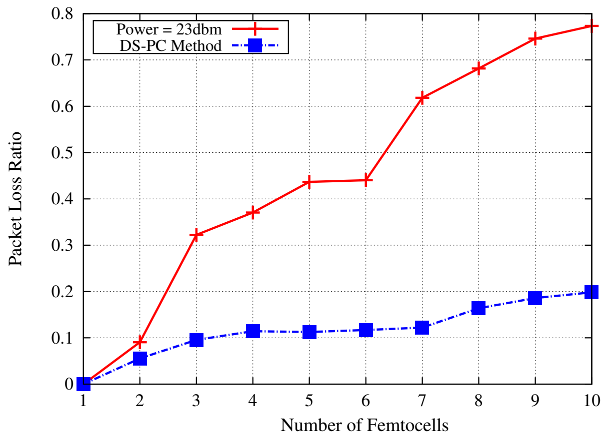

Figure 5.5: packet loss ratio for VoIP flows - transmit power method

find an optimal trade-off between throughput and interference to mitigate interference. This scheme is self-controlled which means that it does not need any signaling implementation. Numerical results show an important improvement of QoS levels when using our method. We can conclude that the transmit power level value plays an important role for performing efficient QoS levels. The proposed scheme allows a low complexity implementation, which is suitable for practical wireless systems.

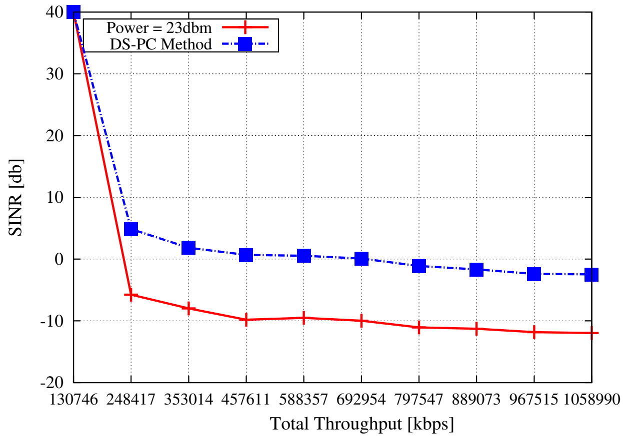

Figure 5.6: Interference in video flows scenario - transmit power method

5.1.2 A Hybrid Mechanism Graph and Game theory based for interference mitigation

5.1.2.1 Problem Formulation and Justification

Graph based mechanisms are considered as efficient choice for interference mitigation. In section 4.2.3.1 we presented the graph based approach. In this context, we highlighted the basic problem when using this scheme which is the reduction of spectral efficiency. On the other hand, the interference is almost totally cancelled which assure a high decrease of packet losses, consequently the QoS level might be improved. The well known four colouring method is part of graph based schemes. This method divides the entire bandwidth in sub-bands assigning one colour to each sub-band in order to force adjacent femtocells to use different colors. This process also forces each femtocell to only use one fourth of the total capacity, no matter the type of services that each femtocell is delivering to femto users. We do not agree with the fact of dividing total bandwith in equal parts is optimal in LTE scenarios because the performed services are heterogeneous. In LTE scenarios several type of services are performed, such as video which bitrate is about (128, 224, 448)$kbps$, VoIP (8.4, 12)$kbps$ or any NRT application. To better explain this point, let us consider the case of two femtocells neighbours (A and B). Femtocell A serves video service of 448 $kbps$ and femtocell B only serves a 8.4 $kbps$ VoIP service. It is not optimal to grant the same portion of bandwidth to femtocell A and B since they have different bitrate needs.

In this context, we focus our research in the optimization of bandwidth division among femtocells taking into account the type of services in a graph based approach.

The problem can be formulated as "How to optimize the bandwidth distribution among femtocells taking into account the service classes and QoS"?

Unlike other technologies such as UMTS, LTE aims to provide support to RT services. NRT services can be exposed to delays and retransmissions without having high impact on the QoS level. Therefore, in our approach at this part of the thesis we principally aim to test the impact of femtocell interferences in RT services in LTE.

5.1.2.2 Analysis

It is clear that in a graph colour based mechanism for interference mitigation an equal bandwidth division for each colour is not an optimal choice. An equal bandwidth division could cause a waste of resources at nodes that perform low bitrate services and a lack of resources at nodes that perform high bitrate services. At this point we can argue that this division is totally unfair. In order to decide how many sub-bands each femtocell deserves depending on the services it grants to UEs, we consider that it is necessary to use any method which performs this task fairly. Let us take again the example of two femtocells neighbours (A and B) where femtocell A serves video service of 448 *kbps* and femtocell B only serves a 8.4 *kbps* VoIP service. Obviously femtocell A requires more bandwidth than femtocell B. In this context femtocell A needs to argue about its requirement with femtocell B. Femtocell B will send its bitrate requirements to femtocell A, so it becomes a bargaining which target is to find the optimal percentage of division. This brings out again the need of an efficient method to perform this task which induce us to the use of game theory approaches.

5.1.2.3 Interference Mitigation Approach

Our approach aims to improve the fourth colouring graph method for interference mitigation to be applied in femtocell scenarios. We justify the choice of this method by the following facts:

(1) By dividing the whole bandwidth and assigning one part of this division to each colour, femtocells will not experiment interference while femtocell neighbours do not use the same colour. (2) The femto user will always experience very high quality of signal because it will always be very close to the HeNb, therefore pathloss, multipath and shadowing should not be taking into account. (3) Based on (1) 'femto users will not experience interferences', and based on (2) 'In a femtocell scenario they might not have losses caused by pathloss, penetration losses and shadowing' we can assume that in a scenario with no packet losses, a high QoS level might be guaranteed, even when

using only a quarter of total bandwidth.

In order to make the four colouring method more efficient, we propose to combine it with game theory. We consider that the decision about the quantity of bandwidth to assign must take into account the types of services, and the fairness factor. Based on the good results given in subsubsection 3.1.2.2, we once again propose the use of the Shapley value [80].

Our approach is performed in two steps. On the first step a fair resource distribution among classes using Shapley value method is performed. HeNb-GW receives information about the number of flows to serve (and the bit-rate that each flow requires) from each HeNb over the S1 interface. On the second step, having the proportion of resource destined to each class (video, VoIP, radio streaming, etc) a sub-band distribution is performed by the HeNb-Gateway among femtocell neighbours following the four-colouring method.

For instance, as it is illustrated by Figure 5.7 the HeNb-GW receives information from HeNB-1, HeNB-2 and HeNB-3 their flow bitrates 128 $Kbps$, 8.4 $kbps$ and 242 $Kbps$ respectively and the number of flows that each HeNB possesses. With this information a femto-bargain is performed at the HeNB-GW using the Shapley value having as result the number of sub-bands or resource blocks that each femtocell is allowed to assign to users.

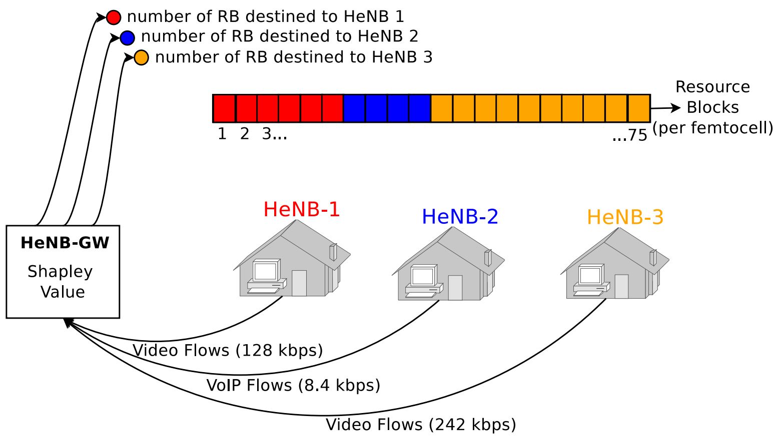

Figure 5.7: Four-colouring method for interference mitigation

Step One: Fair resource distribution among flow classes by using Shapley value. At this level a TU game is carried out, taking into account the parameters shown in Table 5.3.

Table 5.3: Notation and description of variables for bankruptcy game and its adaptation to LTE scenario

Variable	Bankruptcy Game	Bandwidth Allocation
n	total number of players (HeNbs)	total number of flow classes
C	total benefit	total bandwidth capacity
g_i	player's benefit claim	flow class bandwidth claim

Our game model is the same than early described in subsubsection 3.1.2.2.

Step two: Sub-band assignment according to four-colouring method. Mitigating interference by using graph colouring algorithms is a well known method used in wireless networks. This method works by colouring the nodes of a graph with minimum number of colors, such that no two connected nodes (neighbours nodes) have the same colour. By assuming each colour as a different sub-band, this method facilitates the sub-band assignment where neighbor base stations must not use the same sub-band. As we can see, Figure 5.8 represents the worst neighboring scenario where every femtocell has active users asking for resources at the same time. Each colour represents a set of sub-bands assigned to femtocells. Neighbours must not use the same set of sub-bands. This means that according to the classical algorithm, each femtocell is assigned only 1/4 of the total bandwidth accordingly regardless of the number of neighbours.

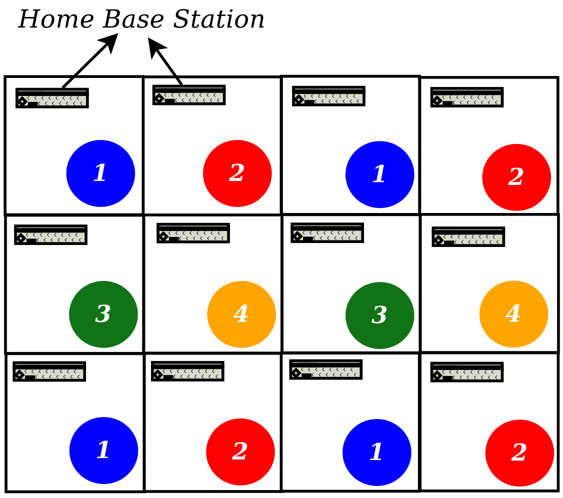

Figure 5.8: Four-colouring method for interference mitigation

In order to improve resource assignment, flexibility in the number of assigned sub-bands per femtocell is therefore desired. Now assuming that it is possible to have the desired flexibility related to the number of sub-bands to be assigned, it is important to find the answer to the following questions, "Who takes this decision"? and "What is the base of this decision ?"In our proposed solution it is the HeNb-gateway which decides the amount of bandwidth to be assigned to each femtocell based on the Shapley value. The number of sub-bands destined to be allocated are chosen considering the type of services that femto users need.

5.1.2.4 Numerical Results

It is helpful here to better appreciate the behaviour of our proposed solution, to compare it to other scenarios. Therefore we defined our curves as:

- *Femto*: This curve represents the femtocell simulation scenario where interference problem is not mitigated.
- *Femto-4Color*: This curve represents the performance of the classical four-colouring algorithm in order to mitigate interference.
- *Femto-SH*: This curve represents our proposed method using Shapley Value to improve the four-colouring method.

The simulation tools, models and scenarios are already defined in subsubsection 5.1.1.6. This scenario presents the following differences: (1) Femtocells increase from 1 up to 8, (2) There are two users per femtocell.

Throughput Figure 5.9 represents the average throughput per video flow. In this figure, we can realize that *Femto-4Color* curve experiments a decrease compared to the *Femto* curve. This can only be adequately explained by the fact that the four-colouring algorithm assigns only one quarter of bandwidth to each femtocell, but the throughput is not reduced to one quarter since the four-colouring method is not affected by interferences. On the other hand our proposed method, the *Femto-SH* curve shows a sharp rise compared to the four-colouring curve, even its performance is close to the *Femto* level curve. By adopting the view that Shapley value assigns resources based on parameters such as number of flows and bitrate, we can explain this important improvement by the considerable difference of video flow bitrate comparing to VoIP. According to those results, only two users are able to use video services at the same time without experiencing losses due to interference.

Figure 5.12 depicts the throughput for VoIP flows. As we can see in *Femto* curve, the VoIP flows performance is reduced due to neighbor interference. It is important to underline the fact that VoIP bitrate is $8.4Kbps$. This is a contributory factor to support the high improve of VoIP performance when using both methods, *Femto-4Color* and *Femto-SH*. The high capacity of bandwidth that LTE technology grants is clearly enough to serve VoIP needs, even if the femtocell uses only a quarter of its capacity (in the worst case). This explains why the performance of those two curves is almost the same as that in a non-interference scenario. According to all PLR curves there is no issue related to throughput when using our proposed method or the four-colouring method when resources are shared among femtocell neighbours.

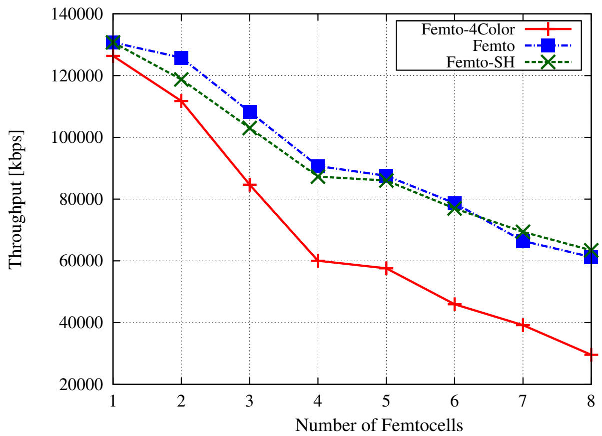

Figure 5.9: Average throughput per video flow

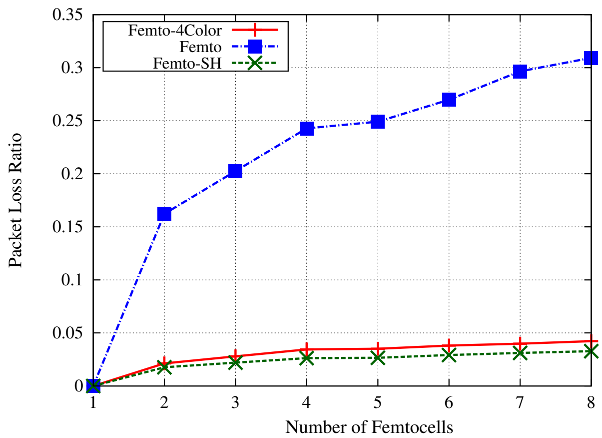

Figure 5.10: Packet loss ratio for video flows

Packet Loss Ratio PLR for video flows is illustrated in **Figure 5.10**. To complement the throughput performance shown and explained in the previous paragraph by the

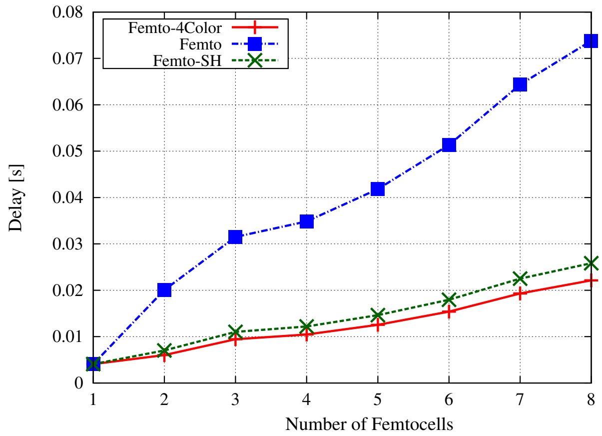

Figure 5.11: Delay for video flows

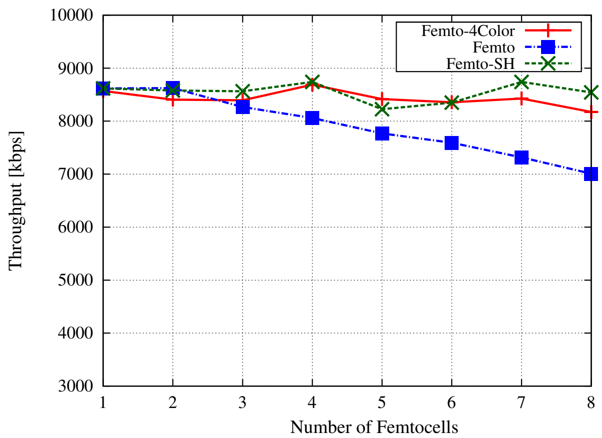

Figure 5.12: Average throughput per VoIP flow

Femto curve, the loss of packets plays an important role in the QoS. The accepted PLR for video flows is 1%, unfortunately the level of PLR shown by *Femto* curve presents a PLR higher than 15% when there are two neighbours transmitting at the same time. This high quantity of PLR is fed by interference losses and buffer losses. On the other hand, *Femto-SH* curve shows an important decrease of PLR. This decrease is explained by the fact that there is no neighboring femtocells asking for the same subchannels. According to this concept if there is no interference there should be no PLR which is not the case as we can see in our curves. To explain this, it is important to recall that there is a maximum delay for video and VoIP flows set in our scenario as we can see in Table 5.2. It means that if a packet exceeds this limit of time, it will be removed from the queue.

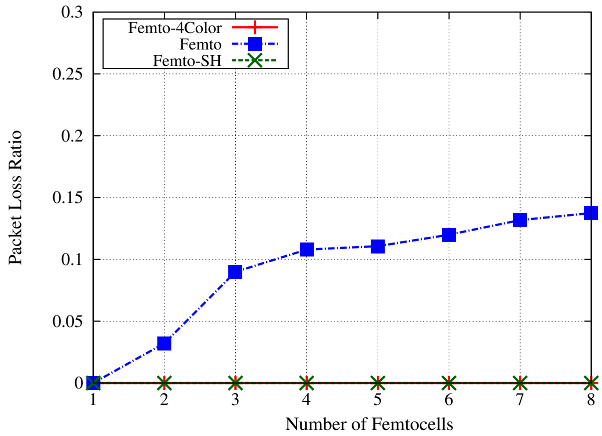

Figure 5.13: Packet loss ratio for VoIP flows

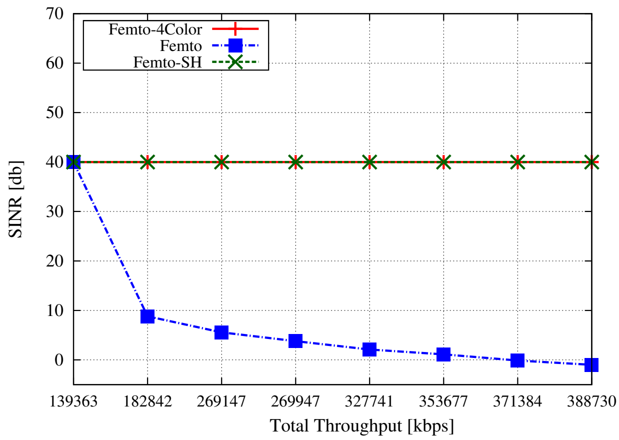

Figure 5.14: Average received SINR

Figure 5.13 illustrates the PLR of VoIP flows. Here we can appreciate how the *Femto* curve complements the throughput behaviour of VoIP flows (Figure 5.12). Due to the LTE-Sim VoIP model which works using *ON/OFF* periods we can justify the picks and falls that all the curves experience. *Femto-SH* and *Femto-4Color* perform a PLR almost null which is logically explained by the sub-band distribution among femto-neighbours. Unlike video flows suffer losses due to the video packets in the queue exceed the maximum delay as early mentioned, VoIP flows are not affected by this issue because of the number of VoIP packets in the queue is relatively small compared to video packets. When performing the resource block distribution among the different types of flows helped by the Shapley value method before performing the scheduling, our method assure resource assignment to all classes of flows, therefore VoIP packets have their own queue considerably shorter than the video packets queue. By those results we can assume that to improve the performance of QoS, this maximum delay parameter is an important factor to control the PLR in video flows which should be tested under different scenarios.

Delay Figure 5.11 represents the delay for video flows. Both curves *Femto-4Color* and *Femto-SH* show shorter delays than *Femto* curve. We can judge this behaviour as normal because of the fact that by avoiding interference we reduce losses therefore the retransmissions rate is reduced as well. Also with this curve we can complement and support our explanations previously presented about throughput increase in Figure 5.9 and why the reduction of PLR in video flows in Figure 5.10.

Interference Figure 5.14 represents the interference mitigation when using our method. As we can see, the value of SINR increases up to 40 which is the limit set in our scenario when using sub-band distribution. Here we can appreciate the important reduction of interference and this information complements the other metrics early analyzed and discussed.

This method focuses on interference mitigation in femtocell scenario in LTE downlink system. With this proposed scheme we aim to improve the QoS level for real time services by mitigating interference. Our scheme is based on a graph based method called 'four colouring', we combine this method with game theory to make it more efficient. We introduced an intelligent alternative to mitigate interference that reduces the PLR without decreasing the throughput which is extremely important in order to perform a desirable QoS when performing real-time services. Our proposed method is centralized and uses more and less one quarter of total capacity efficiently (depending on the type of services) taking into account the traffic types in femtocells, it also reduces 99% of packet losses. Numerical results show that by using one quarter of total capacity without having packet losses it is possible to perform a more efficient QoS level than using total bandwidth and having packet losses caused by interferences, specially for non-elastic services such as video and VoIP.

5.2 Summary

In this chapter, we proposed two mechanisms to improve the QoS level for real time services in femtocell scenarios in LTE networks. Both schemes are tested under QoS metrics such as throughput, PLR, delay and SINR to analyze their performance for real time services. This chapter has drawn attention on interference mitigation in femtocell scenarios. We analyzed the impact that interference can cause in QoS performances for non elastic services such as video and VoIP. Both algorithms are hybrid and game theory based.

Our first scheme belongs to the transmit power control family. Our algorithm called 'DS-PC method' provides a smart and efficient method to set the transmit power level based on game theory. This is the principal contribution presented by our hybrid proposed mechanism. This mechanism is self-configured and makes its decision only by measuring interference between neighbours. We tested in a realistic scenario real time services such as video and VoIP. Numerical results show an important improvement of QoS constraints such as throughput, PLR, SINR, etc. Therefore we can conclude that the use of game theory bargaining can help to reach an efficient decision making performance. The transmit power control in small surfaces as offices and apartments is essential to avoid the QoS degradation caused by interferences. A significant limitation is the macrocells power transmit which could steal femtocell users turning them to macro users due to its high power level. Although it has not been contemplated in this work, this proposed scheme could be combined with other cross-tier schemes in order to mitigate interference totally.

Our second scheme is graph based, it is an amelioration of the four colouring method. Due to the use of game theory (cooperative games), we build an efficient scheme which focus on real time services performances. It works by assigning to each HeNb only a chunk (computed taking into account type of services by using game theory) of total bandwidth to avoid neighboring interference. This scheme has reduced the packet losses caused by interferences. By analysing the obtained numerical results we can conclude that by using only a chunk of bandwidth without packet losses, it is possible to reach the same throughput gain as a system that uses total bandwidth and experiments packet losses. The throughput reaches the same level in both schemes but our proposed scheme does not perform packet losses which is extremely important in real time services. By minimizing the packet losses generated in PHY layer, the system will considerably reduce HARQ retransmissions, and by avoiding retransmission, the queues will be less busy, having light queues the packet delay will be shorter and the probability of experiencing buffer overflows is reduced. Therefore, based on this analysis we can conclude that our proposed scheme improves considerably the QoS level in femtocell scenarios. There are obvious limitations in our proposed scheme. One is about the femtocell density deployment. In a dense femtocell deployment such as residential buildings the complexity increases for the gateway because this scheme is centralized.

Both schemes allow a low complexity implementation, which is suitable for practical wireless systems. Our work is limited to perform indoor scenarios therefore future work could be focused on finding out a way to include the macrocell into this scenario.

Chapter 6

Conclusions

Long term Evolution technology is presently the most promising global telecommunication system. LTE provides QoS support for heterogeneous classes of traffic with different QoS requirements. In this thesis, we focus our attention on the quality of service in downlink system for macrocell and femtocell scenarios.

We started our work, by highlighting the limitations of existent solutions for packet scheduling techniques in downlink system in macrocell scenarios.

We thus proposed three resource allocation schemes specifically focusing on real time services such as video and VoIP for macrocell scenarios. We can argue this choice by the fact that there already exist efficient algorithms for non real time services such as PF and M-LWDF in 3G technologies. Our first scheme combines a virtual token mechanism to the EXP-RULE algorithm. This scheme improves the QoS for video flows and maintains a good QoS for VoIP flows, on the other hand NRT flows experiment really poor performances. The second algorithm is based on game theory to improve the fairness among classes of service when performing the resource allocation.

Numerical results seem to perform a high level of fairness, however, the performance of NRT flows are considerably poor. Finally, we combined the first two mechanisms to create a third one. This last scheme, improves the QoS performance for video flows and it maintains a good performance for VoIP flows.

To summarize, our three propositions enhance the QoS for RT flows. We consider this fact as an important advance for the QoS because nowadays the tendency of mobile applications is related to multimedia. Our work is mostly focused on RT services, therefore it does not show good results for NRT services. On the other hand, those flows belong to non GBR flows for which the operators mainly have to guarantee no loss.

However, as mentioned earlier there already exist efficient algorithms such as M-

LWDF and PF to satisfy this type of services. Another point to highlight in this research is that by using game theory the fairness index increases, and during this research we have not found any alternative method to reach such a high fairness level among flow classes.

The second part of this thesis focuses on the QoS for RT services in LTE in femtocell scenarios. Femtocells are considered as promising solutions for QoS improvement, specially in macrocell coverage zones where the signal reception is low. However, the QoS can be considerably degraded by interferences, so it is extremely necessary to mitigate this issue.

We proposed two methods to mitigate interference among femtocells in order to reduce the physical packet losses to improve the QoS. Our first scheme works based on game theory (non-cooperative games) in order to perform a constant bargain between throughput and SINR values to find an optimal femtocell transmit power level. This scheme is distributed and aims to take advantage of the small femtocell surfaces. Based on femto-user positions our scheme aims to minimize the transmit power level as much as possible without decreasing the bitrate. Numerical results show a QoS improvement. Throughput increase, PLR decrease and interference decrease.

The second scheme also bases its optimization mechanism on game theory to reduce interference. Our mechanism is an evolution of the well known four colouring method for interference mitigation. It works in a centralized manner whose central entity is the HeNb GW. The central entity divides the total bandwidth into subbands in order to assign subbands to femtocells based on the classes of services that each femtocell performs. Numerical results show a high decrease of interference level. Throughput is maintained and PLR is highly reduced. Although our scheme performs efficient results, a serious and most important limitation is the complexity factor. When the femtocell density becomes high, the complexity level becomes higher.

It is important to highlight that most works do not take into account the QoS when proposing interference mitigation schemes. This is meaningful in femtocell scenarios because RT services such as video streaming and interactive real time gaming can be highly degraded by interferences, consequently degrading the QoS level. Bearing in mind that, interference in small surfaces is lethal for QoS performances as we can see in numerical results. In this part of the thesis we can conclude that, although femtocell scenarios is considered as a promising solution for the QoS improvement, interference issues are more dangerous than for macrocells due to the small coverage surfaces. The powerful characteristics of OFDMA are reduced considerably. By using our proposed schemes we reached a decreased interference, thereby decreasing packet losses and retransmissions. By minimizing retransmissions the packet delays is shorter and the QoS performance for RT services becomes as expected.

Perspectives and Future Work

As with all such studies, there are limitations that offer opportunities for further research. In order to complement our work, we propose several fields of future research in short, mid, and long term.

Short term

In this thesis we introduced three mechanisms for resource allocation in RT services. Numerical results show the efficiency of our algorithms when performing RT services, however, the performance for NRT services is low. Future work must focus on proposing mechanisms for NRT services. Nevertheless, it must be taken into account that in our simulations we tested algorithms such as PF and M-LWDF for NRT services whose performances are high. Future work must consider whether it is possible to use more than one algorithm for the resource allocation task or not. In fact, the question is: Is it possible to set the scheduler to use two different algorithms, one for RT services and another for NRT services? However, to test NRT services, it might be necessary to perform simulations under realistic models for specific applications such as HTTP, FTP, P2P, and underlying TCP protocol.

Mid term

There are obvious limitations in the resource allocation mechanisms that was introduced. Since all of them focus only on downlink system, future research is required in order to perform resource allocation in uplink system. Although unlike downlink system, uplink system works under SC-FDMA, we consider that both mechanisms possess several aspects in common such as the queues state for instance. It is important to remark that in uplink the UEs play an important role in the scheduling decision making, so this task can be shared between the eNb and the UEs.

This implies that, one part of the scheduling decision is made by the eNb which allocates resources among UEs based on basic information such as channel conditions and queues state. Another part of the scheduling decision is made by each UE which must figure out how to distribute the resource blocks (previously allocated by the eNb) among its flows.

Therefore, we consider that our approaches should be modified to be adapted to uplink system. Game theory approaches can be used for both decisions, a potential solution can be cooperative games for the eNb decision and non cooperative games for the UE decision. However, we leave this topic open as a potential future research.

Our proposed femtocell interference mitigation mechanisms focus only on mitigate co-tier interference which is already an important contribution. However, any model of interference mitigation in femtocell scenarios which does not take cross-tier interference into account needs to be improved. So, the challenge for future research will be to include some mechanism to handle the impact of cross-tier interference in femtocell scenarios. However, this task will not be easy to handle since the architecture of interconnection between eNbs and HeNbs will cause longer delays in signaling. However, it must be carefully taken into account that the the minimum latency for exchange of information between base stations is 20 ms [85]. Consequently, to enhance our centralized interference mitigation mechanism proposed in subsection 5.1.2, the decisions should be performed at two time scales. The co-tier level decision can occur in a short time scale, while the cross-tier level decision needs a longer period since signaling must imperatively go through the HeNb GW and the MME S-GW (see Figure 4.1).

Long term

In practical terms, our mechanisms seem to be an efficient solution to be applied in LTE scenarios. However, future evolution can lead researchers to extend this study to LTE-Advanced. LTE-Advanced introduces several enhancements such as Multiple-Input and Multiple-Output (MIMO), relay-nodes, and mesh based interfaces. We also consider that it is necessary to develop a simulation tool or build an LTE-Sim module to support these types of scenarios and evaluate appropriate mechanisms. Also it would be recommended an implementation of these mechanism not only in simulation tools but also in a real networks.

References

[1] Video trace library. In *http://trace.eas.asu.edu/*.

[2] Technical Specification Group Radio Access Network 3GPP. *Evolved Universal Terrestral Radio Access (E-UTRA) and Evolved Universal Terrestral Radio Access Network (Release 10)*. Technical report, 3GPP TS 36.300.

[3] Technical Specification Group Radio Access Network 3GPP. *Evolved Universal Terrestrial Radio Access (E-UTRA), Physical layer procedures (Release 10)*. Technical report, 3GPP TS 36.213.

[4] Technical Specification Group Radio Access Network 3GPP. *Feasibility Study for Orthogonal Frequency Division Multiplexing (OFDM) for UTRAN enhancement (Release 6)*. Technical report, 3GPP TS 25.892.

[5] Technical Specification Group Radio Access Network 3GPP. *Further enhancements to LTE Time Division Duplex (TDD) for Downlink-Uplink (DL-UL) interference management and traffic adaptation (Release 11)*. Technical report, 3GPP TR 36.828.

[6] Technical Specification Group Radio Access Network 3GPP. *Medium Access Control (MAC) protocol specification (release 9)*. Technical report, 3GPP TS 36.321.

[7] Technical Specification Group Radio Access Network 3GPP. *Physical layer aspect for evolved universal terrestrial radio access (utra) (release 7)*. Technical report, 3GPP TS 25.814.

[8] Technical Specification Group Radio Access Network 3GPP. *Simulation assumptions and parameters for FDD HeNb RF requirements*. TSG RAN WG4 meeting 51, May 2009.

[9] Technical Specification Group Radio Access Network 3GPP. *Technical Specification Group Services and System Aspects; GPRS Enhancements for E-UTRAN Access (Release 8).* Technical report, 3GPP TS 23.401.

[10] J. Hamalainen A.A Dowhuszko; M. Husso; L. Juan and Z. Zheng. Performance of practical transmit beamforming methods for interference suppression in closed-access femtocells. In *IEEE Future Network Mobile Summit (FutureNetw)*, pages 1 –12, June 2011.

[11] Z. Bharucha; G. Auer; T Abe and M. Miki. Femto-to-macro control channel interference mitigation via cell id manipulation in lte. In *IEEE Vehicular Technology Conference (VTC)*, pages 1 –6, September 2011.

[12] S. Uygungelen; G. Auer and Z. Bharucha. Graph-based dynamic frequency reuse in femtocell networks. In *IEEE Vehicular Technology Conference (VTC)*, pages 1–6, May 2011.

[13] B. Sadiq; S.J. Baek and G; de Veciana. Delay-optimal opportunistic scheduling and approximations: The log rule. In *IEEE/ACM Transactions on Networking*, **Vol. 19(2)**, pages 405 –418, April 2011.

[14] M. Bennis and D. Niyato. A q-learning based approach to interference avoidance in self-organized femtocell networks. In *IEEE Global Telecommunications Workshops (GLOBECOM)*, pages 706 –710, December 2010.

[15] S. Borst. User-level performance of channel-aware scheduling algorithms in wireless data networks. In *IEEE International Conference on Computer and Communications Conference (INFOCOM)*, **Vol. 1**, pages 321–331, April 2003.

[16] G.Piro; L.A. Grieco; G. Boggia; P. Camarda. A two-level scheduling algorithm for qos support in the downlink of lte cellular networks. In *IEEE European Wireless Conference (EW)*, pages 246 –253, April 2010.

[17] G. Piro; L. Grieco; G. Boggia; F. Capozzi and P. Camarda. Simulating lte cellular systems: an open source framework. In *IEEE Transactions Vehicular Technology*, **Vol. 60**, pages 498–513, October 2010.

[18] V. Chandrasekhar and J. Andrews. Spectrum allocation in tiered cellular networks. In *IEEE Transactions on Communications*, **Vol. 57(10)**, pages 3059 –3068, October 2009.

[19] S. Lien; C. Tseng; K. Chen and C. Su. Cognitive radio resource management for qos guarantees in autonomous femtocell networks. In *IEEE International Communications Conference (ICC)*, pages 1 –6, May 2010.

[20] R. Jain; D. Chiu and W. Hawe. A quantitative measure of fairness and discrimination for resource allocation in shared computer systems. In *Digital Equip. Corp., Littleton, MA, DEC Rep - DEC-TR-301*, September 1984.

[21] W. Park; S. Cho and S. Bahk. Scheduler design for multiple traffic classes in ofdma networks. In *IEEE International Conference Communications (ICC)*, **Vol. 2**, pages 790 –795, June 2006.

[22] C. Chuah and R. H. Katz. Characterizing packet audio streams from internet multimedia applications. In *IEEE International Communications Conference (ICC)*, **Vol. 2**, pages 1199–1203, April 2002.

[23] C. Jiang; L. Cimini and N. Himayat. Interference mitigation with mimo precoding in femtocellular systems. In *IEEE Information Sciences and Systems (CISS)*, pages 1 –6, March 2010.

[24] R.W. Cottle and G.B. Dantzig. Complementary pivot theory of mathematical programming. In *Linear Algebra Appl.*, pages 103–125, September 1986.

[25] C.Westphal. Monitoring proportional fairness in cdma2000 high data rate networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, **Vol. 6**, pages 3866–3871, December 2004.

[26] H. Ekstrom. Qos control in the 3gpp evolved packet system. In *IEEE Communications Magazine*, **Vol. 47(2)**, pages 76 –83, February 2009.

[27] G. Piro; L.A. Grieco; G. Boggia; R. Fortuna; and P. Camarda. Two-level downlink scheduling for real-time multimedia services in lte networks. In *IEEE Transactions on Multimedia*, **Vol. 13(5)**, pages 1052 –1065, Octobre 2011.

[28] A. Galindo and J. Giupponi. Distributed q-learning for interference control in ofdma-based femtocell networks. In *IEEE Vehicular Technology Conference (VTC)*, pages 1 –5, May 2010.

[29] G. Na; Z. Yiqing; T. Lin; S. Gang and S. Jinglin. Qos guaranteed resource block allocation algorithm for lte systems. In *IEEE Wireless and Mobile*

Computing, Networking and Communications (WiMob), pages 307 –312, October 2011.

[30] T. Hui; W. Xi-Jun; J. Fan; D. Gang and Z. Jie-Tao. An inter-cell interference mitigation scheme based on mimo-relay technique. In *IEEE Vehicular Technology Conference (VTC),*, pages 1 –5, May 2010.

[31] C. Daskalakis; P.W. Goldberg; and C.H. Papadimitriou. The complexity of computing a nash equilibrium. In *IEEE Ellec. Colloc. on Computer Complexity (ECCC)*, pages 1–13, September 2005.

[32] M. A. Ismail; G. Piro; L. A. Grieco; and T. Turletti. An improved ieee 802.16 wimax module for the ns-3 simulator. In *Proc. of SIMUTools 2010*, March 2010.

[33] M.Bennis; S. Guruacharya; and D. Niyato. Distributed learning strategies for interference mitigation in femtocell networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, pages 1 –5, December 2011.

[34] S. Elayoubi; O. Ben Haddada; and B. Fourestie. Performance evaluation of frequency planning schemes in ofdma-based networks. In *IEEE Transactions on Wireless Communications*, **Vol. 7(5)**, pages 1623 –1633, May 2008.

[35] J. Leinonen; J. Hamalainen and M. Juntti. Performance analysis of downlink ofdma resource allocation with limited feedback. In *IEEE Transactios on Wireless Communications*, **Vol. 8(6)**, pages 2927–2937, June 2009.

[36] G. Zhioua; P. Godlewski; S. Hamouda and S. Tabbane. A femtocells ressources allocation scheme in ofdma based networks. In *IEEE Conference Communications and Networking (ComNet)*, pages 1 –5, November 2010.

[37] S. Guruacharya; D. Niyato; E. Hossain and D. In Kim. Hierarchical competition in femtocell-based cellular networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, pages 1 –5, December 2010.

[38] M. Iturralde and T. Ali Yahiya. *Performance Study of Opportunistic Scheduling in LTE Networks. In: Understanding LTE and its Performance.* Springer, August 2011.

[39] P. Lee; T. Lee; J. Jeong and J. Shin. Interference management in lte femtocell systems using fractional frequency reuse. In *IEEE Advanced Communication Technology (ICACT)*, **Vol. 2**, pages 1047 –1051, February 2010.

[40] Z. Han; Z. Ji and K.J.R. Liu. Fair multiuser channel allocation for ofdma networks using nash bargaining solutions and coalitions. In *IEEE Transactions on Communications*, **Vol. 53(8)**, pages 1366–1376, August 2005.

[41] L. Tan; Z. Feng; W. Li; Z. Jing and T. Gulliver. Graph coloring based spectrum allocation for femtocell downlink interference mitigation. In *IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1248–1252, March 2011.

[42] N. Arulselvan; V. Ramachandran; S. Kalyanasundaram and G. Han. Distributed power control mechanisms for hsdpa femtocells. In *IEEE Vehicular Technology Conference (VTC)*, pages 1 –5, April 2009.

[43] B. Varadarajan; R. Chen; E. N. Onggosanusi; II Han Kim and A. G. Dabak. Efficient channel quality feedback schemes forofdma systems with different schedulers. In *IEEE Vehicular Technology Conference (VTC)*, pages 1–5, April 2009.

[44] T. Kim and T. Lee. Throughput enhancement of macro and femto networks by frequency reuse and pilot sensing. In *IEEE International Performance, Computing and Communications Conference (IPCCC)*, pages 390 –394, December 2008.

[45] A. Attar; V. Krishnamurthy and O.N. Gharehshiran. Interference management using cognitive base-stations for umts lte. In *IEEE Communications Magazine*, **Vol. 49(8)**, pages 152 –159, august 2011.

[46] K.I Pedersen; T.E. Kolding; F. Frederiksen; I.Z. Kovacs; D. Laselva and P.E. Mogensen. An overview of downlink radio resource management for utran long-term evolution. In *IEEE Communications Magazine*, **Vol. 47(7)**, pages 86 –93, July 2009.

[47] D. Oh; H. Lee and Y. Lee. Power control and beamforming for femtocells in the presence of channel uncertainty. In *IEEE Vehicular Technology Conference (VTC)*, **Vol. 60(6)**, pages 2545 –2554, July 2011.

[48] T. Lee; J. Yoon; S. Lee and J. Shin. Interference management in ofdma femtocell systems using fractional frequency reuse. In *IEEE International Conference Communications, Circuits and Systems (ICCCAS)*, pages 176 –180, July 2010.

[49] R. Kwan; C. Leung; and J. Zhang. Proportional fair multiuser scheduling in lte. In *IEEE Signal Processing Letters*, **Vol. 16(6)**, pages 461–464, June 2009.

[50] G. Kim; Q. Li and R. Negi. A graph-based algorithm for scheduling with sum-interference in wireless networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, pages 5059–5063, November 2007.

[51] T. Bu; L. Li and R. Ramjee. Generalized proportional fair scheduling in third generation wireless data networks. In *IEEE International Conference on Computer and Communications Conference (INFOCOM)*, **Vol. 1**, pages 1–12, April 2006.

[52] S. Park; W. Seo; Y. Kim; S. Lim and D. Hong. Beam subset selection strategy for interference reduction in two-tier femtocell networks. In *IEEE Transactions on Wireless Communications*, **Vol. 9(11)**, pages 3440 –3449, November 2010.

[53] R. Juang; P. Ting; H. Lin and D. Lin. Interference management of femtocell in macro-cellular networks. In *IEEE Wireless Telecommunications Symposium (WTS)*, pages 1 –4, April 2010.

[54] S. Lien; Y. Lin and K. Chen. Cognitive and game-theoretical radio resource management for autonomous femtocells with qos guarantees. In *IEEE Transactions on Wireless Communications*, **Vol. 10(7)**, pages 2196 –2206, July 2011.

[55] Q. Li; Z. Feng; W. Li; Y. Liu and P. Zhang. Joint access and power control in cognitive femtocell networks. In *IEEE Wireless Communications and Signal Processing (WCSP)*, pages 1 –5, 2011.

[56] M. Nazir; M.Bennis; K. Ghaboosi; A.B. MacKenzie and M. Latva-aho. Learning based mechanisms for interference mitigation in self-organized femtocell networks. In *IEEE Signals, Systems and Computers Conference (ASILOMAR)*, pages 1886 –1890, November 2010.

[57] B. Sadiq; R. Madan and A. Sampath. Downlink scheduling formulticlass traffic in lte. In *EURASIP Journal on Wireless Communications and Networking*, **2009**, pages 1–18, February 2009.

[58] H. Adibah Mohd Ramli; K. Sandrasegaran; R. Basukala; R. Patacha-ianand; X. Minjie and L. Cheng-Chung. Resource allocation technique for

video streaming applications in the lte system. In *IEEE Wireless and Optical Communications Conference (WOCC)*, pages 1 –5, May 2010.

[59] D. Martin-Sacristan; J. Cabrejas; D. Calabuig; J.F. Monserrat. Mac layer performance of different channel estimation techniques in utran lte downlink. In *IEEE Vehicular Technology Conference (VTC)*, pages 1 –5, April 2009.

[60] H. Jo; C. Mun; J. Moon and J. Yook. Interference mitigation using uplink power control for two-tier femtocell networks. In *IEEE Transactions on Wireless Communications*, **Vol. 8(10)**, pages 4906 –4910, October 2009.

[61] H. Jo; J. Yook; C. Mun and J. Moon. A self-organized uplink power control for cross-tier interference management in femtocell networks. In *IEEE Military Communications Conference (MILCOM)*, pages 1 –6, November 2008.

[62] J. Nash. The bargaining problem. In *Econometrica*, **Vol. 18(2)**, pages 155–162, December 1950.

[63] J. Nash. Non cooperative games. In *The Annals of Mathematics, Second-Series*, **Vol. 54(2)**, pages 286 –295, September 1951.

[64] H. Lee; D. Oh and Y. Lee. Mitigation of inter-femtocell interference with adaptive fractional frequency reuse. In *IEEE Conference Communications (ICC)*, pages 1 –5, May 2010.

[65] H. Lee; D. Oh and Y. Lee. Coordinated user scheduling with transmit beamforming in the presence of inter-femtocell interference. In *IEEE International Communications (ICC)*, pages 1 –5, June 2011.

[66] C. Wengerter; J. Ohlhorst and A. Elbwart. Fairness and throughput analysis for generalized proportional fair frequency scheduling in ofdma. In *IEEE Vehicular Technology Conference (VTC)*, **Vol. 3**, pages 1903–1907, June 2005.

[67] Omnet++. Lte module for the ns-3 simulator. In *[OnLine] Available: http://www.nsnam.org/docs/release/3.10/manual/html/lte.html*.

[68] Omnet++. Numbat - new ubiquitous mobility basic analysis tools: Wimax, dhcpv6 implementation in omnet++. In *[OnLine] Available:*.

[69] K. Norlund; T. Ottosson; and A. Brunstrom. Fairness measures for best effort traffic in wireless networks. In *IEEE International Symposium on Personal,*

Indoor and Mobile Radio Communications (PIMRC), **Vol. 1**, pages 1953–2957, September 2004.

[70] Z. Yuan; S. Pagadarai and A.M. Wyglinski. Cancellation carrier technique using genetic algorithm for ofdm sidelobe suppression. In *IEEE Military Communications Conference (MILCOM)*, pages 1 –5, November. 2008.

[71] D. Astely; E. Dahlman; A. Furuskar; Y. Jading; M. Lindstrom; S. Parkvall. Lte: the evolution of mobile broadband. In *IEEE Communications Magazine*, **Vol. 47(4)**, pages 44 –51, April 2009.

[72] L. Mohjazi; M. Al-Qutayri; H. Barada; K. Poon and Raed M. Shubair. Self-optimization of pilot power in enterprise femtocells using multi objective heuristic. In *Journal of Computer Networks and Communications,*, pages 1 –14, May 2012.

[73] A. Stefan; M. Ramkumar; R. Nielsen; N. Prasad and R. Prasad. A qos aware reinforcement learning algorithm for macro-femto interference in dynamic environments. In *IEEE Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, pages 1 –7, October 2011.

[74] X. Li; L. Qian and D. Kataria. Downlink power control in co-channel macrocell femtocell overlay. In *IEEE Conference Information Sciences and Systems (CISS)*, pages 383 –388, March 2009.

[75] R. Basukala; H. Mohd Ramli and K. Sandrasegaran. Performance analysis of exp/pf and m-lwdf in downlink 3gpp lte system. In *IEEE First Asian Himalayas Conference*, **Vol. 1**, pages 1–5, November 2009.

[76] D.M Blough; G. Resta and P. Santi. "approximation algorithms for wireless link scheduling with sinr-based interference". In *IEEE/ACM Transactions on Networking*, **Vol. 18(6)**, pages 1701 –1712, December 2010.

[77] W. Rhee and J. M. Cioffi. Increase in capacity of multiuser ofdm system using dynamic subchannel allocation. In *IEEE Vehicular Technology Conference (VTC)*, pages 1085–1089, 2000.

[78] B. Sadiq and G. de Veciana. Optimality and large deviations of queues under the pseudo-log rule opportunistic scheduling. In *IEEE Allerton Conference ,Communication, Control, and Computing*, pages 776 –783, September 2008.

[79] S. Shakkottai and A. Stolyar. Scheduling algorithms for a mixture of real and non real time data in hdr. In *Bells Laboratories*, 2004.

[80] L. S. Shapley. A value for n-person game. In *Annals of mathematics Studies, Princeton University press*, **Vol. 2**, pages 307–317, 1953.

[81] A. Sharifian; and H. Yanikomeroglu. On the delay-fairness through scheduling for wireless ofdma networks. In *IEEE Vehicular Technology Conference (VTC)*, pages 1 –5, May 2011.

[82] S. Sivanandam and S. Deepa. *Introduction to Genetic Algorithms*. Sringer, 2008.

[83] Q. Yunzhi; R. Canjun; T. Suwen and C. Ming. Multi-service qos guaranteed based downlink cross-layer resource block allocation algorithm in lte systems. In *IEEE Wireless Communications Signal Processing (WCSP)*, pages 1 –4, November 2009.

[84] S. Vatsikas; S. Armour; M. De Vos; and T. Lewis. A distributed algorithm for wireless resource allocation using coalitions and the nash bargaining solution. In *IEEE Vehicular Technology Conference (VTC)*, pages 1 –5, May 2011.

[85] G. Boudreau; J. Panicker; N. Guo; R. Chang; N. Wang and S.Vrzic. Interference coordination and cancellation for 4g networks. In *IEEE Communications Magazine*, **Vol. 47(4)**, pages 74 –81, April 2009.

[86] M. Iturralde; T. Ali Yahiya; A. Wei and A.L. Beylot. Performance study of multimedia services using virtual token mechanism for resource allocation in lte networks. In *IEEE Vehicular Technology Conference (VTC)*, pages 1–5, September 2011.

[87] M. Iturralde; T. Ali Yahiya; A. Wei and A.L. Beylot. Resource allocation using shapley value in lte networks. In *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pages 31–35, September 2011.

[88] M. Iturralde; T. Ali Yahiya; A. Wei; and A.L. Beylot. Interference mitigation by dynamic self-power control in femtocell scenarios in lte networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, December 2012.

[89] M. Iturralde; T. Ali Yahiya; A. Wei; and A.L. Beylot. A real-time services performance and interference mitigation for femtocell scenarios in lte networks. In *IEEE Conference on Local Computer Networks (LCN)*, October 2012.

[90] M. Iturralde; T. Ali Yahiya; A. Wei and A.L. Beylot. Resource allocation for real time services using cooperative game theory and a virtual token mechanism in lte networks. In *IEEE Consumer Communications and Networking Conference (CCNC)*, pages 879–883, January 2012.

[91] M. Andrews; K. Kumaran; K. Ramanan; A. Stolyar; P. Whiting and R. Vijayakumar. Providing quality of service over a shared wireless link. In *IEEE Communications Magazine*, **Vol. 39(2)**, pages 150–154, February 2001.

[92] P. Ameigeiras; J. Wigard and P. Mogensen. Performance of the m-lwdf scheduling algorithm for streaming services in hsdpa. In *IEEE Vehicular Technology Conference (VTC)*, **Vol. 2**, pages 999–1003, September 2004.

[93] W. C. Wong and S. Talwar. Interference mitigation using downllink transmit beamforming with nulling techniques. In *IEEE C802.16m-08/653r2*, July 2008.

[94] E. Yaacoub; and Z. Dawy. A game theorical formulation for proportional fairness in lte uplink scheduling. In *IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1–5, April 2009.

[95] L. Zhang; L. Yang and T. Yang. Cognitive interference management for lte-a femtocells with distributed carrier selection. In *IEEE Vehicular Technology Conference (VTC)*, pages 1 –5, September 2010.

[96] Q. Ai; P. Wang; F. Liu; Y. Wang; Feifei Yang and Jing Xu. Qos-guaranteed cross-layer resource allocation algorithm for multiclass services in downlink lte system. In *IEEE Wireless Communications and Signal Processing (WCSP)*, pages 1 –4, October 2010.

[97] J. Yun and K. Shin. Adaptive interference management of ofdma femtocells for co-channel deployment. In *IEEE journal Selected Areas in Communications*, **Vol. 29(6)**, pages 1225 –1241, June 2011.

[98] G. Zhang and H. Zhang. Adaptive resource allocation for downlink ofdma networks using cooperative game theory. In *IEEE International Conference on Communication Systems (ICCS)*, pages 98–103, November 2008.

[99] J. Zhang and G. de la Roche. *Femtocells: Technologies and deployement*. Wiley, 2010.

[100] J.M Zolezzi and H. Rudnick. Transmission cost allocation by cooperative games and coalition formation. In *IEEE Transactions on Power Systems*, **Vol. 17(4)**, pages 1008 – 1015, November 2002.

Publications List

Conference papers

1. M. Iturralde; T. Ali Yahiya; A.Wei; and A.L. Beylot. “Interference mitigation by dynamic self-power control in femtocell scenarios in lte networks”. In IEEE Global Telecommunications Conference (GLOBECOM), December 2012.

2. M. Iturralde; T. Ali Yahiya; A.Wei; and A.L. Beylot. “A Real-Time Services Performance and Interference Mitigation for Femtocell Scenarios in LTE Networks ”. In IEEE Conference on Local Computer Networks (LCN), October 2012.

3. M. Iturralde; T. Ali Yahiya; A. Wei and A.L. Beylot. “Resource allocation for real time services using cooperative game theory and a virtual token mecha- nism in lte networks ”. In IEEE Consumer Communications and Networking Conference (CCNC), pages 879 – 883, January 2012.

4. M. Iturralde; T. Ali Yahiya; A. Wei and A.L. Beylot. “Resource allocation using shapley value in lte networks”. In IEEE Personal Indoor and Mobile Radio Communications (PIMRC), pages 31 – 35, September 2011.

5. M. Iturralde; T. Ali Yahiya; A. Wei and A.L. Beylot. “Performance study of multimedia services using virtual token mechanism for resource allocation in lte networks.”In IEEE Vehicular Technology Conference (VTC), pages 1 – 5, September 2011.

Books Chapters

1. M. Iturralde and T. Ali Yahiya. “Performance Study of Opportunistic Scheduling in LTE Networks. In: Understanding LTE and its Performance”. Springer, Agoust 2011.