Performance Analysis of QoS in LTE - Advanced Heterogeneous Networks

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Master Thesis Information

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Performance Analysis of QoS in LTE - Advanced Heterogeneous Networks

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ABSTRACT

The increasing demands for data mobile traffic is bringing new challenges on cellular networks in terms of user capacity and increased data throughput. In order to fulfill these demands, Heterogeneous Networks (HetNets) made up by macro and small cells have appeared as a promising solution. Moreover, the addition and co-existence of cells with different scales brings several interference problems, which are managed by means of enhanced Inter-Cell Interference Coordination (eICIC) techniques. The influence of this method has been studied previously. Herein, a more efficient manner to manage interference is proposed.

With the evolution of mobile networks and popularity of smartphones, more and more applications having Quality of Service requirements are coming up. The study of users under Guaranteed Bit Rate (GBR) requirements has been done.

Based on the results obtained in this report through different simulations, the options presented in this thesis for both managing interference and dealing with users under GBR requirements in HetNets can be seen as positive solutions.

Preface

This Long Master Thesis has been written by David Ruiz Grande (group 10o3) from September 2012 to May 2013 at Aalborg University. It has been possible to execute this project thanks to the collaboration between Radio Access Technology Section (Aalborg University) and Nokia Siemens Networks.

This report was written in LaTeX and consists of six chapters and two appendices. A Nokia Siemens Networks proprietary LTE System Level Simulator was used to perform the simulations, while MATLAB was used to post-process the results and plot the figures.

Literature references follow IEEE recommendations. Texts, figures and tables are referenced using a number in brackets which indicates the position in the reference list:

Text [Reference Number]
Figure (number): Figure Description [Reference Number]
Table (number): Table Description [Reference Number]

David Ruiz Grande
Aalborg University, 29th May, 2013

Acknowledgments

First of all, I would like to thank Aalborg University, especially the Radio Access Technology Section and Nokia Siemens Networks, for giving me the opportunity to be part of this challenging project.

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Many thanks to all my friends and people I have met in Aalborg, which made these months be some of the best of my life.

Finally, I would strongly like to thank my family, especially my parents and brother, for their constant and valuable support throughout this year.

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List of Abbreviations and Symbols

ABS	Almost Blank Subframe
AC	Admission Control
BE	Best Effort
BLER	Block Error Rate
CBR	Constant Bit Rate
CDF	Cumulative Distribution Function
CoMP	Coordinated MultiPoint
CQI	Channel Quality Indicator
CRS	Common Reference Signals
CRS-IC	Cell-specific Reference Symbols - Interference Cancellation
dB	Decibel
dBi	Decibel-Isotropic
dBm	Decibel-mili-Watt
DL	Downlink
eICIC	enhanced Inter-Cell Interference Coordination
eNB	eNodeB
EPC	Evolved Packet Core
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FD	Frequency Domain
FDD	Frequency Division Duplexing
FDPS	Frequency Domain Packet Scheduler
G-factor	Geometry Factor
GBR	Guaranteed Bit Rate
HARQ	Hybrid Automatic Repeat Request
HETNET	Heterogeneous Network
HSDPA	High-Speed Downlink Packet Access
ICIC	Inter-Cell Interference Coordination
IE	Information Element
IEEE	Institute of Electrical and Electronic Engineers
IMT	International Mobile Telecommunications
IP	Internet Protocol
IRC	Interference Rejection Combining
ITU - R	International Telecommunication Union Radiocommunication Sector

LA	Link Adaptation
LPN	Low Power Node
LTE	Long Term Evolution
m	Meter
Mbps	Megabits per second
MCS	Modulation and Coding Scheme
MHz	Megahertzs
MIMO	Multiple-Input Multiple-Output
MME	Mobility Management Entity
OFDM	Orthogonal Frequency Division Multiplexing
PDN - GW	Packet Data Network Gateway
PF	Proportional Fair
PF - B	Proportional Fair Barrier Function
PRB	Physical Resource Block
PS	Packet Scheduler
QAM	Quadrature Amplitude Modulation
QCI	QoS Class Identifier
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RE	Range Extension
RRH	Radio Remote Head
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
s	Second
SAE	System Architecture Evolution
S-GW	Serving Gateway
SINR	Signal to Interference-plus-Noise Ratio
S&W	Stop & Wait
TDM	Time Domain Multiplexing
TDPS	Time Domain Packet Scheduler
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
VoIP	Voice-over-IP
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation

Chapter 1

Introduction

This chapter presents a brief introduction to the research area along with a description of the problems addressed in this Master Thesis.

1.1 Motivation of the Study

The number of mobile broadband subscriptions continues to grow at a huge rate as the internet goes mobile since the last two decades. Indeed, the number of mobile subscribers is expected to reach around 3.5 billion by 2015, being in their majority smartphone-based subscribers [1]. This potential growth implies also a considerable increase in mobile data traffic. According to Cisco, global mobile data traffic is expected to grow up to 11.2 exabytes per month by 2017 [2]. With the evolution of new technologies devices, smartphones are now capable of displaying high quality videos or real time video traffic, which will definitely put high efforts on cellular networks' capacity.

In order to fulfil the aforementioned traffic demands from [2], a new generation of mobile networks is being deployed by mobile operators. During the last years, deployment of Third Generation Partnership Project (3GPP)'s Long Term Evolution (LTE) has become more and more present [3]. However, even with the enhancements offered by LTE, the continuous growing demands in terms of capacity and increased data throughput are not able to be managed. This fact is aggravated in the case of densely populated areas (e.g. shopping centres or airports) where a high number of users desire to connect to the base station at the same time and the system might go beyond the capacity limit. The traditional macro cell network architecture is not enough for these environments.

Regarding the exponential growth of subscribers and traffic volumes, in order to improve the capacity and coverage the architecture of the existing Radio Access Networks (RANs) should be enhanced. Different solutions have already been proposed so as to improve

RANs, being worth mentioning:

- Increase the density of the macro layer by increasing the number of macro base stations in the same cell site area. However, site acquisition of macro base stations is expensive in urban areas as well as the deployment process might be complex.
- Combining macro cells with low power nodes (LPNs) with different types of transmission power, backhaul connectivity, etc. usually placed in a planned manner to overcome the problem of coverage holes, thus improving the capacity in hot-spots areas.

The latter option, also referred to as a heterogeneous network (HetNet), is considered a promising way of increasing the average user capacity and coverage [4]. From now, the study carried out along this thesis will focus on the use of HetNets made up by macro cells embedded by pico base stations and Radio Remote Heads (RRHs) as small cells placed in hot-spot areas and deployed at the same carrier frequency than the macro cell (i.e. co-channel deployment).

Furthermore, one of the biggest challenges with the fast growth of multimedia applications over Internet is to maintain Quality of Service (QoS), meaning that the service through Internet should be guaranteed. Different methods are suggested to maintain QoS, even though it is not always possible to guarantee the quality of all requirements. Basically, the QoS requirements are translated into some specific variables that define the performance experienced by users. Thus, different QoS parameters are assigned to each user depending on the application data it carries, enabling therefore differentiation among them. To this purpose, different classes of QoS services have been defined by means of QoS Class Identifiers (QCIs), which are scalar values used as a reference for driving specific packet forwarding behaviours [5]. Each QCI is characterized by a resource type (Guaranteed Bit Rate (GBR) or non-GBR), a priority level, the maximum permitted packet delay as well as the acceptable packet loss rate.

Finally, since most traffic flows in the downlink (DL) side of the communication, this investigation is made to improve the performance on this link.

1.2 Related Work

Different contributions and studies have already been done about the use of HetNets as a way of improving the performance in relation to homogeneous networks. For instance, the authors in [6] provide a high-level overview of 3GPP LTE and discusse the need for an alternative strategy with emphasis on the use of HetNets. Also, some interference management techniques critical for HetNets are greater detailed. In [7], the authors describe several techniques enabling the move from macro-only to HetNets including range extension and enhanced inter-cell interference management techniques over HetNets, which will be further explained in Chapter 2. Concretely, different numbers of pico base stations are used as small cells to offload the macro. In addition, in [8] the major advantages of using HetNets and their technical challenges and research problems are detailed. Furthermore, the main activities currently under discussion in 3GPP related to enhanced intercell interference coordination have been evaluated. Finally, in [9] the advantages of using HetNets over the conventional networks are also presented, addressing especially aspects related to downlink co-channel interference management in a macro - pico scenario. Extensive system performance results are presented with bursty and non-bursty traffic to cover the analysis.

Moreover, several publications discussed the QoS evaluation over High-Speed Downlink Packet Access (HSDPA) and LTE systems. In [10], two QoS-aware packet schedulers are carefully studied and analysed under different traffic mixes of Best Effort (BE) and Constant Bit Rate (CBR) traffic over HSDPA. Regarding LTE systems, in [11] a different alternative based on the study of QoS through a decoupled time/frequency domain packet scheduler approach is used under different user conditions.

1.3 Problem Statement

Migration from conventional network architecture to HetNets by complementing a homogeneous mobile network with small cells is not an insignificant transformation. Despite the relevant advantages produced by the HetNet design, it brings also some new challenges which have to be successfully treated.

The deployment of LPNs in macro cell areas where users are clustered in hot-spots is expected to offload some traffic from the macro base station. On the other hand, addition and co-existence of cells with different size and scale introduce several interference problems which, if not managed appropriately, can degrade the overall system performance (i.e. the overall user throughput and coverage).

In order to further increase the number of users offloaded from the macro cell, a technique of range extension is used to extend the LPN coverage area and push more users to connect to the small cell. However, those users in the extended area (i.e. cell-edge users) will suffer from strong interference from the macro base station as depicted in Figure 1.1, being necessary to mitigate it for the proper operation and improvement of the coverage throughput.

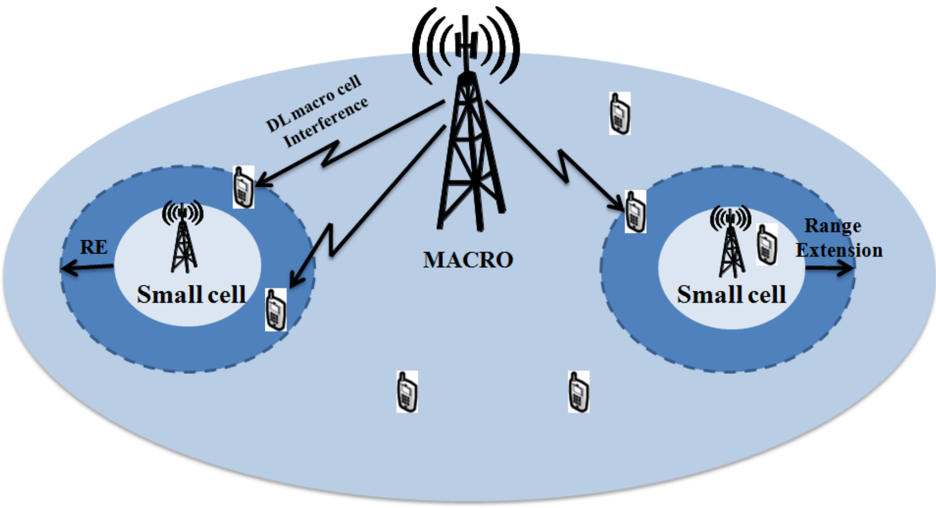

Figure 1.1: DL Interference from the macro cell to users in the extended area

This thesis mainly relates to the area of Radio Resource Management (RRM) and Inter-Cell Interference Coordination (ICIC) in HetNets, with special focus on managing the co-channel interference from the macro cell to the cell-edge users connected to the LPN through time-domain resource partitioning between the macro and LPN layers as will be further described in Chapter 2.

Furthermore, due to the huge popularity of smartphones and the improvement of mobile networks, new applications including video live streaming or real time gaming are becoming more and more ubiquitous, requiring certain GBR requirements. It is also needed, therefore, some techniques to guarantee QoS to users making use of these applications.

The following activities are identified as the main points covered by this investigation:

1. Perceive the impact of range extension and time domain resource partitioning based ICIC mechanisms on the user throughput performance. In order to do that, a reference scenario with macro and pico base stations forming a distributed architecture is first considered.

2. Given a centralized architecture made up by macro and RRHs, investigate the performance of enhanced ICIC techniques able to mitigate the interference between macro and RRH proposing a more efficient manner. Also, determine the gain obtained in terms of user throughput over the reference scenario.

3. Study of QoS requirements in HetNets, focusing on users having certain GBR requirements. For the study, a GBR - aware frequency domain packet scheduler (FDPS) is evaluated

and compared with the case of a non-GBR-aware FDPS (i.e. Proportional Fair for the case).

The two latest points should be noted as the most relevant ones in this investigation, since there are not previous studies regarding these topics on HetNets as it was discussed in the former section. Especially regarding the GBR traffic analysis, it is worth emphasizing the new challenges that requiring a certain GBR bring in HetNets design and which has not been studied so far. The full study will be further detailed in Chapter 5.

Moreover, to achieve the mentioned goals, the next steps have been followed in this report:

- A research on existing solutions to manage interference in the evaluated scenarios has been made to fully understand about the topic covered in this investigation.
- Different simulations are run in order to get the different results under different conditions. In order to do that, a Nokia Siemens Networks proprietary LTE Simulator has been used. The most important features of the simulator are described in Appendix A.
- The obtained results are post-processed and analysed.
- Comparison between the different results and conclusions on the impact of the proposed solutions are extracted.

1.4 Thesis Outline

The structure of this Master Thesis is organized as follows:

- Chapter 1. Introduction: This chapter outlines the motivation and scope of the work.
- Chapter 2. LTE - Advanced Heterogeneous Networks: This chapter presents some basic background on LTE - Advanced and describes the main features and enhancements on Heterogeneous Networks including key design features or interference management techniques.
- Chapter 3. System Model: The main scenarios to be tested and the main differences between them are described, as well as the key performance indicators used in order to evaluate the performance of these scenarios.
- Chapter 4. Load Balancing and Fast ABS Adaptation Solutions for HetNets: This chapter presents the features for the reference scenario with macro and pico base

stations and, more importantly, the investigated algorithm so as to perform the correct operation in the scenario with macro and RRHs. Also, the scheduling metric utilized to support QoS is explained.

- Chapter 5. Analysis of the results: This chapter provides results from a performance evaluation in heterogeneous networks deployment for different types of users.
- Chapter 6. Conclusions: The main ideas presented in the report are collected and summarized in this chapter.

In order to support the mentioned chapters, the following appendices are included:

- Appendix A. System Level Simulation: It collects the main features of the simulator as well as my personal contribution to it.
- Appendix B. Optimal Setting for the Fast ABS Adaptation Algorithm: This appendix presents the different configurations that can be used in the macro - RRH scenario as well as the optimal settings considered for this investigation.

Chapter 2

LTE - Advanced Heterogeneous Networks

This chapter presents a general description of the most important topics related to this work. A LTE - Advanced overview is first described including architecture and main features. Besides that, a focus is done on Heterogeneous Networks and the main key design features concerning to this study, including offloading techniques and interference management.

2.1 LTE - Advanced Overview

During the last two decades, telecommunication industry has grown explosively. The huge popularity of smartphones has brought the need for mobile broadband networks. Apart from voice transmission, the current mobile networks can provide users with a variety of services, including web browsing, real time gaming, video live streaming, etc. Users and new applications need faster access speed as well as lower latency while operators need more capacity and higher efficiency. In order to fulfill these demands, the first Release LTE standard (Release 8) was deployed by the 3GPP, and it has already been finalized with Release 9 as its final version [12]. However, the improvements offered by LTE are not enough to fulfill all the requirements for these potential demands. Furthermore, 3GPP keeps working on further enhancements of LTE. The evolved versions of LTE under work (LTE Release 10 and beyond) are called LTE-Advanced, which is all about even higher data rates, higher base station densities and higher efficiencies [13]. LTE - Advanced is able to fulfill the above mentioned requirements.

One of the main goals of this evolution is to reach or even exceed the International Mobile Telecommunications (IMT)-Advanced requirements established by the ITU-R in [14] as follows:

- Enhanced peak rates to support advanced services and applications (enable 100 Mbps for high mobility and up to 1 Gbps for low mobility cases).
- A high degree of commonality of functionality world-wide while retaining the flexibility to support a wide range of services and applications in a cost-efficient manner.
- Compatibility of services within IMT and with fixed networks.
- Allow internetworking with other radio access systems.
- Enabling high-quality mobile devices.
- User equipment suitable for worldwide use.
- User-friendly applications, services, and equipment.
- Worldwide roaming capability.

LTE Release 8 could meet the requirements for IMT - Advanced in many areas already, although it is not able to fulfill all of them. Therefore, it is more informally considered within 3.5 generation (3.5G) systems. On the other side, 3GPP established the requirements for LTE - Advanced [15], which were set to achieve or even exceed the IMT - Advanced (also known as fourth generation (4G)) requirements. 3GPP desired to make sure that there would be sufficient improvements when developing from Release 8/9 LTE to Release 10 LTE-Advanced capabilities and, eventually, being able to fulfill the 4G requirements. From a link performance perspective, LTE already achieves data rates very close to the Shannon limit. Therefore, as mentioned in [15], a special focus should be put on improving the cell-edge user throughput and the average spectrum efficiency rather than on peak spectrum efficiency or Voice-over-IP (VoIP) capacity. The relationship between the main requirements of LTE-Advanced and IMT-Advanced are shown in Table 2.1.

Item	Transmission path	Antenna configuration	LTE - Advanced	IMT - Advanced
Peak data rate	DL	8 x 8	1 Gbps	1 Gbps
	UL	4 x 4	500 Mbps	-
Peak spectrum efficiency (bps/Hz)	DL	8 x 8	30	15
	UL	4 x 4	15	6.75
Capacity (bps/Hz/cell)	DL	2 x 2	2.4	-
		4 x 2	2.6	2.2
		4 x 4	2.0	1.4
	UL	1 x 2	1.2	-
		2 x 4	2.0	1.4
Cell-edge user throughput (bps/Hz/cell/user)	DL	2 x 2	0.07	-
		4 x 2	0.09	0.06
		4 x 4	0.12	-
	UL	1 x 2	0.04	-
		2 x 4	0.07	0.03

Table 2.1: LTE - Advanced and IMT - Advanced performance targets for Downlink (DL) and Uplink (UL) [14] [15]

Some relevant technologies in order to improve the performance provided by LTE - Advanced include carrier aggregation, advanced MIMO techniques, wireless relays, enhanced inter-cell interference coordination (eICIC) or coordinated multipoint (CoMP) transmission and reception [14] [15]. Some of these features relevant in the scope of this work will be further described along this chapter.

Unlike LTE, LTE - Advanced is able to fulfill IMT - Advanced requirements. Furthermore, being an evolution of LTE, LTE - Advanced should be backwards compatible i.e. it should be possible to deploy LTE - Advanced in spectrum already occupied by LTE without suffering any impact on existing LTE terminals. Therefore, the evolution from LTE to LTE-Advanced will be a smooth one.

2.1.1 Network Architecture

Motivated by the increasing demand for mobile broadband services, 3GPP not only started working on LTE standard, but also on the "System Architecture Evolution" (SAE), with the purpose of defining the network core of the system. The elements and requirements that will serve as a basis for the next generation networks were defined by 3GPP in its Release 8 [16]. In the context of 4G systems, both the air interface and radio access network are being enhanced. However, thus far the core network architecture is passing through minor changes from the already standardized SAE architecture. As represented in Figure 2.1, the SAE is made up of a core network, namely the "Evolved Packet Core"

(EPC), and a radio access network, namely the Evolved-Universal Terrestrial Radio Access Network (E-UTRAN).

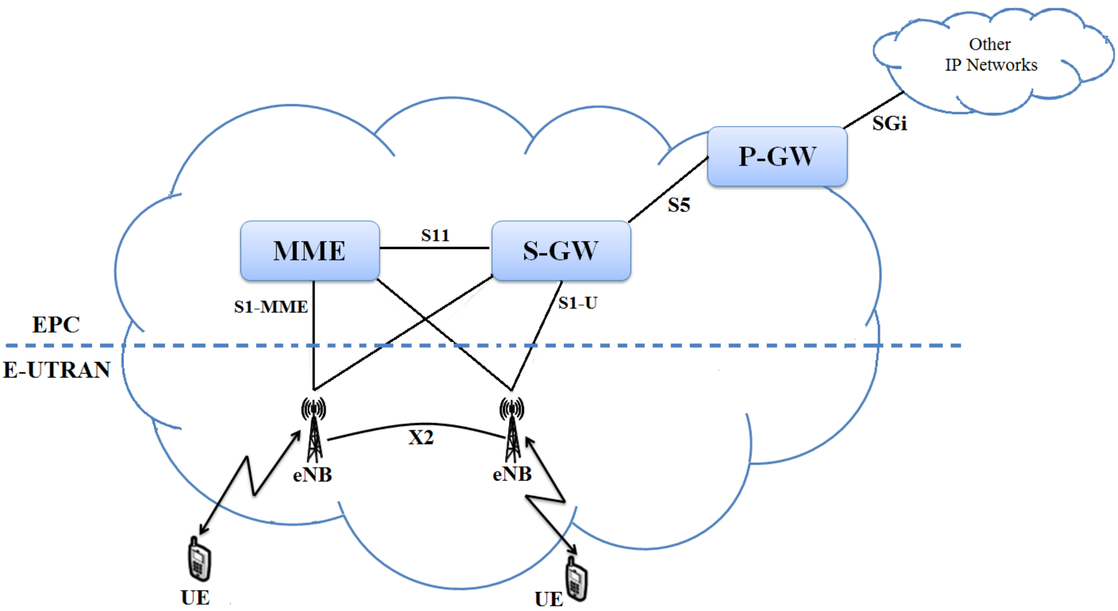

Figure 2.1: LTE - Advanced Network Architecture

LTE-Advanced E-UTRAN overview

The core part in the E-UTRAN architecture is the enhanced Node B (eNodeB or eNB), the evolution of the NodeB in a 3G system, which communicates with User Equipments (UEs) and it can serve one or several E-UTRAN cells at one time. The eNB nodes are directly connected to each other (this speeds up signaling procedures) through the called X2 interface.

Evolved Packet Core Network

The EPC is an all-IP based core network specified to support the E-UTRAN through a reduction in the number of network elements, simpler functionality and most importantly allowing for connections and handover strategies to other fixed line and wireless access technologies, giving the providers the capacity to deliver a seamless mobility experience [17]. The main components and functionalities of the EPC are as follows:

- The Mobility Management Entity (MME) is a key control plane element. It is responsible for user mobility, intra-LTE handover as well as security functions (authentication, authorization, NAS signaling). The MME also selects the Serving Gateway (S-GW) and Packet Data Network Gateway (PDN-GW) nodes. It is connected to the eNBs via the S1-MME interface.

- The S-GW is the termination node of the EPC. The main aim of the SGW is to route and forward user data packets among different LTE nodes and it also serves as a mobility point for both local inter-eNB handover and inter-3GPP mobility. It is connected to the E-UTRAN via the S1-U interface.
- The Packet Data Network Gateway (P-GW) provides the UE with access to a Packet Data Network (PDN). The PGW accomplishes policy enforcement, packet filtering for each user or charging support among other functions.

2.1.2 Frame structure and Transmission Scheme

The radio frame in LTE adopts the 0.5 ms slot structure and uses the 2 slot (1 subframe) allocation period, with duration of 10 ms (i.e. 10 subframes) per frame. In addition, for every subframe, each slot consists of either 6 or 7 Orthogonal Frequency Division Multiplexing (OFDM) symbols for the DL depending on whether extend or short cyclic prefix is used, with a Transmission Time Interval (TTI) of 1 ms. Multiple UEs can share the available resources within each TTI. Figure 2.2 illustrates an example of the LTE frame structure for the short prefix case.

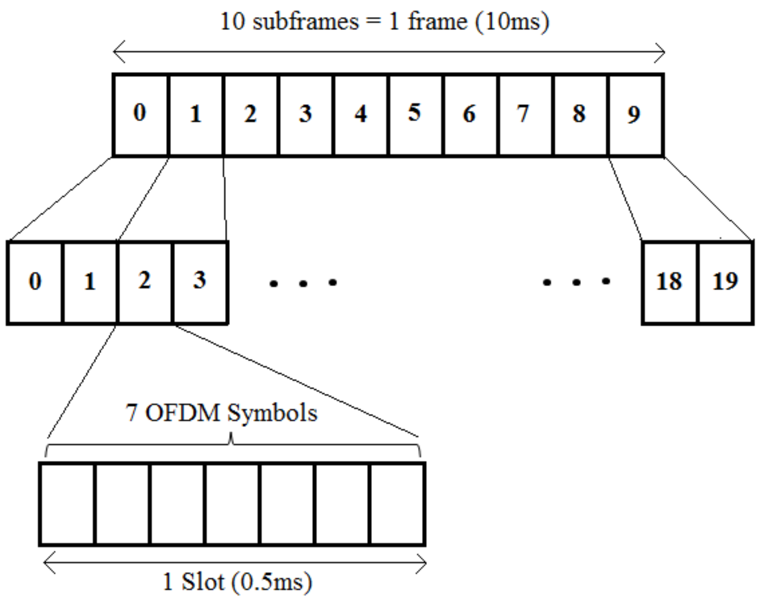

Figure 2.2: LTE Downlink Frame Structure [14]

The time-frequency grid resource in LTE-Advanced is depicted in Figure 2.3 when short cyclic prefix is used. The minimum resource element that can be assigned to a UE for data transmission is called Physical Resource Block (PRB), composed by 12 consecutive subcarriers and having a bandwidth of 180 kHz in the frequency domain. Moreover, one

PRB also makes reference to a subframe in the time domain i.e. 14 OFDM symbols for the DL.

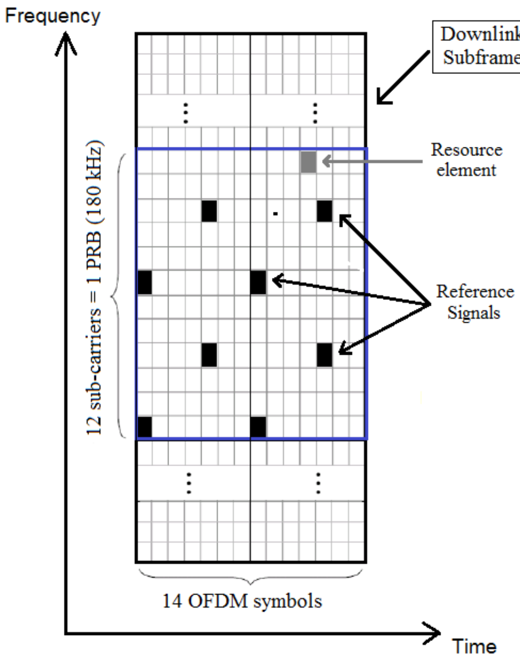

Figure 2.3: Time-frequency domain DL LTE frame structure [18]

LTE can operate on variable bandwidth as described in [19] and, therefore, the name of available PRBs to be allocated for the UEs is higher or lower depending on the used transmission bandwidth. Table 2.2 summarizes the different configurations available:

Transmission Bandwidth (MHz)	1.4	3	5	10	15	20
Number of Available PRBs	6	15	25	50	75	100

Table 2.2: LTE Transmission Bandwidth Configuration

Furthermore, different modulation schemes are supported in LTE downlink including QPSK, 16QAM and 64QAM schemes as well as different code rates [20] so as to achieve a trade-off between high data rates and low Block Error Rate (BLER). Basically, using low order modulation scheme (i.e. few data bits per modulated symbol, e.g. QPSK) the eNB guarantees a more robust transmission at the expense of a lower bit rate. On the contrary, with a high-order modulation scheme (i.e. more data bits per modulated symbol, e.g. 64QAM) the eNB allows a higher data rata but lower robustness since it is more susceptible to errors because of higher sensitivity to interference and noise. The code rate adjusts the chosen modulation scheme to the channel conditions so as to get a more reliable transmission. The idea is, therefore, to use higher modulation levels and higher coding rates when channel conditions are good, and vice versa.

2.1.3 Radio Resource Management

Radio Resource Management (RRM) is used in LTE-Advanced to assure that the available radio resources are utilized as efficiently as possible [21]. In order to do that, it includes strategies for controlling different parameters such as transmit power, handover measures, modulation scheme, error coding scheme and channel allocation.

In LTE-Advanced, a dynamic RRM is considered, meaning that the radio network parameters are adaptively adjusted to the traffic load, user positions, QoS requirements, etc [21]. For that purpose, Link Adaptation (LA) and other objects like the Packet Scheduling (PS) or Hybrid Automatic Repeat Request (HARQ) play such an important role as it will be further described in this section.

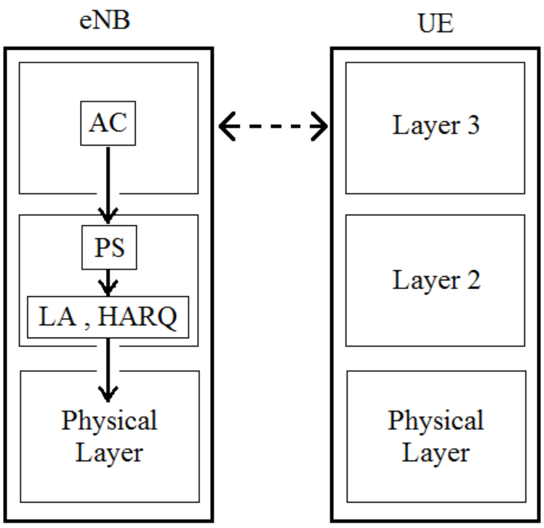

Figure 2.4: Radio Resource Management in a single carrier LTE-Advanced system

Figure 2.4 illustrates a flowchart of RRM in LTE-Advanced. It comprises Admission Control (AC) in layer 3, the mentioned PS, LA and HARQ management in layer 2, apart from the physical layer processes. These entities are located directly in the eNB and are performed on a millisecond basis in order to support fast adaptation to radio channel conditions.

Firstly, a UE will be served by an eNB only if it is admitted by the admission control based on the QoS requirements of the UE, the channel quality, etc. Once the UE is admitted to a cell, the PS is taken into consideration. It is the entity in charge of allocating transmission and retransmission requests over the available resources. LA is part of the RRM in layer 2. It basically tries to maximize the spectral efficiency while satisfying a certain BLER constraint. Moreover, HARQ management is done to improve the performance by combining the retransmissions with previous transmission. Independent layer 1 transmissions are finally performed. The main concepts appearing in the RRM procedures are explained below.

Link Adaptation

Generally, in any cellular communication systems, the quality of the received signal depends on many factors belonging to wireless environments including path loss, interferences or multipath propagation phenomenon. LA is a technique which adjusts dynamically some transmission parameters including modulation and coding schemes (MCS) to the radio channel conditions [22]. This way, strong variations in the received signal measured in the UE are avoided.

However, in downlink transmissions, the eNB does not directly know the actual channel conditions of a certain UE, so it requires a Channel Quality Indicator (CQI) feedback from the UE in order to make a suitable selection of the MCS. This CQI value provides some knowledge about the channel in the latest TTIs, being the result of measurements based on signal to interference-plus-noise ratio (SINR) estimated by listening to some reference symbols. It allows matching the transmission parameters to the variations of that indicator.

Normally, a higher CQI indicates a higher SINR and, therefore, better channel conditions for an UE. The CQI feedback is periodically reported from the UE to the eNB. Apart from the CQI report, information about positive or negative acknowledgments from the HARQ can be involved in the LA operation.

Hybrid ARQ

In LTE, a physical layer retransmission procedure called Hybrid Automatic Repeat Request (HARQ) is performed by eNB and UE in order to provide data at physical layer in a quickly and reliably way [3]. For that purpose, the Stop & Wait (S&W) protocol is used. After a transmission is done, the transmitter entity stops and waits for either a positive or negative acknowledgment (ACK/NACK) before transmitting a new packet or retransmitting the same one.

In order to achieve continuous transmission and avoid wasting important time, eight independent S&W HARQ parallel processes can be active at the same time. Every time a new packet is transmitted to the UE, the eNB starts an HARQ process that will be active until the end of the transmission.

Furthermore, two sorts of HARQ schemes are defined. The first scheme is synchronous and non-adaptive, meaning that transmissions and retransmissions can only take place at predefined instants of time. In this case, the eNB knows exactly when and which HARQ process must be processed, avoiding signaling the HARQ process number and the transmission configuration. On the other hand, the second scheme employs asynchronous and adaptive retransmissions. They can occur at any instant of time, being necessary to signal the HARQ process number and transmission parameters.

Packet Scheduler

The packet scheduler is the entity responsible for allocation transmission and retransmission requests over the available resources. The PS between a Radio Access Network (RAN) and the users over the air-interface takes a very important role due to the fast changing nature of the channel and the diversity of the channel quality among users.

The overall scheduling decision can be taken simultaneously in time and frequency domain or be divided into two steps: a time-domain packet scheduling (TDPS) and a frequency domain packet scheduling (FDPS). A possible packet scheduling framework is illustrated in Figure 2.5.

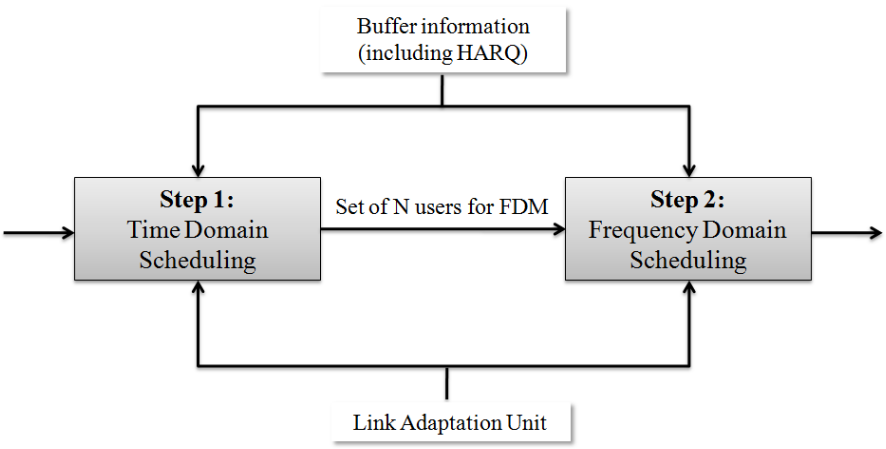

Figure 2.5: Packet Scheduler framework [23]

For the overall packet scheduler framework a simple two step algorithm is considered. First, the TD scheduler selects N users with the highest scheduling priority, being this set of users passed to the FD scheduler in each subframe. The FD scheduler allocates the available resources to the N selected users. This framework is attractive from a complexity point of view, since the FD scheduler only needs to apply frequency multiplexing of a limited number of N users in each TTI. For this study, however, since the number of users per cell in the system will not be large enough compared with the set value of N during most of the time, the TDPS influence is reduced. Special attention is paid, therefore, on the FDPS.

A proper scheduling operation can be achieved if the packet scheduler is continuously fed with updated information about the link status and retransmissions as illustrated in Figure 2.6, so LTE places it within the eNB. Information regarding the status of the link is achieved by means of the LA functionality. Also, the packet scheduler is in charge of allocating retransmissions ordered by the HARQ processes.

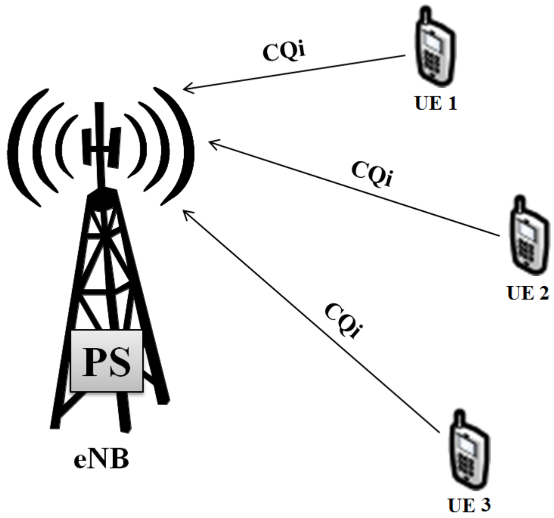

Figure 2.6: CQi reporting between UE and eNB

Scheduling Metrics

The scheduling metric is in charge of assigning a specific numerical value to every UE following certain criterion. This value is then used to prioritize the UEs when taking scheduling decisions (i.e. the higher the scheduling metric is for a certain UE, the more priority he has to be scheduled). Different criteria like fairness, maximization of the average cell throughput or the cell edge user throughput can be chosen in order to calculate this value and allocate the available resources [23]. Therefore, a wide range of different metrics can be defined depending on the objectives in the allocation of the resources (e.g. channel unaware, channel aware, QoS aware, etc.).

Proportional Fair Packet Scheduling

The Proportional Fair (PF) is a well-known scheduling metric where the priority to be scheduled is set according to the following expression:

$$M_{k,n}^{PF} = \frac{\hat{r}_{k,n}(t)}{R_n(t)} \tag{2.1}$$

where $\hat{r}_{k,n}(t)$ is the instantaneous achievable throughput of user n on PRB k, and $R_n(t)$ denotes the past average delivered throughput of user n until the current TTI t, obtained with an iterative filter. More details about its calculation will be given in Chapter 4.

From expression 2.1, two factors impact the PF metric for the user n to be scheduled on PRB k in the next TTI t:

1. The better the radio condition is for the user k (i.e. higher $\hat{r}_{k,n}(t)$), the more likely to be scheduled.
2. The lower past average throughput $R_n(t)$ so far for the user k, the more likely to be scheduled.

Therefore, a tradeoff between user achievable throughput and fairness is done for the user to be scheduled.

2.1.4 Downlink MIMO

One of the most relevant technologies introduced in LTE Release 8 is the Multiple-Input Multiple-Output (MIMO) operation including spatial multiplexing as well as pre-coding and transmit diversity. The basic principle of MIMO makes reference to the use of multiple antennas at both the transmitter and receiver sides. Base station and terminals are equipped with multiple antenna elements planned to be used in transmission and reception in order to make MIMO functionalities available at the downlink and the uplink. Transmission diversity obtained with multiple transmission and reception antennas can be used to achieve high diversity gain and, therefore, improving also the overall system performance. As a huge number of UEs with high data rates requirements have to be provided by the future cellular systems, MIMO becomes an important tool for wireless transmission.

Even though MIMO operation in LTE is available already in Release 8 LTE specifications, Release 10 supplies some new enhancements to improve the performance including different modes of antenna configuration with up to 8x8 MIMO in the downlink and 4x4 MIMO in uplink [4]. For the purpose of this work, a 2x2 MIMO configuration in downlink is considered.

The basic 2x2 MIMO configuration is illustrated in Figure 2.7. The basic principle consist of sending signals from two different antennas with different data streams, being processed and separated in the receiver, hence increasing the peak data rates by a factor of 2.

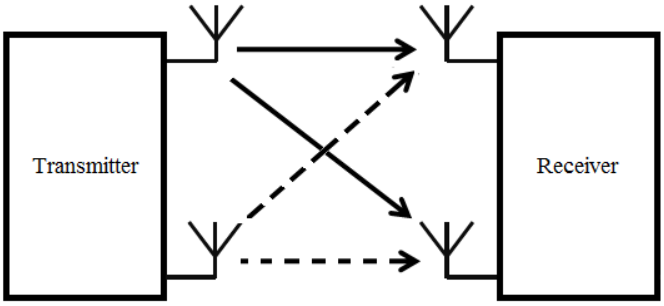

Figure 2.7: 2x2 MIMO Configuration

The receiver is able to separate different antennas from each other thanks to the reference symbols. In order to avoid transmission from another antenna that may corrupt the channel estimation needed to separate the MIMO streams, each reference symbol resource can only be used by a single transmit antenna. This principle is shown in Figure 2.8, where the reference symbols and empty resource elements are depicted to alternate between both antennas [3]. As mentioned, this principle can be also extended for the case with more than two antennas. When the number of antennas increases, the complexity in the transmitter and receiver as well as the reference symbols is also higher.

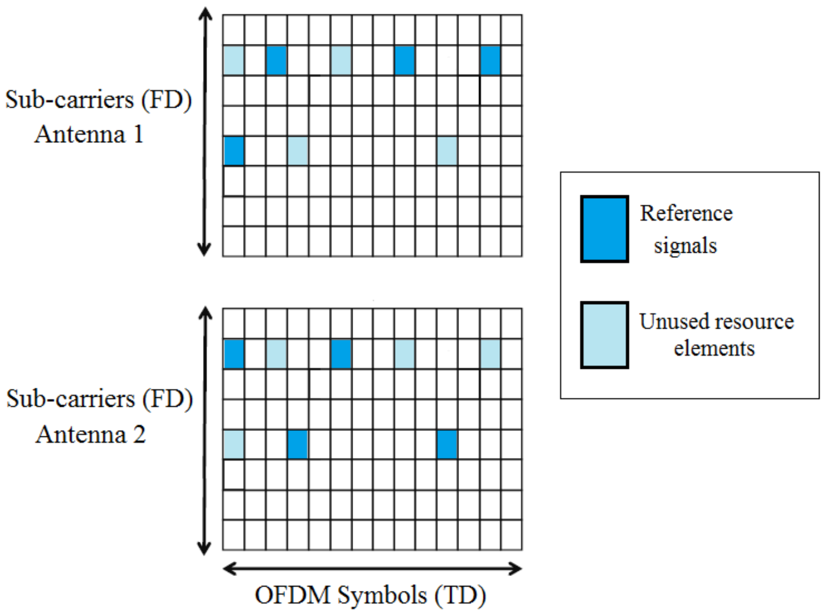

Figure 2.8: Reference symbols-based principle to support two eNBs transmit antennas [3]

2.2 Heterogeneous Networks

Up to now, wireless cellular networks have been typically deployed as homogeneous networks using wide area macro cells that provide coverage for several square kilometers by using high power transmitters and high mounted antennas.

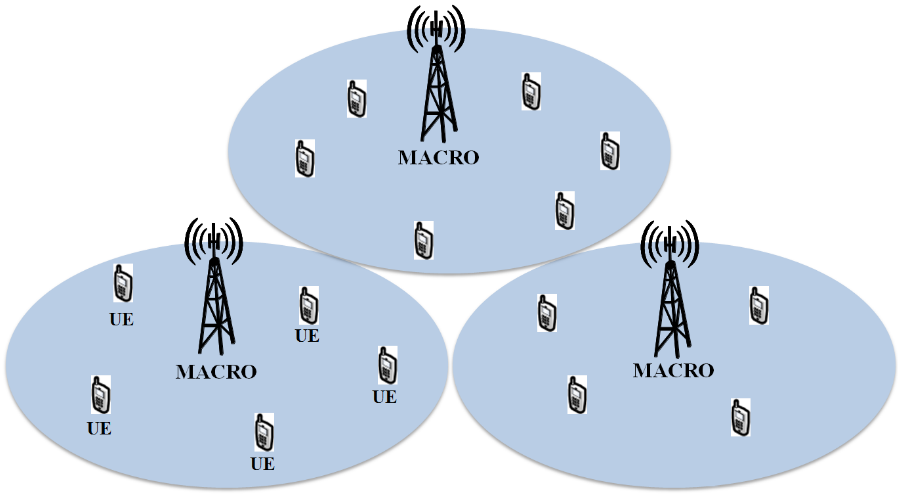

Figure 2.9: Traditional Network Deployment

As depicted in Figure 2.9, a homogeneous cellular system is a network consisting of base stations in a planned layout and a group of user terminals, with all the base stations having similar transmit power levels, antenna patterns, receive noise limit and also similar backhaul connectivity to the data network [24]. Further, all base stations offer unrestricted access to user terminals in the network and are able to serve approximately the same number of UEs which carry similar data flows with similar QoS requirements.

The macro base stations are carefully located according to a network planning and properly set up in order to get as maximum coverage as possible and control the possible interference among different base stations. Cellular system deployment has reached practical limits in many dense urban areas while data traffic only continues to increase. This fact leaves cellular operators with few options to increase one of the most relevant metric: area spectral efficiency. Unfortunately, radio link improvements including coding or multiple antenna techniques are approaching theoretical limits. As a result, a more flexible deployment model is needed for operators to enhance broadband user experience in a cost effective way. The most straightforward approach in order to efficiently deal with this continuous traffic demand is the use of advanced network topology, bringing the network closer to the user terminals. As a result, Heterogeneous Networks (HetNets) have been introduced in LTE-Advanced standardization and are expected to be one of the major performance enhancement enablers.

A HetNet is a network consisting of regular macrocells transmitting typically at high power level, overlaid with small cells (also known as Low Power Nodes (LPNs)) including picocells, femtocells, Remote Radio Heads (RRHs) as well as relay stations [6] [8]. An example of HetNet is illustrated in Figure 2.10.

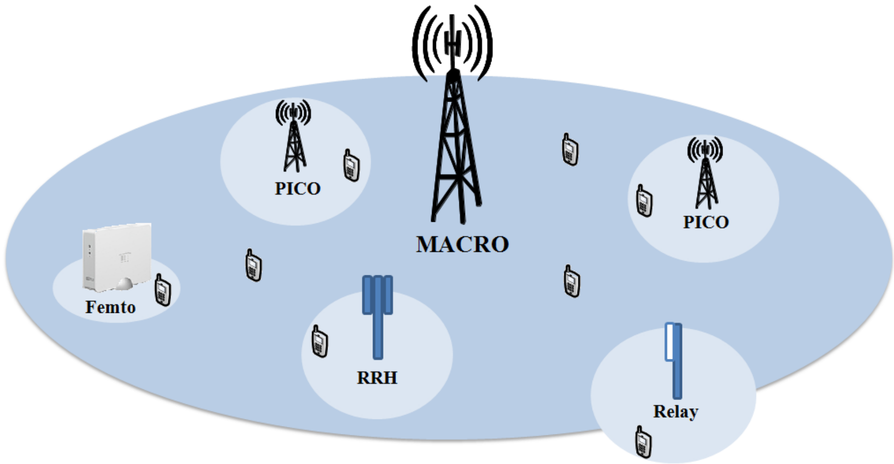

Figure 2.10: HetNet topology using a mix of high-power (macro) and low-power base stations

The incorporation of such small cells allows offloading the macrocells, being able to get a better indoor coverage and improving also the performance of cell-edge users, which is one of the main goals of deploying small cells. Also, the spectral efficiency is increased via spatial reuse. While macrocells are normally placed in a cellular network attending to a prudently network plan, the placement of LPNs is typically based on just a knowledge of coverage issues and traffic densities (e.g. hotspots) in the network.

Even though there are different eNBs to be deployed as small cells as depicted in Figure 2.10, following some details about the eNBs of HetNets in the scope of this work are mentioned:

- Macro cells consist of traditional powerful base stations, forming the backbone in the Heterogeneous Network solution. Also called eNBs in LTE, they provide open public access and a wide area of coverage around a few kilometers. Macrocells usually transmit at a high power (up to 46 dBm when using a bandwidth of 10MHz), being able to serve thousands of customers and using a dedicated backhaul.
- Picocells are basically regular eNBs with a lower transmit power that the mentioned macro cells, but with the same access features and backhaul. They are deployed

indoors or outdoors frequently placed in hotspots areas. Furthermore, picocells have typically a transmission power ranging from 23 to 30 dBm for outdoor environments, providing service to tens of customers within a coverage area of 300 m or less [8].

- RRHs are powerful and low-weight elements, which are typically connected to the macrocell via high speed and low latency link (i.e. fronthaul connection), consequently forming a distributed base station. The central macro cell controls signal processing, while RRHs improve flexibility to deployments for operators having site acquisition challenges or physical limitations. Basically, compared to the use of pico cells, faster coordination with the macro eNB will be allowed in this case as it will be described in Chapter 3.

Furthermore, different deployment options for HetNets can be considered as described in [6]. Basically, small cells can either be deployed on a different carrier frequency than the macro eNB (i.e. multicarrier deployment) or at the same carrier (i.e. co-channel deployment). It is worth stating that the rest of this work will be focused on a co-channel deployment. In this scenario, since all network eNBs are deployed in the same frequency, bandwidth segmentation is avoided, being a solution when the spectrum is limited (20 MHz or less). However, interference management should be done between the different eNBs for this deployment to be efficient, as it will be further described in Section 2.3.

2.3 HetNets Key Design Features

For this section, a scenario with co-channel deployment of macro and pico base stations is taken into consideration, where each UE is served by only one cell. The considered scenario is depicted in Figure 2.11.

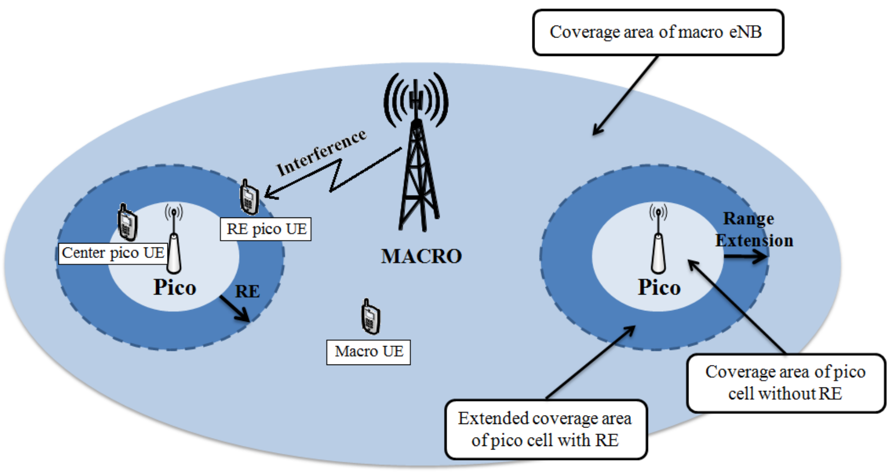

Figure 2.11: Macro-Pico Scenario with increased pico cell area coverage using range extension

2.3.1 Cell Range Extension

A pico base station is a regular eNB with lower transmit power compared to macro base stations and generally placed ad-hoc in the network. The deployment of these networks can cause large areas with low signal to interference values, resulting in a challenge to improve the performance of cell-edge users. For the case, the huge difference between the transmit power levels of macro and small (e.g. pico) cells (around 15 - 20 dBm) implies a much smaller downlink coverage of a pico cell compared to that of the macro cell.

In cellular networks, when a mobile moves from cell to cell and performs cell selection and handover, it has to measure the signal strength of the neighbor cells. For the UE the following measurements are carried out in LTE [3] [25]:

- Reference Signal Received Power (RSRP) which, for a particular cell, measures the average of the power measured over the resource elements that contain cell-specific reference signals within the considered measurement frequency bandwidth.
- Reference Signal Received Quality (RSRQ) is the ratio between the RSRP and the E-UTRA Carrier Received Signal Strength Indicator (RSSI) within the considered measurement frequency bandwidth. E-UTRA RSSI measures the average total received power on a given frequency including the total noise. RSRQ measurement provides additional information when RSRP is not enough to make a reliable handover or cell selection decision.

Typically, UE cell selection based on UE measurements of RSRP is done. This method is also performed along this study. In the case of traditional homogeneous networks, the eNB that offers the highest RSRP (i.e. highest quality of the received signal) is selected as the serving eNB for the UE.

However, in a heterogeneous deployment scenario, the different scale transmission power levels of the eNBs make this selection decision not be a trivial task. Given the considered scenario with both macro and pico eNBs, if the cell decision is still based on the downlink RSRP, the larger coverage of macro cells can limit the advantages of using cell-splitting by bringing most UEs towards macro cells even though they may not have enough resources to serve these UEs efficiently, while pico cells may not be delivering service to any UE. Further, this fact will result in only few UEs being served by the pico cells due to their much lower transmit power. The RSRP-based cell selection can therefore lead to unbalanced cell load for HetNet deployments, thus overloading macro-cells.

In order to solve this macro eNB overloading and force more UEs to be served by the pico eNB, a positive offset can be applied to the RSRP measured from pico cells, expanding their coverage area and subsequently increasing cell splitting gains [26] [27] [28]. Mathematically it can be expressed as follows,

$$Selected\,cell = argmax\{RSRP_{macro}, RSRP_{pico} + RE\} \tag{2.2}$$

We will refer to this concept as *Range Extension* (RE). This bias in the cell selection decision allows more UEs to be pushed to the pico layer as shown in Figure 2.11.

The concept of RE enables an optimal association of UEs throughout the coverage area, which will lead to enhanced system performance and load reduction from the macro eNB at the same time. However, it will be necessary to carry out methods to reduce the downlink interference caused by macro cells to the UEs served by the pico eNB in the extended coverage area. In addition, the RE technique requires careful evaluation when deciding on the offset values and only low values of RE up to 6dB are recommended to be used in co-channel deployments without any explicit interference management.

Depending on the base station where it is connected, different types of users can be distinguished as illustrated in Figure 2.11 and will be named as follows:

- Macro UEs to those in the coverage area of the macro eNB and connected to it.
- Center pico UEs to those in the coverage area of the pico eNB and connected to it.
- RE pico UEs to those in the cell-extended area and connected to the pico eNB.

Similar explanation can be used for the case of small cells in the form of RRHs instead of pico eNB. In that case, the different types of users to be considered are macro UEs, center RRH UEs and RE RRH UEs, respectively.

2.3.2 Interference Management

The interference management in HetNets is a non-trivial task and plays an important role to get an optimal overall performance. In particular, due to a large number of heterogeneous cells that could exist in a certain area, inter-cell interference becomes a challenging subject in these scenarios.

According to the considered scenario in Figure 2.11 with both macro and pico base stations, the main DL inter-cell interference problem that may occur for the co-channel deployment is the DL macro-eNB interference to pico UEs. Basically, a UE connected to a pico eNB placed close to a macro eNB can suffer interference from the macro because of the different transmit power between macro and pico eNBs. Among others, the commented interference problem may result in a strong degradation of the overall HetNets performance, being necessary the use of interference coordination schemes in order to decrease the interference and guarantee its proper operation.

Enhanced Inter-Cell Interference Coordination (eICIC)

LTE release 8 and 9 of 3GPP had already defined ICIC messages which are exchanged among the different cells via the X2 interface in order to coordinate their resource allocation and mitigate interference problems. Basically, three indicators were defined: Relative narrowband Transmit Power (RNTP) indicator for downlink ICIC and Overload Indicator (OI) as well as High Interference Indicator (HII) to cover uplink ICIC [29].

The discussed ICIC methods through the sending of the commented messages, however, do not specifically take into consideration HetNet settings and may not be effective for dominant interference scenarios of HetNets caused by the difference in the transmission power between the macro and pico cell base stations. Consequently, new enhanced ICIC (eICIC) techniques for HetNets have been developed for LTE-Advanced (introduced in Release 10), which can be grouped under three major categories according to [12]: time-domain resource partitioning, frequency domain resource partitioning and power control techniques. For this investigation, interference management through time-domain techniques are performed between the different layers to achieve a better performance [7]. More concretely, a focus will be done on mitigating the downlink interference from the macro eNB to the users in the extended area (i.e. RE pico users) as can be seen in Figure 2.11.

TDM Resource Partitioning

The main operation of TDM eICIC resource partitioning between macro and pico base stations is shown in Figure 2.12 for the macro - pico scenario with co-channel deployment.

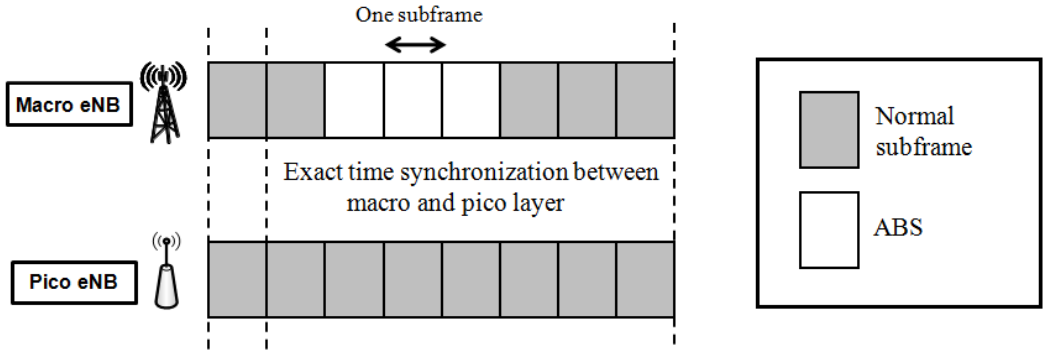

Figure 2.12: Basic principle of TDM eICIC for LTE-Advanced [6]

The eICIC concept relies basically on precise time and phase synchronization between all eNBs within a certain geographical area. In this case, the idea is to prevent the macro-eNB from transmitting on certain subframes reducing the interference to its surrounding neighbours. These subframes are named Almost Blank Subframes (ABS).

An ABS is defined by minimum transmission, where no data signal will be transmitted from the macro-eNB but only the most critical information required for the system also to provide support to legacy LTE UEs. Therefore, during ABS, the signals that are mainly sent are Common Reference Signals (CRS) and other obligatory system information. As a result, during subframes where the macro-eNB transmits ABS, the picocell is able to schedule UEs from a larger geographical area and that otherwise would experience too high interference from the macro layer. This basically implies that using ABS at macro-eNB makes possible to increase the offloading of traffic to the pico-layer. Moreover, this concept allows the use of higher values of RE for the picocells.

Network configuration of ABS muting patterns

TDM muting patterns are configured semi-statically and signaled between the macro and pico eNBs over the X2 interface. The ABS muting pattern in the macro-eNB is periodical with 40 subframes for the Frequency Division Duplexing (FDD) [30].

Regarding the Release 10 specification, the macro eNB supports techniques for the configuration of ABS muting patterns, being able to obtain the maximum overall system performance while considering also QoS requirements of individual UEs. An example of X2 signaling between the macro and pico eNB is considered in Figure 2.13, where it can be seen how

ABS muting pattern configuration is configured between both eNBs.

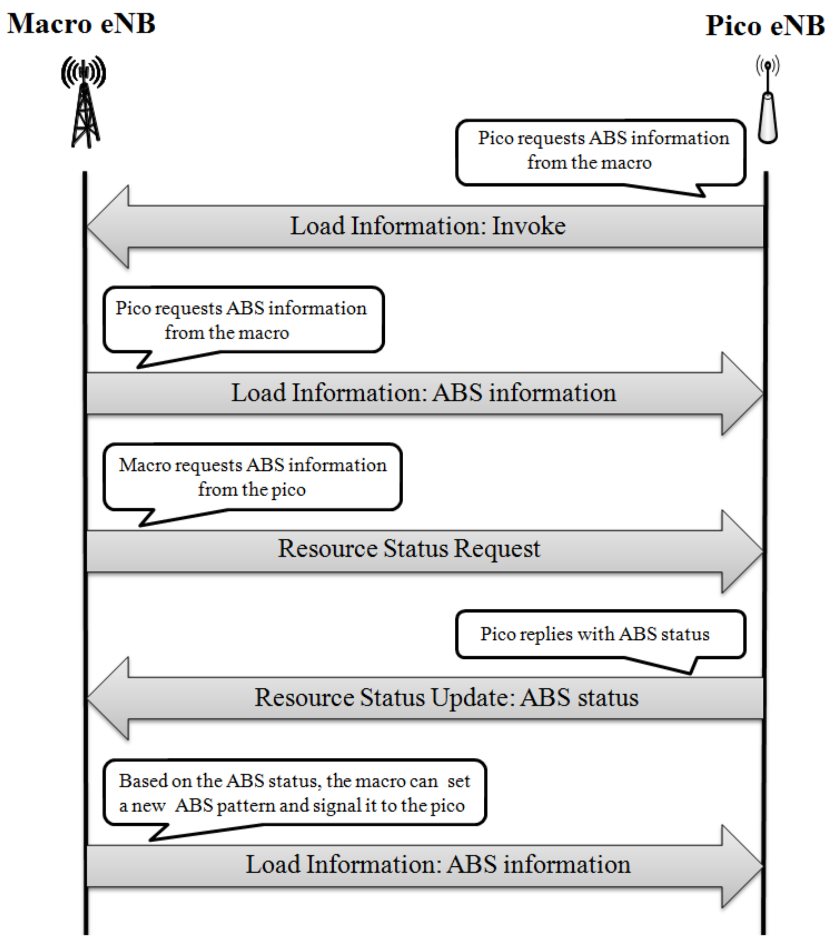

Figure 2.13: Example of X2 signalling for distributed coordinated adaptation of ABS muting pattern [9]

The macro eNB is supposed to act as the master that decides which subframes are to be set as ABS depending on different information regarding the cluster. Moreover, some improvements for the X2 application protocol are included in the Rel-10 specifications, which make easier the configuration of ABS muting pattern among eNBs [31].

As depicted in Figure 2.13, the pico eNB can send request ABS information from the macro eNB. In order to do that, a Load Information X2 message is sent with information element (IE) Invoke. The macro eNB answers by sending back another Load Information X2 message with IE ABS information, which includes the current ABS muting pattern used at the macro eNB. In addition, the macro-eNB can ask the pico to communicate the utilization of the allocated ABS resources by starting a Resource Status Reporting initialization mechanism. The pico eNB responds and provides the required information with a Resource Status Update X2 message with IE ABS status. In this message, different information can be sent to the macro eNB. It contains useful information about how much of the ABS resource is used at the pico eNB. Also, the pico eNB can inform in the ABS status the part of the allocated ABS resource which is not utilizable (e.g. because of interference from other macro eNBs). Based on the ABS status from the pico, the macro eNB has sufficient information to determine whether to use more or less subframes as ABS before deciding on a new ABS muting patter. If the macro eNB makes the decision of changing the ABS muting pattern, it informs the pico eNBs within the cluster by means of an ABS information message.

UE Measurements Restrictions

With the use of ABS muting patterns, more interference fluctuations occur in the network depending on whether a subframe is being used as ABS or normal. Therefore, it becomes more difficult for the eNBs to perform LA procedures (i.e. selection of MCS) as well as channel aware packet scheduling based on CQI feedback from UEs. As a result, the network needs to configure restricted CQI measurements for Rel-10 UEs such that they can send the reports corresponding to both normal subframes and ABS to the eNB. In Figure 2.14 an example about CQI reporting is illustrated. Note that, when the macro is transmitting an ABS, then the interference is minimum, so the SINR is higher. Furthermore, It can be seen that Rel-10 UEs can report different CQI measurements during ABS and normal subframes. On the other hand, Rel-8 and Rel-9 UEs do not support measurement restrictions, so the reported CQI is done based on an interference estimation averaged in time domain through a particular time window. These users may, hence, experience lower performance in network where eICIC is enabled. Finally, from the moment that the CQI information is reported from the UE to the eNB and the packet scheduler gets it, a certain delay is suffered because of the time that the physical layer needs to process the information. Therefore, with measurement restrictions, the last CQI report during ABS is applied at the eNB until a new update is available, and the same is applied for normal subframes.

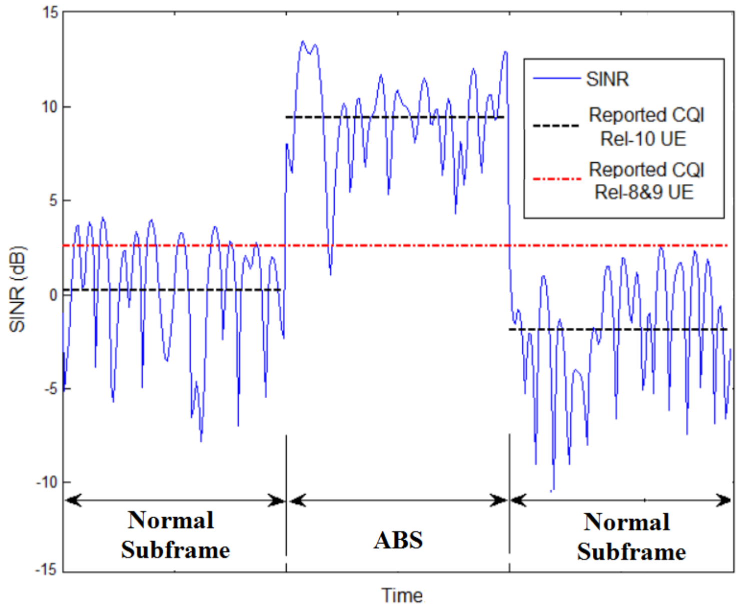

Figure 2.14: UE CQI measurement restrictions [9]

For the rest of the study, in order to fully benefit from eICIC techniques and obtain potential capacity gains, advanced LTE-Release 10 compliant UEs are assumed (i.e. they support different reporting of CQI for ABS or non-ABS subframes as explained above).

Chapter 3

System Model

In this chapter, the scenarios under investigation and its main features are described. Basically, two main scenarios for an outdoor environment have been tested according to the 3GPP proposals: macro - pico deployment and macro - RRH deployment, respectively [32]. Finally, the main considered measures to evaluate the performance are also mentioned.

3.1 3GPP Overview Simulation Assumptions

Even though the simulation assumptions carried out in this study will be commented in Chapter 5, in order to have a better understanding of this chapter, the main considerations taken into account for both macro + outdoor pico and macro + outdoor RRH deployments according to 3GPP simulation baselines are described as follows [32]:

- Scenario Configuration: 4b (i.e. 4 pico / RRH eNBs deployed per each macro-cell and placed in hotspots within a cluster[1]).
- Users distribution: 2/3 of the users are placed within the hotspot, the rest are uniformly distributed in the cluster.

Moreover, some of the considerations to be mentioned so as to better understand some of the techniques explained along this chapter are:

- Downlink RSRP-based cell selection is considered.
- Each UE is served only by one cell, which will be the serving eNB during the whole transmission for the considered UE.
- RE technique is enabled in order to offload the macro-cell. For a matter of simplicity, the RE value is the same one for each pico/RRH eNB in a cluster.

[1]When talking about 4 pico/RRH eNBs within a cluster, it means that the network is made up by 4 pico/RRH eNBs deployed within a macro-cell area. Therefore, a cluster makes reference to the area covered by the macro eNB.

3.2 Macro - Pico Scenario

A general illustration with the main elements of this first approach for the study can be seen in Figure 3.1.

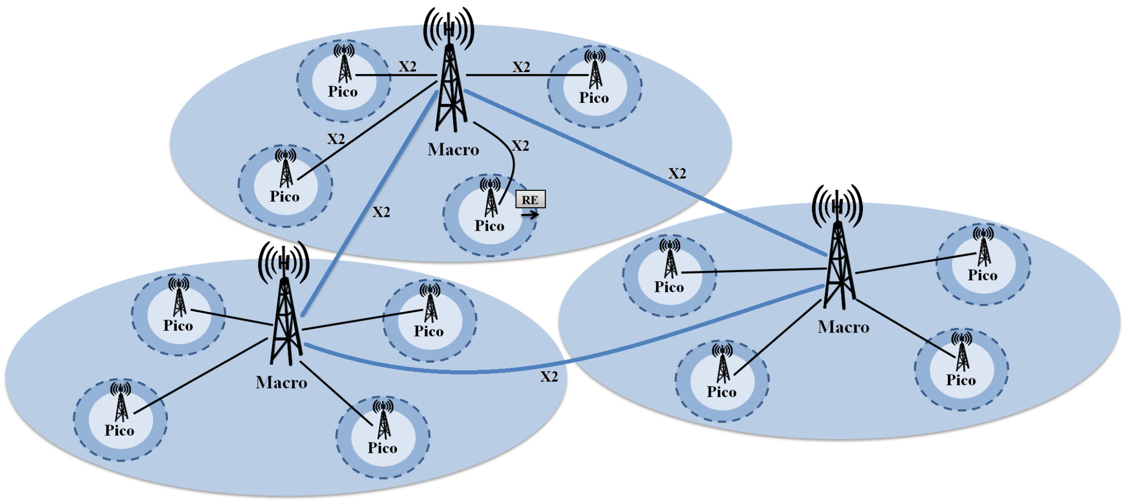

Figure 3.1: Macro - Pico Deployment

For the depicted scenario, several clusters are considered. Introducing pico eNBs within an existing macro cell network provides coverage improvements by offloading users from the macro to the pico eNB, taking advantage of the RE. This, however, added to the difference in the transmission power of the macro and the pico eNBs, will bring some inter-cell interference problems for users on the whole extended area of the pico eNB. These problems have to be solved in order to not suffer degradation in the overall system performance. In this first approach, interference is managed through the eICIC techniques described in Chapter 2. In order to achieve that, a loose coordination between macro and pico eNBs is carried out over the X2 interface. Also, UE measurement restrictions in Release 10 are performed as explained in Chapter 2.

In this first approach, a distributed architecture is used, where explicit modeling of major RRM algorithms such as packet scheduling, HARQ or LA, which have already been explained in Chapter 2, are performed at each eNB (i.e. each eNB makes them separately for the UEs under its coverage area) as shown in Figure 3.2. As a result, only light signaling and coordination between the macro and pico eNB is carried out through open access X2 interface. Therefore, this architecture is attractive for HetNet cases where the number of cells can increase significantly.

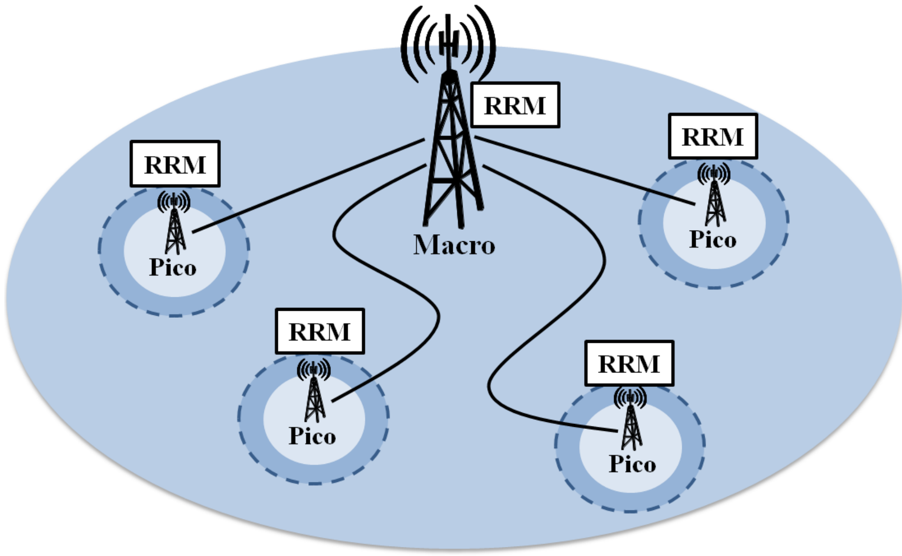

Figure 3.2: Distributed Architecture - Explicit RRM at each eNB

Furthermore, for this scenario, two different types of subframes are distinguished in the macro eNB: normal subframes (i.e. normal transmission) and mandatory ABS (i.e. only mandatory information is transmitted). The number of normal subframes and mandatory ABS in each frame is semi-static. Furthermore, for simplicity, we conceive all macro eNBs using the same ABS muting pattern.

In Figure 3.3 the basic muting coordination between macro and pico eNBs so as to take the proper scheduling decisions is shown:

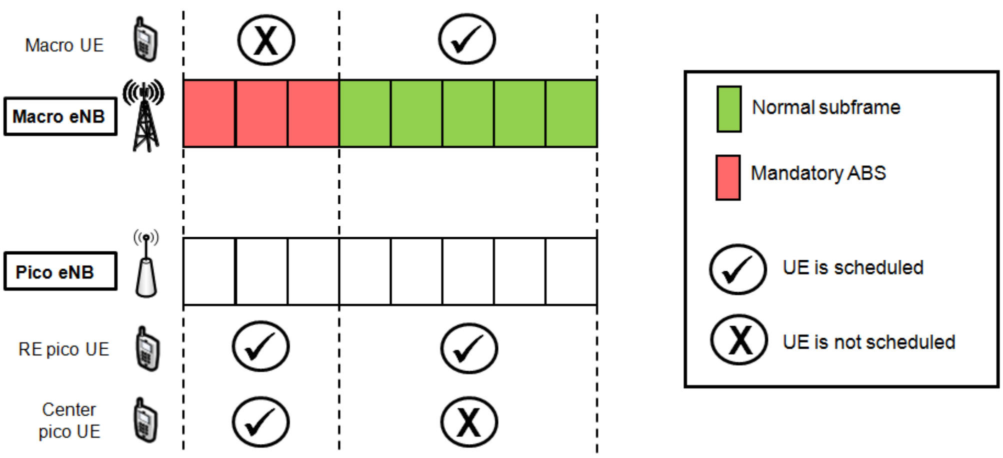

Figure 3.3: Basic muting coordination between macro and pico eNB

In order to benefit from eICIC, the following considerations are taken into account according to Figure 3.3:

- During normal subframes at the macro eNB, center pico UEs are desirable to be scheduled by the serving pico eNB. Also, macro UEs will be scheduled by the serving macro eNB.
- During mandatory ABS at the macro eNB, RE pico UEs are desirable to be scheduled by the serving pico eNB. Since those users receive highest interference from the macro eNB, they should only be scheduled when the macro cause less interference (i.e. during mandatory ABS). Center pico UEs can also be scheduled during mandatory ABS. On the other hand, macro UEs are not scheduled during these subframes.

3.3 Macro - RRH Scenario

In this second approach, a scenario combining macro and RRHs is considered as illustrated in Figure 3.4. The main motivation to deploy this second approach is to achieve an improvement over the eICIC techniques used in the macro - pico scenario by means of additional enhancements which will be detailed along this section.

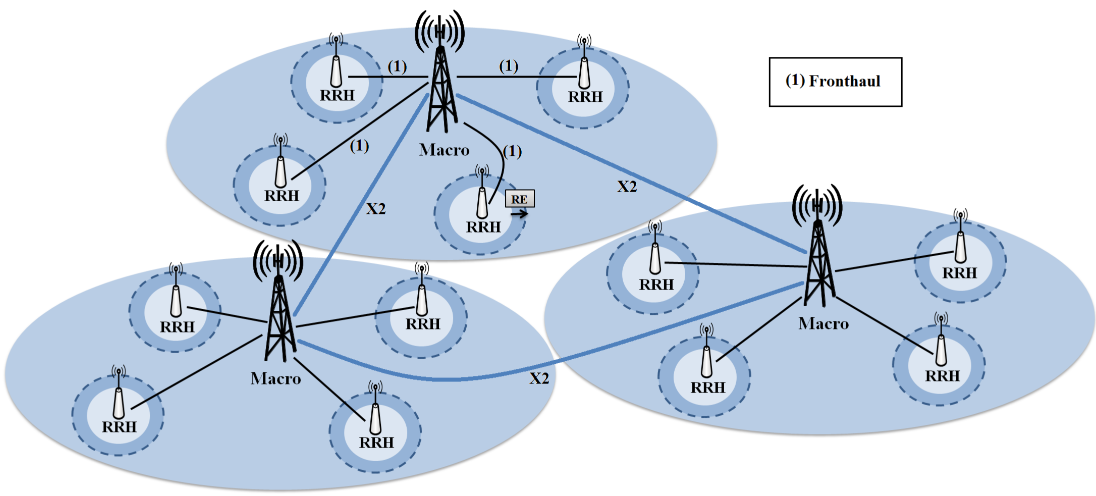

Figure 3.4: Macro - RRH deployment

Unlike the aforementioned scenario in Section 3.3, a centralized deployment is considered now. Thus, a macro cell acts as a central unit, being able to collect channel information from all UEs covered by the coordinating RRHs as well as baseband signals from them. The macro cell is also responsible for performing baseband signal processing and higher layer processing.

Some challenges of this architecture are related to the new associated communication links between the central unit and the eNBs. As mentioned, the macro cell and RRHs in the same cluster must be directly connected through a low-latency and high-capacity interface (i.e. fronthaul). Although there are some different options, a fronthaul based on optical fiber is suitable for RRH deployment, while macro cells are connected to each other via X2 interface. Only mandatory ABS configuration is exchanged among different macro eNBs i.e. ABS information through an X2 Load Information message including information about the currently used ABS muting pattern. Furthermore, no coordination between neighboring clusters is considered.

In this deployment, taking advantage of the high coordination among the macro cell and RRH by means of fronthaul, some important improvements can be obtained since all information regarding physical and MAC layers can be processed at the macro eNB. Therefore, RRM procedures are jointly performed at the macro cell for the different RRH in the cluster, as depicted in Figure 3.5:

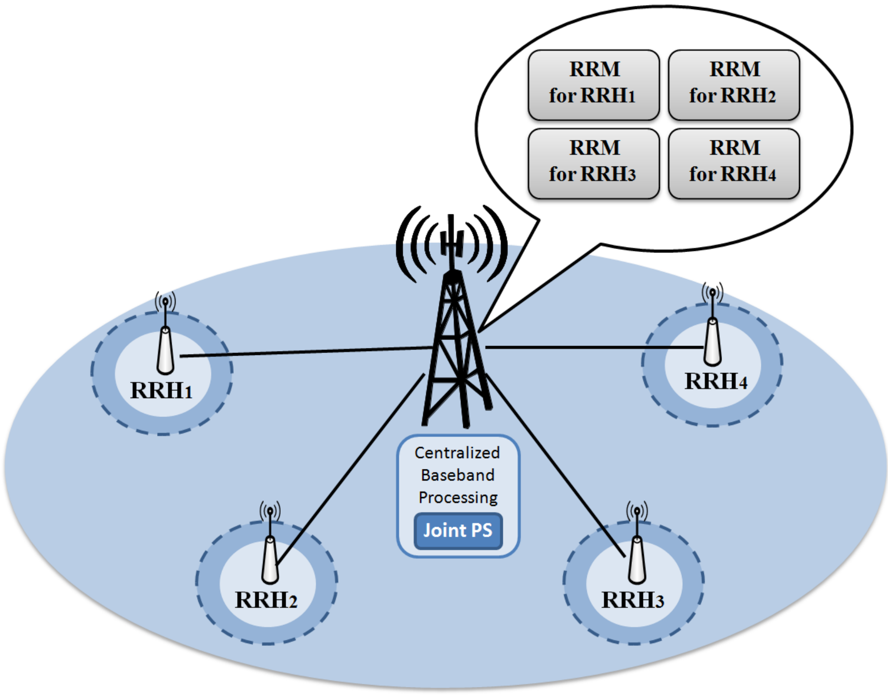

Figure 3.5: Centralized Architecture - Joint PS at the macro eNB

However, an important fact needs to be taken into account. For all practical purposes in this study, given that one UE is always served by the same eNB, the easiest way to carry out RRM algorithms such as PS, LA or HARQ is to make them independently at the macro cell and RRHs, similarly as we explained for the macro - pico deployment.

In order to manage the inter-cell interference in this scenario, since fast coordination can be done among the different eNBs via fronthaul, some enhancements are done and evaluated in relation to the eICIC techniques used for the first scenario. Basically, the focus is put on having fast ABS adaptation between the macro and RRH so as to achieve a more efficient interference management. In order to do that, a new kind of subframe is internally defined at the macro eNB. As a consequence, three different types of subframes are considered for this macro - RRH scenario, which are listed as follows:

- Normal subframe: normal data transmission from the macro eNB.
- Mandatory ABS: no data channels are transmitted from the macro eNB. It has the same behavior as it was explained in Chapter 2.
- Optional subframe: it can be used either as mandatory ABS or as normal subframe. This new kind of subframe is internally defined at the macro eNB with the purpose of making possible a faster ABS adaptation between macro and RRH. These optional subframes are the main key design of this scenario in order to improve the eICIC techniques used in the former deployment. Due to the fast adaptation, these subframes can be decided to be used as normal or ABS right before each optional subframe. For that purpose, a proposed algorithm will be further explained in Chapter 4.

In order to exploit further the concept of the optional subframes defined to improve the former approach, the ideal situation would be having all the subframes configured as optional, so there is more flexibility and, therefore, more efficient adaptation. However, at least one normal subframes and one mandatory ABS are needed in order to configure the measurements at the UE properly as will be explained later.

Moreover, the basic muting coordination among the macro eNB and RRH is described below as shown in Figure 3.6. Also, information about the different users that should be scheduled depending on the type of subframe used at the macro eNB is depicted.

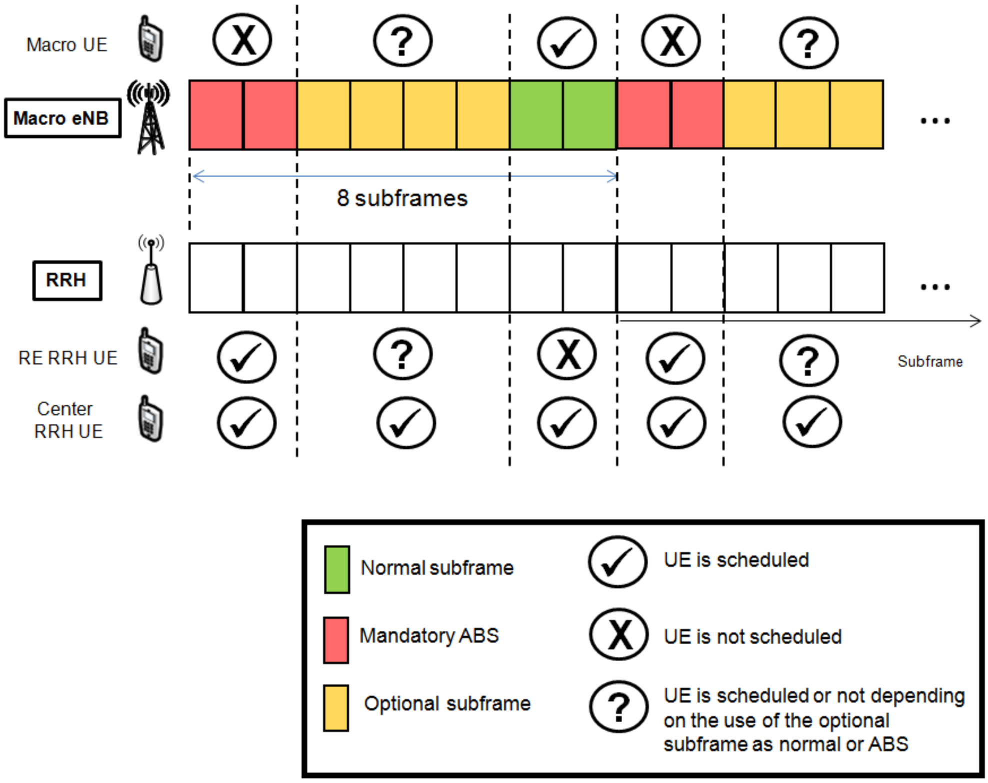

Figure 3.6: Basic muting coordination between macro and RRH eNB

According to Figure 3.6, some considerations for the proper operation between macro eNB and RRH should be mentioned:

- During either normal subframes or optional subframes configured as normal subframes in the macro eNB, center UEs are preferred to be scheduled by the serving RRH eNB. Also, macro UEs will be scheduled by the serving macro eNB.
- During either ABS or optional subframes configured as ABS in the macro eNB, RE RRH UEs are preferred to be scheduled by the serving RRH eNB since during those subframes the macro interference is minimized. In cases where those subframes cannot be used by UEs in the extended area, center UEs might compete for the remaining resources. Macro UEs are not scheduled in this case.

The number of optional subframes to be used in each frame is fixed, as well as the number of mandatory ABS and normal subframes. Moreover, in order to exploit the tight coordination between macro and RRH eNBs and decide the specific use of each optional subframe (i.e. being used as normal or mandatory subframe), a fast multi-cell scheduling algorithm will be performed in a subframe-basis, as will be further detailed in Chapter 4.

UE Measurement Restrictions

Identically to what it was explained in Chapter 2 for the macro - pico scenario, some measurement restrictions at the UE must be taken in this deployment.

Since CQI measurements are only taken during normal subframes or mandatory ABS, an important factor to be emphasized is that it is necessary to keep a minimum number of at least one mandatory ABS and one normal subframe in each frame in order to take appropriate measurements restrictions. As a result, RRH UEs can be correctly configured to carry out the RRH measurements at the proper subframes. The following CQI measurements are applied based on the type of subframe the macro eNB is using:

- RRH UE CQI measurements are taken separately for normal subframes and mandatory ABS. Regarding optional subframes, no CQI measurements are performed during these subframes. In this case, the proper CQI measurement is applied depending on whether the subframe is going to be used as normal or mandatory ABS. Basically, if the optional subframe is to be used as normal subframe, the last CQI of a normal subframe (CQI_{normal}) is taken and, if the optional subframe is to be used as mandatory ABS, the last CQI of a mandatory ABS (CQI_{ABS}) is taken.
- Macro UE CQI measurements are taken during normal subframes.

In order to fully understand how CQI measurements are taken for the different subframes, the following example is taken into account. Consider the macro eNB transmitting a frame configured with 2 normal subframes, 1 mandatory ABS and 5 optional subframes as depicted in Figure 3.7. The reported CQI measurements for normal subframe and ABS are also shown. These are calculated based on SINR measurements as it was explained in Chapter 2. During subframes 1 and 2 in the example, since they are set as normal subframe and ABS respectively, proper CQI measurements can be taken. For the case of optional subframes 3 and 4, two different options are possible:

- If the subframe is to be used as normal, then the CQI measurement is taken from subframe 1 (i.e. the last CQI requirements regarding a normal subframe).
- If the subframe is to be used as mandatory ABS, CQI measurement from subframe 2 is taken (i.e. the last CQI requirements regarding a mandatory ABS).

Later, the UE can take a proper CQI measurement for subframe 5 (normal). In the case of optional subframes 6, 7 and 8, similar procedure as commented above is followed: if the subframe is to be used as normal, the CQI measurement is taken from subframe 5; otherwise, CQI measurement from subframe 2 is used.

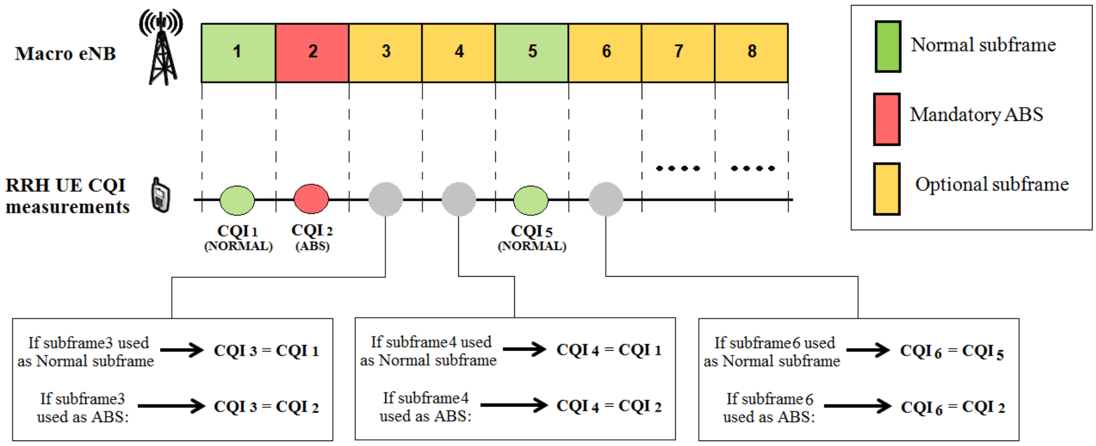

Figure 3.7: Example RRH UE CQI measurements

It is worth mentioning, however, that the real values of CQI taken during an optional subframe is not exactly the last CQI measurement during normal subframe or ABS, since other neighboring clusters should be considered, which can also generate some interference to the UE having influence in the SINR. Nevertheless, this interference is weak compared to the one from the cluster where the UE is, so an approximation considering the last CQI during normal subframe or ABS for the macro eNB in the cluster is made.

3.4 Key Performance Indicators

In this section, the different measures for the downlink side of the communication used in Chapter 5 in order to evaluate the performance of the tested scenarios are described.

Average User Throughput

A familiar definition of user throughput is the ratio between the amount of data (file size) and the time needed to be downloaded [25]. It is probably the most common metric to measure the system performance. Therefore, the average user throughput is defined by the summation of the user throughput in the network, averaged over the total simulation time.

Coverage and median

The coverage can be defined as the 5^{th} percentile of the user throughput, i.e. the minimum throughput achieved by the 95% of all simulated UEs as can be seen in Figure 3.8. Thus, this measure makes reference to the throughput achieved by those UEs having worst conditions, placed in the edge of the small cell. It will be the main focus in our study once we made clear in Chapter 2 the importance of improving the performance for the cell-edge UEs.

Similarly, the median is determined by the 50^{th} percentile of the user throughput. It is a useful measure when measures contain outliers.

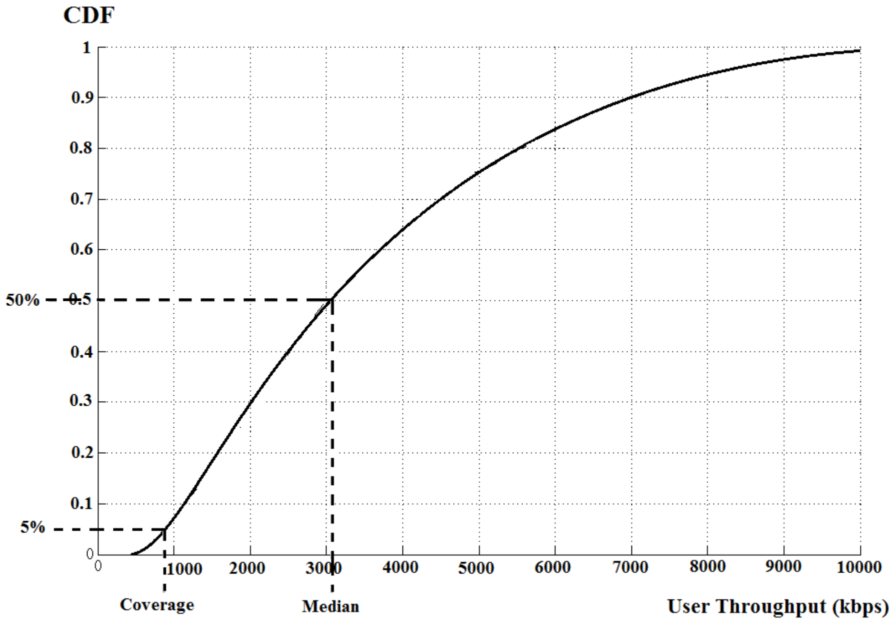

Figure 3.8: Example including the 5^{th} and 50^{th} percentile of the user throughput

PRB Utilization

A definition of the PRB utilization is the number of allocated PRBs by traffic during observation time divided by the total number of available PRBs during observation time. Moreover, mandatory ABS at the macro eNB are not considered to make this calculation.

The PRB utilization can give us a measure of how well resources are being allocated for UEs in the tested deployments.

Geometry Factor

The geometry factor is defined as the ratio between the intra-cell received power that one UE receives and the inter-cell interference plus noise averaged over fast-fading but not shadowing [19].

$$G - factor = \frac{P_S}{P_I + P_N} \tag{3.1}$$

where P_S is the average received power from the own cell, P_I is the average received power from all other cells (interfering cells) and P_N is the noise power. In this case, the average received power from interfering cells also considers the interference during ABS subframes.

The condition of the UE can be deduced from this value. Users with good conditions and low interference will have high G-factor values, while cell-edge users will have lower values.

Guaranteed Bit Rate (GBR)

The Guaranteed Bit Rate (GBR) specifies the minimum required bit rate experienced by one UE within a period of time. It will be the considered measure in order to evaluate QoS requirements in this study. Basically, a UE with GBR requirements will be considered as satisfactory UE if it is able to achieve the GBR, otherwise it will be regarded as unhappy UE.

Chapter 4

Load Balancing and Fast ABS Adaptation Solutions for HetNets

Along this chapter the proposed solutions for the optimal operation in the tested scenarios mentioned in Chapter 3 will be detailed. In addition, the selected scheduling metrics in order to support QoS requirements are also described.

4.1 Optimization of the RE and ABS muting ratio

As it was explained in Chapter 2, the use of RE and eICIC techniques for both balancing the load in the network and managing interference problems are the main features adopted in the heterogeneous network deployment under study. However, setting optimal values of RE and ABS muting ratio is not a trivial task. In order to explain further how these settings are chosen, the macro - pico scenario with different possible values of RE is considered.

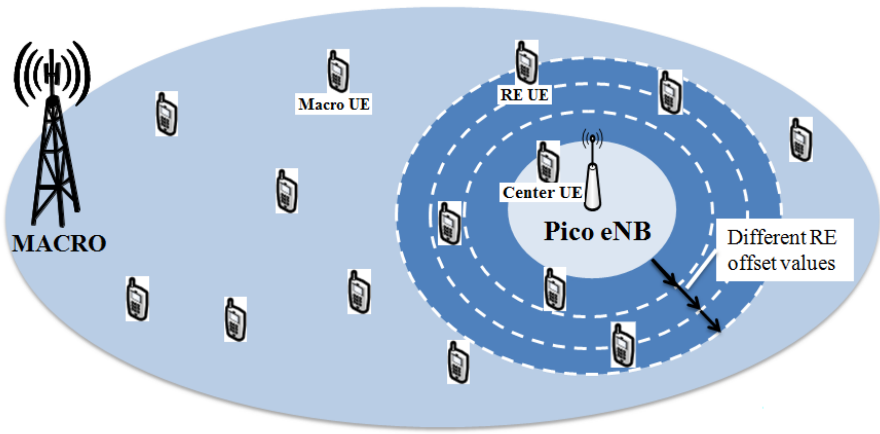

Figure 4.1: Macro - Pico Scenario with different RE values (RE increasing in the direction of the arrow)

As deduced from Figure 4.1, different levels of offloading at the macro eNB can be achieved depending on the RE. In fact, higher values of RE push more UEs to connect to the pico eNB and, therefore, a higher offloading of the macro eNB is achieved. This fact generates, however, more interference from the macro eNB to those UEs in the extended coverage area (i.e. RE pico UEs). Since RE pico UEs are only scheduled during mandatory ABS in the macro eNB, the number of mandatory ABS (i.e. TDM muting ratio) in the macro eNB should increase or decrease accordingly with the RE in the pico eNB and, consequently, with the number of cell-edge UEs in the cluster.

On the other hand, an inappropriate configuration of the RE and TDM muting ratio will cause degradation in the overall network performance. Imagine the case with an increased number of UEs in the cluster as the one illustrated in Figure 4.1. Since the number of UEs is high, more offloading from the macro to the pico eNB is recommended. In that case, a high value of RE is desirable to get the most of the pico eNB. Regarding the number of mandatory ABS, suppose that a low ABS muting ratio is defined in the macro eNB. In that case, even though we have offloaded the macro eNB, the new UEs connected to the pico eNB (cell-edge UEs) will barely be scheduled since there are not enough mandatory ABS subframes, resulting in an unsuitable situation which will cause a worst overall performance.

To sum up, it can be concluded that the optimal setting of RE at the pico eNB and ABS muting ratio at the macro eNB are closely related and depending on the actual load in the system, where the load is defined as number of UEs.

4.2 Fast Multi-Cell Scheduling

Given the centralized architecture in the macro - RRH scenario explained in Section 3.3, besides the use of RE to offload the macro eNB, fast coordination can be performed among the macro and RRH eNBs thanks to the use of fronthaul (i.e. low latency and high-speed communication links). In order to benefit from this fast coordination, the addition of the so-called "optional subframes" at the macro eNB makes possible a dynamic adaptation of the ABS muting ratio in contrast with the standard distributed architecture. This fact, however, brings also an important challenge. A dynamic method to make a proper use of this type of subframes must be defined.

Fast Load Balancing Algorithm

The main purpose of this algorithm is to balance the load dynamically between the macro and RE RRH users. In other words, try to use optional subframes as normal subframes or mandatory ABS depending on the load at the macro and RRH layer, which translates into an efficient offloading of the macro eNB and, therefore, an improvement in the overall performance. This decision is taken by the algorithm at the beginning of each optional subframe (i.e. subframe basis algorithm). For simplicity reasons, the load is here also defined as the percentage of users (macro and RE RRH UEs) in the cluster.

Firstly, some general aspects on a macro eNB subframe as well as the notation to be used in the rest of this section are illustrated in Figure 4.2. Moreover, the pseudocode used to make the proposed algorithm operate properly and achieve dynamic macro ABS adaptation is shown in Figure 4.3. For a matter of clarification, it is worth mentioning that the algorithm has been defined in an 8-basis frame for this work. However, it can be also extended for different numbers of subframes per frame.

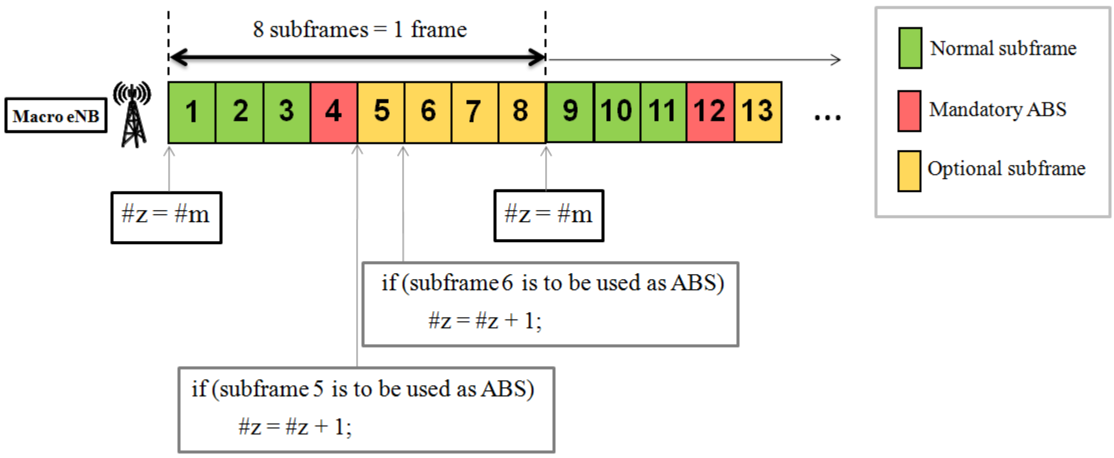

Figure 4.2: General aspects and basic macro eNB subframe notation to be used in the algorithm

```
while(new_subframe() )
    if(mod (new_subframe_id, 8) == 0)   // new frame
        #z = #m;
    end;
    if(new_subframe == optional)
        if( ( #macro/#total < (#t - #z)/#t ) && ( #RE/#total > #z/#t ) )
            use new_subframe as ABS;
            #z = #z + 1;
        else
            use new_subframe as normal;
        end;
    end;
end;
```

Check if the percentage of normal subframes so far is higher than the percentage of macro UEs

Check if the percentage of mandatory ABS so far is lower than the percentage of RE UEs

Figure 4.3: Pseudocode Fast Load Balancing algorithm at the macro eNB

Where:

- #m = number of mandatory ABS subframes.
- #z = number of subframes used as ABS in current frame (i.e. mandatory ABS plus optional subframes used as ABS so far).
- #t = 8 = total number of subframes in one frame.

Additionally, the notation employed according to the users is:

- #macro = number of macro users in the cluster.
- #RE = number of RRH users in the range extended area (i.e. cell-edge UEs). This value is calculated from the RSRP difference between the macro eNB and the serving RRH eNB.
- #total = total number of users in the cluster including macro UEs, RE RRH UEs and center RRH UEs.

As can be seen in Figure 4.2, the counter #z is reset with the number of mandatory ABS (#m) at the beginning of each frame. In addition, in each optional subframe the value of #z is updated if the subframe is to be used as ABS; otherwise it keeps its value.

From Figure 4.3, the number of users in the RE area of the RRH is needed. Indeed, a differentiation in the RRH eNB should be done to separate between UEs in its coverage area (i.e. center RRH UE) and UEs in the extended area (i.e. RE RRH UEs). For that purpose, the difference of RSRPs between the macro and RRH layer is measured. If a certain RRH UE receives more power signal from the macro eNB that from the RRH, then it is a RE RRH UE; otherwise it is a center RRH UE. In other words, for a certain UE, if $RSRP_{macro} > RSRP_{RRH}$, then that UE is RE RRH UE, otherwise it is center RRH UE. This distinction is illustrated in Figure 4.4:

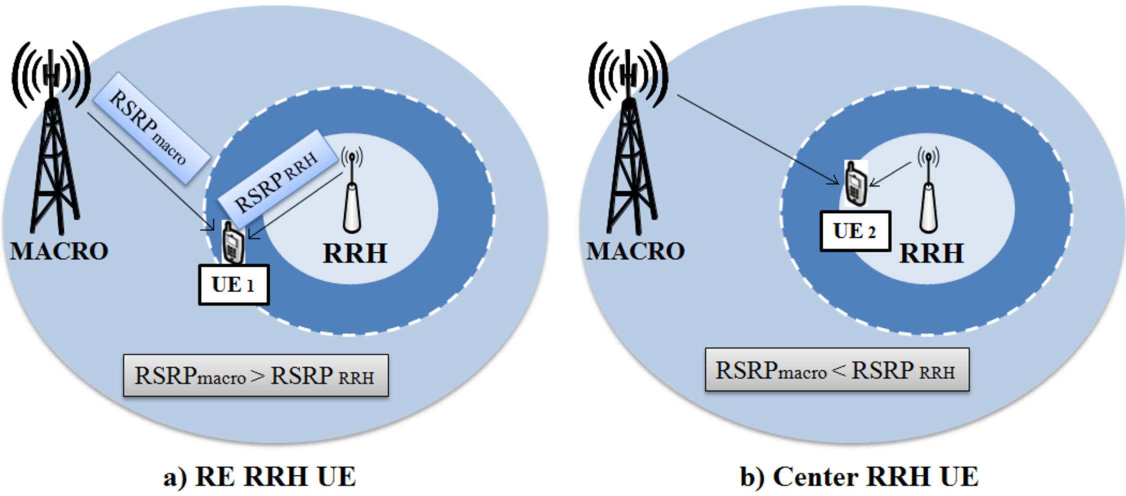

Figure 4.4: Differentiation RRH UEs based on RSRP measurements)

In summary, for the proper operation of the algorithm, the main steps followed at the beginning of each optional subframe are listed below:

- The scheduler evaluates the load at the RRH layer, i.e. the percentage of RE RRH UEs in the cluster.
- The scheduler evaluates the load at the macro layer, i.e. the percentage of macro UEs in the cluster.
- Based on the load measurements, a decision about whether there is more load in the macro or in the RRH layer is made. Basically, in the case there is more load in the macro layer, then the optional subframe should be used as normal subframe; otherwise, the optional subframe should be used as mandatory ABS.
- Concretely, as depicted in Figure 4.3, an optional subframe will be used as ABS if the following two conditions are accomplished:
  - The percentage of normal subframes so far is higher than the percentage of macro UEs in the cluster.
  - The percentage of mandatory ABS subframes so far is lower than the percentage of RE RRH UEs in the cluster.

In case that these both conditions are not achieved, the optional subframe will be used as normal subframe.

By doing so, the algorithm is able to assign as many mandatory ABS or normal subframes as percentage of RE RRH UEs or macro UEs, respectively.

Based on the explanation given in this section, an example is considered in order to see how the algorithm would work to assign the different optional subframes: a cluster with 6 macro UEs, 4 RE RRH UEs and 2 center RRH UEs is supposed. In that case, there are 50% macro UEs and 33% RE RRH UEs in the cluster. In addition, the current frame is set as depicted in Figure 4.2, i.e. 1 mandatory ABS, 3 normal and 4 optional subframes. Therefore, in order to balance the load, two of the optional subframes will be used as ABS to serve the RE UEs during 37.5% of the time, i.e. time when ABS is used.

On the other hand, another example having one cluster with 6 macro UEs, 1 RE RRH UE and 5 center RRH UEs is considered. There are, therefore, 50% macro UEs and 8.3% RE RRH UEs in the cluster. Moreover, the same configuration of the current frame is considered (i.e. 1 ABS, 3 normal and 4 optional subframes). In this case, all the optional subframes will be used as normal subframe, since only one mandatory ABS is enough to serve the RE RRH UE in the cluster during 12.5% of the time.

With these two examples, it has been fully clarified how the algorithm self-adjusts to load conditions.

4.3 QoS - aware Packet Scheduling

The PF metric explained in Chapter 2 does not explicitly consider user's QoS requirements in order to allocate resources to them. Hence, in this study some modifications have been proposed to enhance the QoS-awareness of the scheduler. From now, the GBR is the considered QoS parameter to be accomplished for the UEs.

The explanation given in Chapter 2 regarding the packet scheduling through a decoupling between the time and frequency domain can be also extended to this section as illustrated in Figure 4.5. In this case, GBR - aware packet schedulers can be used in both TD and FD.

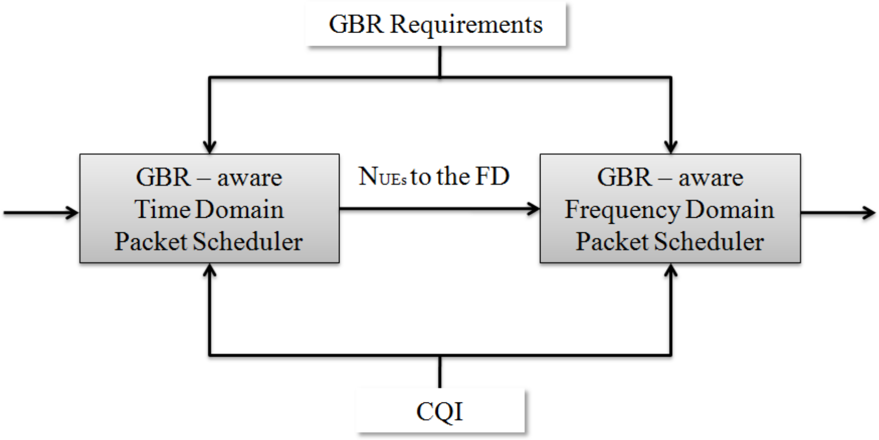

Figure 4.5: GBR - aware packet scheduler design

It is worth mentioning that, unlike happened in homogeneous networks with only macro eNBs where there could be a large number of UEs per cell, now the addition of small cells within the macro cell area makes possible some offloading from the macro eNB to the small cell and, therefore, the number of UEs per cell is quite lower. In fact, for the rest of the study, since the number of active UEs in the cell will not be great enough compared to the number of UEs passing to the FD N_{UEs}, the influence of the TDPS decreases, being even deactivated when the number of active UEs is lower than N_{UEs}. Thus, the focus will be only made on the FD in order to guarantee the GBR for the UEs, not making emphasis on the TD.

Among the different FD schedulers which could provide GBR fulfillment, a GBR - aware scaling factor w_{GBR} is usually applied to the main scheduling metric. Assuming the PF metric as the main scheduling metric, the GBR - aware metric for the user n on the PRB k would have the following formulation:

$$M_{k,n}^{GBR} = M_{k,n}^{PF} \cdot w_{k,n}^{GBR} = \frac{\hat{r}_{k,n}(t)}{R_n(t)} \cdot w_{k,n}^{GBR} \tag{4.1}$$

where t denotes the current scheduling interval, $\hat{r}_{k,n}(t)$ is the instantaneous achievable throughput of user n on PRB k, $R_n(t)$ denotes the past average delivered throughput to user n until TTI t, and $w_{k,n}^{GBR}$ is the GBR-aware scaling factor of user n on PRB k.

The past average delivered throughput to user n until TTI t in expression (4.1) is calculated recursively as follows [33]:

$$R_n(t) = (1 - \frac{1}{N_n}) \cdot R_n(t-1) + \frac{1}{N_n} \cdot r_{k,n}(t) \tag{4.2}$$

where N_n denotes the memory of the filter and it is kept constant during all simulation time in this study. Also, $r_{k,n}(t)$ is the actual confirmed throughput transmitted to the UE during TTI t (e.g. a user that is not currently being scheduled has $r_{k,n}(t) = 0$).

The filter length N_n should be properly set based on the session time of the user and, therefore, it is related to the maximum time for which a certain user can be without being served. As a general rule of thumb, N_n should be set low enough such that the past averaged throughput converges relatively quickly i.e. within 1/4 - 1/3 of the user session time, and large enough in order to average over fast fading. For the simulations regarding this work, a fix value of N_n equal to 400 TTIs (i.e. 0.4s) has been set which appeared to be good compromise between the two considerations mentioned above.

Furthermore, the initial value of the past average throughput for a user n $R_n(0)$ has to be carefully configured and depending on whether there are users with certain GBR requirements or not. First, if a value of $R_n(0) = 0$ is chosen, then the classical "divide-by-zero" issue occurs and when a UE arrives to the system, it has too high priority, taking a long time until the value of R_n starts to converge. On the other hand, it is not recommended a very high value of $R_n(0)$ either since, in case it is not a good estimation, it will also take a long time until it converges. With these two constraints and for the chosen value of N_n=0.4s, $R_n(0) = 128$kbps has been seen as a good estimation for non-GBR UEs, while $R_n(0) =$ GBR is set for the case of UEs with GBR requirements.

Now, according to the GBR-aware metric in (4.1), in addition to the channel conditions and the achieved throughput in the past, the scaling factor is also taken into account for the user to be scheduled. Therefore, the higher the scaling factor is for user k, the more likely is the user to be scheduled. Unlike happened when using the PF scheduler described in Chapter 2, now the desired goal will be to determine the scheduling metrics as much as possible by the GBR requirements rather than by the channel quality.

Different packet schedulers have different ways to express the scaling factor. For this work, among the various FD GBR - aware packet schedulers, the PF scheduler with Barrier Function family (PF - B) has been selected [10] [34] [35].

4.3.1 PF PS with Barrier Function

The family of the Barrier function schedulers includes different variants, which aim at scheduling all the UEs according to their GBR requirements. In particular, UEs will be applied either a penalty or advantage depending on whether they exceed or fall below their GBR, respectively [10] [34].

The PF-Barrier schedulers make use of a negative exponential barrier function as scaling factor $w_{k,n}$ which depends on the difference between the delivered throughput and the required GBR, $R_n(t)$ - GBR_n. Therefore, the scaling factor $w_{k,n}$ grows fast when $R_n(t)$ becomes smaller than GBR_n in order to avoid $R_n(t) < GBR_n$ situations. Otherwise, when $R_n(t) > GBR_n$, the scaling factor decreases since the user has already fulfilled its GBR.

The barrier function scheduler used for this study has the following scheduling metric [34]:

$$M_{k,n}^{PF_B} = \begin{Bmatrix} \frac{\hat{r}_{k,n}(t)}{R_n(t)} \cdot (1 + \alpha \cdot e^{-\beta(R_n(t) - GBR_n)}), & GBR_n > 0 \\ \frac{\hat{r}_{k,n}(t)}{R_n(t)}, & GBR_n = 0 \end{Bmatrix} \tag{4.3}$$

where α and β are empirical parameters that need to be properly chosen.

From (4.3), it can be deduced that the weight added to the PF metric is:

$$w_{k,n}^{PF_B} = \begin{Bmatrix} (1 + \alpha \cdot e^{-\beta(R_n(t) - GBR_n)}), & GBR_n > 0 \\ 1, & GBR_n = 0 \end{Bmatrix} \tag{4.4}$$

The scale and steepness of the barrier function can be controlled by these empirical parameters α and β, respectively. Consequently, by adjusting their values, the influence of the QoS scaling factor can be appropriately changed over the PF factor in the scheduling metric, allowing different balances between the radio performance and the QoS performance of the scheduler [35].

The idea in order to properly choose α and β is achieving a value of the weight dominant enough relatively to the PF factor when a UE requires a certain GBR over UEs without GBR requirement.

Impact when varying β

The value of β affects the steepness of the barrier function. In Figure 4.6, the GBR weight of the barrier function versus (R-GBR) is illustrated in the range [-GBR:+GBR], where the negative values mean that the user is exactly that amount below the desired GBR and the positive values mean that the user is achieving a bit rate that higher than the desired GBR. Moreover, three different values of β have been chosen with a fixed value of α=1.25. The GBR considered in this example is 2Mbps.

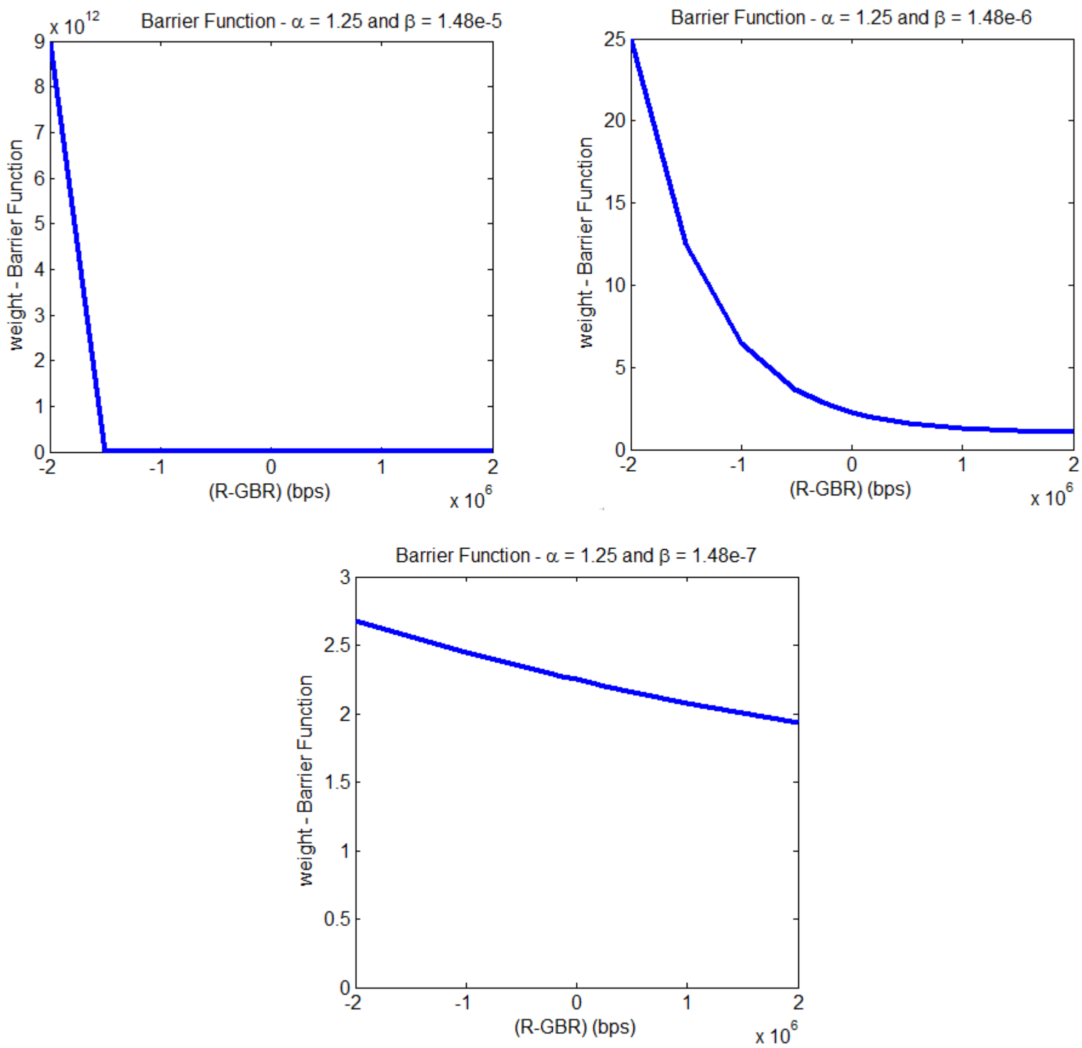

Figure 4.6: Effect of β in the barrier function scaling factor (α=1.25))

As Figure 4.6 shows, by increasing β the scaling weight get steeper and more priority is given to UEs lacking of the desired bit rate. In this case, the scheduling metric is mainly given by the GBR requirements rather than by the channel quality. That will lead, however, to a lower average cell throughput. On the other hand, decreasing β the opposite explanation is valid: The scheduler tends to behave closely to the PF scheduler.

Impact when varying α

The value of α affects the scale of the barrier function. In Figure 4.7, the barrier function is now represented for three different values of β versus (R-GBR) with a fixed value of $\beta = 1.48 \cdot 10^{-6}$. Again, the desired GBR is 2Mbps.

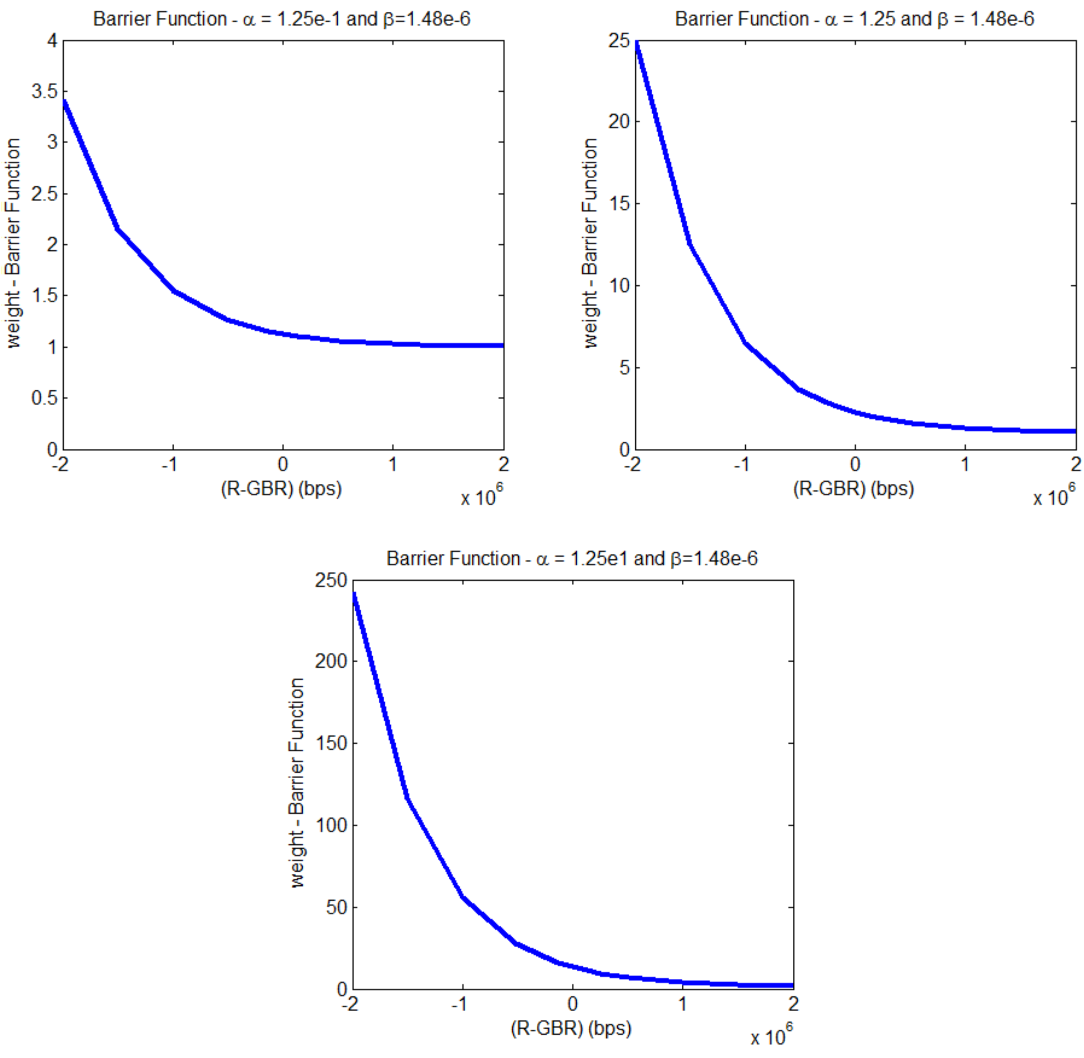

Figure 4.7: Effect of α in the barrier function scaling factor ($\beta = 1.48 \cdot 10^{-6}$))

In this case, it can be seen that by varying α the scale also does, while the shape of the curve remains similar. Higher values of α results in higher values of the weight factor over the PF factor, leading to a lower cell throughput.

For the rest of the study and based on simulations, the values of α and β have been set according to the two following selected values of the scaling factor depending on whether a user has achieved the desired GBR or not:

1. If $R_n = GBR_n \Longrightarrow w_{k,n}^{PF-B} = 10$: When the user has just fulfilled the GBR, a low scaling factor is set. However, it is still applied some weight in the order of 10 times the PF metric so as to not be damaged by possible fades in the instantaneous throughput.

2. If $R_n = \frac{GBR_n}{2} \Longrightarrow w_{k,n}^{PF-B} = 100$: In this case, the user is in a critical situation far below the GBR. Hence, a very high scaling factor is set to make him have higher scheduling metric and, therefore, priority to be scheduled.

From these two conditions and expression (4.4), the value of α and β can be obtained as follows:

1. If $R_n = GBR_n \Longrightarrow w_{k,n}^{PF-B} = 10 = 1{+}\alpha\cdot\ e^{-\beta\cdot 0} \Longrightarrow \boxed{\alpha = 9}$

2. If $R_n = \frac{GBR}{2} \Longrightarrow w_{k,n}^{PF-B} = 100 = 1{+}\alpha\cdot\ e^{-\beta\cdot(\frac{GBR}{2}-GBR)} = 1{+}9\ \cdot\ e^{\beta\cdot\frac{GBR}{2}} \Longrightarrow$
   $\Longrightarrow \beta = \frac{2}{GBR}\ \cdot\ \ln(\frac{99}{9}) \Longrightarrow \boxed{\beta = \dfrac{4.8}{GBR}}$

While the scale of the barrier function will always be the same (i.e. α does not change), the value of β will vary depending on the GBR in order to achieve always the same barrier function regardless of the GBR value.

Chapter 5

Analysis of the Results

In this chapter, the main results that give support to the concepts explained along this thesis are presented and analyzed. First, considerations about the simulated scenarios and traffic model considered as well as the main simulations assumptions are given. Later, the DL results for best effort traffic and traffic with GBR requirements are shown and explained.

5.1 Simulation Assumptions

Simulated Scenario

As mentioned in Chapter 3, two main scenarios are considered for this work according to the proposals given in [25]. For these scenarios, the network topology is composed by a traditional hexagonal grid of three-sector macro eNBs (i.e. one macro site), complemented with a set of 4 LPNs (pico eNB or RRH depending on the case) with omni-directional antennas placed in each macro-cell area. In line with the assumptions in [25], each LPN is assumed to have a higher user density in order to model traffic hotspots in a simplified manner. For the simulations results depicted along this chapter, a system layout consisting of 21 macro-cells (i.e. 7 macro sites) with wrap-around[1] and 4 pico / RRH eNBs as illustrated in Figure 5.1 is used.

[1]The wrap around technique is an alternative way to calculate the path loss and antenna gain between an UE and the eNB [36]

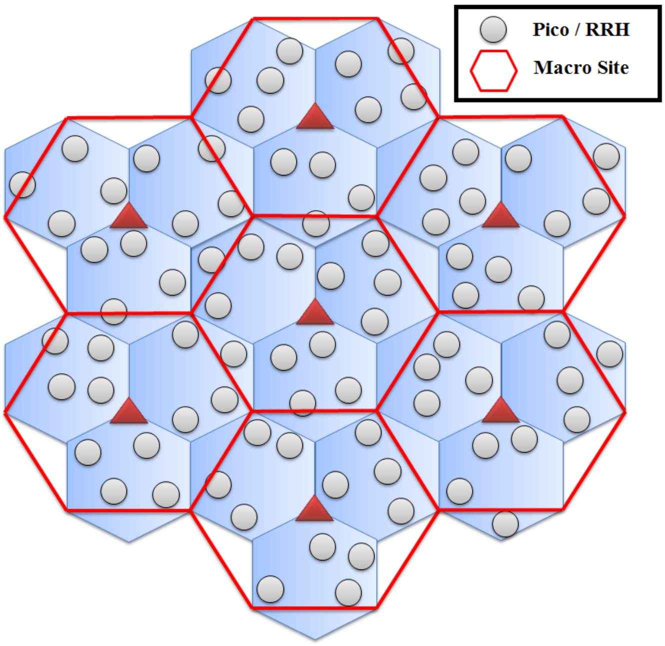

Figure 5.1: System Layout

Traffic Model
Along this thesis, different types of traffic models as well as call arrivals have been used so that different types of results can be provided. Firstly, two different UEs call arrival modes have been considered: full buffer UEs and finite buffer UEs:

- Full buffer: these simulations consist of a certain number of N_{RUN} runs of T_{FULL} seconds each. In each run, a fixed amount of N_{UE} UEs is dropped per cell, with a total of N_{TOT} UEs in the simulated network. These UEs have a "full buffer" (aka infinite buffer) in the eNB to download. Hence, these UEs last in the system from the beginning of the simulation until the run ends. Even though this case is not very realistic, it is useful to understand the main operation of the algorithms used and can be taken as starting point in the study. Since both the number of UEs and the time of each UE in the network are fixed, an easy analysis and interpretation of the results can be done.

- Finite Buffer: these simulations consist of only one run of T_{FIN} seconds. A number of N_{UE} UEs is dropped in the beginning of the simulation, and each UE has a finite payload of B_{FIN} Mb for each call. Once the payload has been successfully delivered to the UE, the call is terminated. Moreover, Poisson call arrival is used for this type of UEs. In that case, new arrivals of UEs at each cell follow a Poisson distribution.

The main simulation parameters regarding number of simulated UEs in the network as well as simulation time depending on the call arrival mode are illustrated in Table 5.1:

Full Buffer simulations	Number of Runs (N_{RUN})	5
	Simulation time per run (T_{FULL})	3s
	N_{UE} per macro cell area	30
	N_{TOT} UEs in the network	630
Finite Buffer simulations	Homogeneous Poisson call arrival	
	Average offered load per cell	10 - 70 Mbps
	Payload for each call (B_{FIN})	10 Mb
	Simulation Time (T_{FIN})	Different T_{FIN} depending on the load in order to achieve at least 2500 ended calls in the system

Table 5.1: Main parameters assumptions for full buffer and finite buffer simulations

Furthermore, two different traffic models have been tested so as to evaluate the performance of the system: Best Effort (BE) traffic and Guaranteed Bit Rate (GBR) traffic:

- BE traffic: this type of traffic model uses as many resources as available, trying to obtain the highest throughput and complete its transmission as fast as possible. Hence, users having good radio conditions and suffering from low interference will achieve higher throughput and will be served faster than those with poor conditions. Both full and finite buffer UEs have been used as BE traffic.
- GBR traffic: for this traffic model users have a certain GBR requirement to be fulfilled. Therefore, higher priority should be given to achieve the minimum required throughput for all UEs rather than to exploit the channel conditions, even though it will also be an important factor for the scheduling decision. In this case, only full buffer UEs have been analysed.

In conclusion, the main simulation parameters used along this work are summarized in Table 5.2:

Parameter	Setting / Description
Cell Layout	7 macro-sites (21 macro cells) with wrap-around [36]
Number of LPNs per macro cell	4
Macro to macro distance	500 m
Bandwidth (both macro or LPN)	10 MHz

Carrier frequency	2 GHz	
Sub-carrier spacing	15 kHz	
Number of sub-carriers	600	
Number of PRBs	50	
Transmission Power	Macro eNB	46 dBm
	LPN	30 dBm
UE Distribution	2/3 UEs close to the pico / RRH eNB; the remaining UEs are uniformly distributed within the macro cell area	
Subframe	1 ms (11 data plus 3 control symbols)	
Modulation and coding schemes	QPSK (1/5 to 3/4)	
	16QAM (2/5 to 5/6)	
	64QAM (3/5 to 9/10)	
1st transmission BLER target	20%	
HARQ modeling	Ideal chase combining with maximum 4 transmissions	
Antenna configuration	2x2 with rank adaptation and Interference Rejection Combining (IRC)	
Antenna gain	Macro eNB	14 dBi
	LPN and UE	0 dBi
Path Loss	Macro eNB to UE	$128.1+37.6 \cdot \log10(R[km])$
	LPN to UE	$140.7+36.7 \cdot \log10(R[km])$
Traffic Model	BE traffic simulations	Full Buffer
		Finite Buffer
	GBR traffic simulations	Full Buffer
eNB Packet Scheduling	Scheduling Metric	PF (BE Traffic)
		PF - Barrier Function (GBR Traffic)
	PF Filter Length (FDPS)	400 TTIs
	Initial R_n value	$R_n(0) = 128$ kbps (BE Traffic)
		$R_n(0) =$ GBR (GBR Traffic)
Link Adaptation and CQI reporting	Enabled	

CQI delay	6 ms
Cell Selection procedure	RSRP based
UEs Information	Rel-11 UEs: • Receivers with Cell-specific Reference Symbols - Interference Cancellation (CRS - IC) [37] [38] • Capability to report different CQI measurements

Table 5.2: General simulation assumptions for the tested scenarios

5.2 Best Effort Traffic Results

In this section, the study made for BE traffic is presented. For the rest of the section, the distinction between the following two strategies should be done:

- Static strategy: this case makes reference to the macro + pico scenario described in Section 3.2. Here, RE and eICIC techniques are used to improve the performance. From now, it is referred as "static" since the number of ABS does not have a fast adaptation, but it is fixed accordingly depending on the load in the network. It will be taken as a "reference", since some related studies have already been done for this way of managing interference as mentioned in Chapter 1.

- Dynamic strategy: this case makes reference to the macro + RRH scenario described in Section 3.3. In this case, the use of RE and eICIC techniques is also done, but proposing a more efficient manner to manage interference through the addition of the so-called "optional subframes" and the Fast Load Balancing algorithm described in Section 4.2, allowing a fast ABS adaptation. It is referred as "dynamic" since the number of ABS is dynamically configured depending on the load. This is the proposed solution to manage inter-cell interference supported by this work, versus the static strategy commented above.

Moreover, the performance of the distributed architecture with disabled RE and eICIC techniques will be shown so as to completely cover the different cases and notice the evolution in the system performance when adding different improvements to manage inter-cell interference.

Full Buffer UEs

Firstly, UEs with an infinite buffer to be downloaded are considered for the study. In this case, a fixed quantity of UEs remains in the system during the whole simulation time as was illustrated in Table 5.1. Therefore, since the number of macro and RE UEs (i.e. those in the coverage extended area) within the macro-cell area is constant, the muting ratio (i.e. number of mandatory ABS) at the macro eNB is also constant. The settings of the chosen number of mandatory ABS, normal and optional subframes as well as the RE for both strategies are summarized in Table 5.3, which have been found as the best configuration that maximizes the 5^{th} percentile UE throughput through simulations. The simulations run to tune up the dynamic algorithm and find its optimal settings are shown in Appendix B.

Static strategy	
Number of mandatory ABS	3
Number of normal subframes	5
RE	12 dB

Dynamic strategy	
Number of mandatory ABS	1
Number of normal subframes	1
Number of optional subframes	6
RE	14 dB

Table 5.3: Optimal settings of ABS and RE for the static and dynamic strategies - Full Buffer

First of all, the UE downlink throughput for all UEs in the network is shown in Figure 5.2 through the representation of the Cumulative Distribution Function (CDF). As illustrated, the overall performance of the UE throughput improves when using dynamic ABS adaptation in relation to the static adaptation. Further, both strategies show a better overall performance than the case without RE or eICIC.

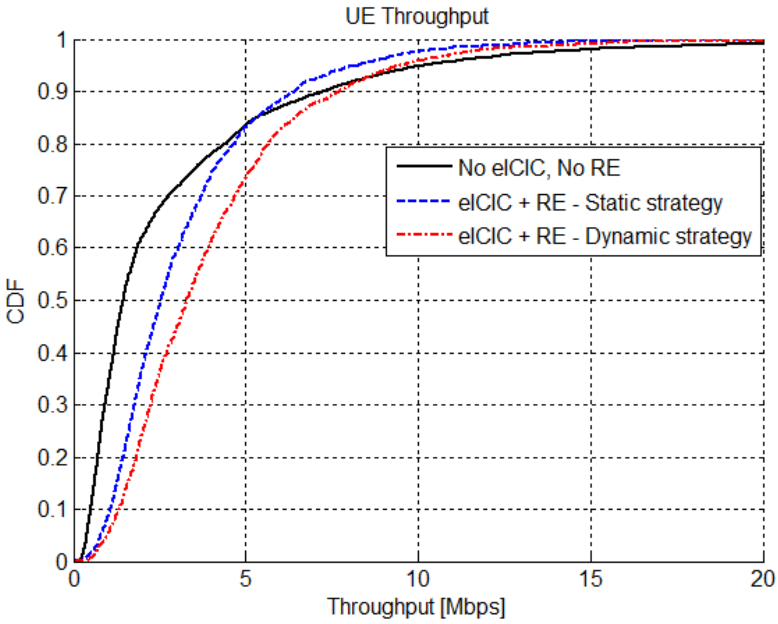

Figure 5.2: UE throughput for cases with and without RE and eICIC techniques

Even though the CDF of the UE throughput allows us to obtain overall conclusions and a better overall performance is observed when using eICIC techniques and RE, this study is specially focused on the 5^{th} and 50^{th} percentile of the UE throughput. Therefore, in order to perceive the throughput gain when using eICIC, the normalized coverage and median performance with respect to the no-eICIC case is shown in Figure 5.3.

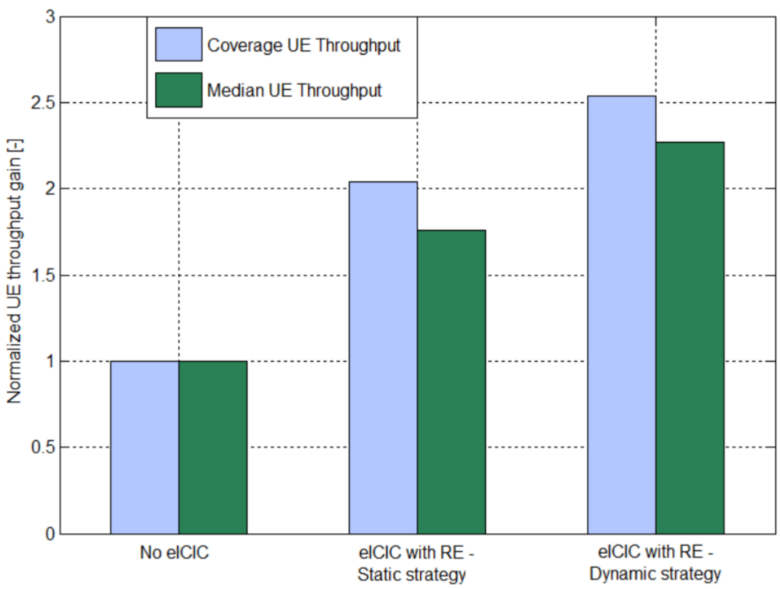

Figure 5.3: Normalized UE Throughput performance gain with/without eICIC

It is observed that the performance improvement from enabling RE and eICIC is in excess of around a factor 2 for the static strategy, while it increases to a factor 2.5 for the dynamic strategy. Aiming at giving a proper explanation to this throughput gain, it is worth mentioning the purpose of having a certain RE and using eICIC techniques to manage the interference. Basically, through the use of the RE more UEs are pushed to connect to the LPN layer, being able to achieve a higher offloading of the macro eNB compared to the case without RE. Consequently, a better performance in terms of UE throughput is also obtained. Table 5.4 illustrates the offloading rate from the macro eNB to the LPN for the three cases depicted in Figure 5.3. Indeed, for the static and dynamic case, a higher offloading of around 40% is achieved with respect to the no-eICIC and no-RE case.

Case	**Total Number of UEs**	**Macro eNB**	**LPN**	**Offloading**
		Macro UEs	**LPN UEs**	
No eICIC, No RE	630	389	241	38%
eICIC + RE - Static	630	166	464	74%
eICIC + RE - Dynamic	630	136	494	78%

Table 5.4: Offloading from the macro eNB to the LPN with/without eICIC and RE

Naturally, the achieved gain in terms of UE throughput would not be possible only using RE but no eICIC techniques, since the use of RE makes also more UEs to be under strong interference conditions from the macro eNB, which has to be managed to not generate degradation in the overall performance. In Figure 5.4 the CDF of the G-factor is represented for all UEs for the different cases, where an estimation of users' conditions can be deduced from the different G-factor values (the lower G-factor, the poorer conditions the user has). It can be observed that, as mentioned, the addition of RE results in more UEs suffering from strong interference (i.e. with lower G-factor) and, therefore, it is necessary to perform eICIC techniques to improve the performance.

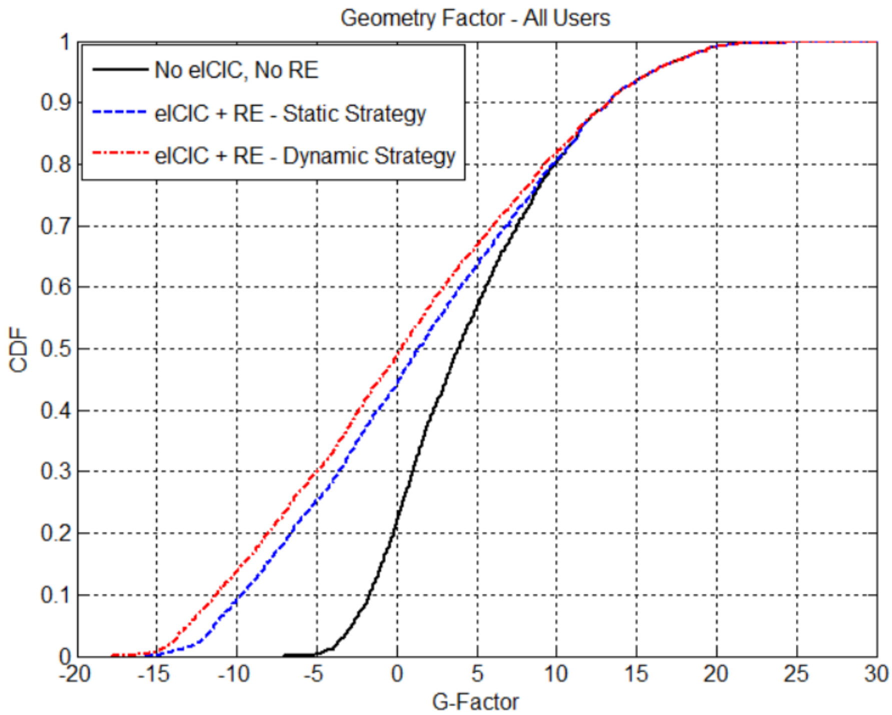

Figure 5.4: G-Factor for the cases with and without RE and eICIC techniques

Furthermore, once it has been commented the better performance when using interference coordination as well as achieving a higher offloading from the macro eNB to the LPN, now especial attention is paid on the two tested ways to manage the interference through eICIC techniques. For this purpose, Figure 5.5 depicts the coverage and median for the two studied options. As illustrated, a relative UE throughput gain using the dynamic strategy for ABS adaptation of around 25% and 30% in the coverage and median respectively is obtained over the static adaptation. A deeper analysis has to be done so as to further explain where these gains come from. When having HetNets with two different types of eNBs, a good way to proceed is to show and analyze the results for each layer individually to extract clearer conclusions.

The coverage and median for all UEs as well as for UEs connected to the macro and LPN eNB separately are shown in Figure 5.6, for the two different static and dynamic strategies.

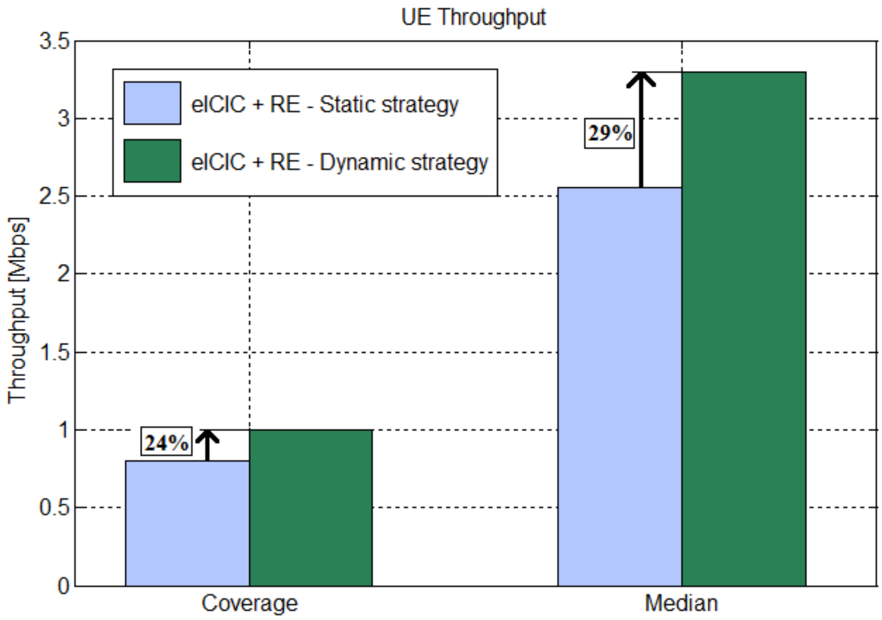

Figure 5.5: UE throughput performance when using eICIC: static and dynamic strategy

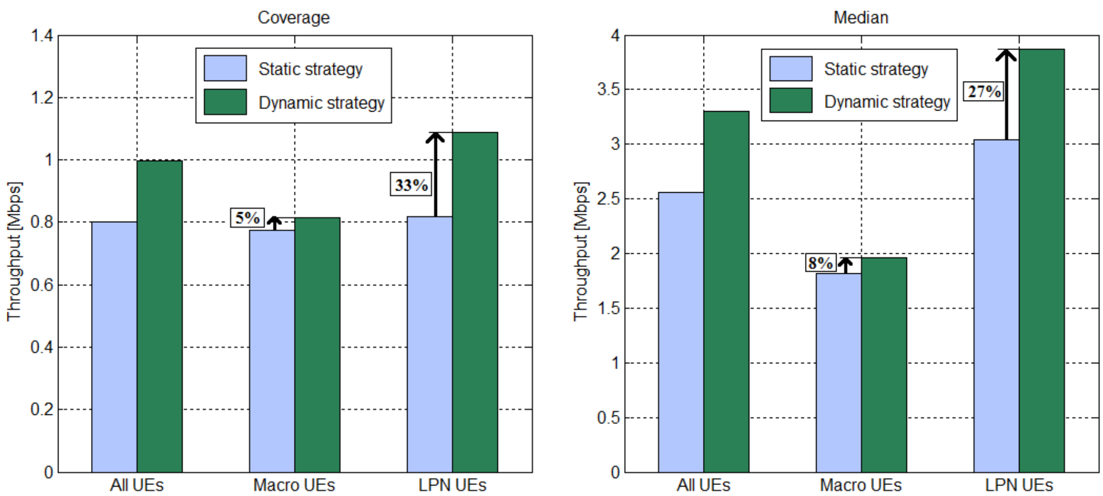

Figure 5.6: Coverage and median UE throughput for static and dynamic strategy: results for the whole network as well as for the macro and LPN layers separately

From Figure 5.6, it can be seen that most part of the gain is obtained in the LPN layer i.e. for UEs connected to the LPN (pico or RRH eNB depending on the case). While the macro layer behaves similarly for both strategies, the dynamic strategy makes the LPN layer obtain a better performance in terms of UE throughput of around 30% over the static case, not only for the UEs in worst conditions (i.e. coverage) but also for the median.

In this case, when full buffer UEs are used and, therefore, the number of UEs in the network is fixed, the dynamic algorithm is not indeed "dynamic", since it does not self-adjust dynamically to load conditions (the load is fixed), but it is fixed during the whole simulation. Hence, the improvement observed in Figure 5.6 is not due to the fast ABS adaptation compared with the static strategy. However, an important consideration must be taken into account to explain the better performance of the dynamic strategy. As illustrated in Table 5.2, 2/3 of the UEs are placed within the LPN, while the rest are uniformly distributed in the cluster. Hence, each macro-cell area will have specific load conditions (i.e. different number of UEs from one cluster to another), being convenient to have a different muting ratio in each macro eNB. This is not done for the static strategy where the muting ratio is accordingly chosen but, for a matter of simplicity, the same for all macro eNBs as mentioned in Chapter 3. On the other hand, with the dynamic strategy each macro is able to use a certain muting ratio, resulting in a better overall system performance.

To support the aforementioned explanation, Figure 5.7 illustrates the muting ratio distribution for the 21 different macro eNBs in the network for both static and dynamic cases. As depicted, for the dynamic strategy, even though most of the macro eNBs use 3 ABS (like the optimal muting ratio in the static case), there are some macro eNBs using more than 3 ABS. That means that, in the coverage area of those macro eNBs using more than 3 ABS, the number of RE RRH UEs is higher and, therefore, a higher muting ratio at the macro eNB is needed. Since RE UEs are only served during ABS, for those macro eNBs, a muting ratio with 3 ABS as used with the static strategy is not enough to serve all the RE pico UEs in those clusters, resulting in a worse performance as it was shown in Figure 5.6.

Moreover, it can be observed that 2 macro eNBs use 2 ABS in the dynamic strategy, meaning that in the cluster corresponding to those 2 macro eNBs, the number of RE LPN UEs is lower, not being necessary to use 3 ABS to serve them as in the static strategy. In that case, macro UEs within those two clusters will have worst performance using the static strategy since they are only served during normal subframes in the macro eNB. This is precisely the main reason of the small improvement of the dynamic strategy observed in Figure 5.6 also in the macro layer.

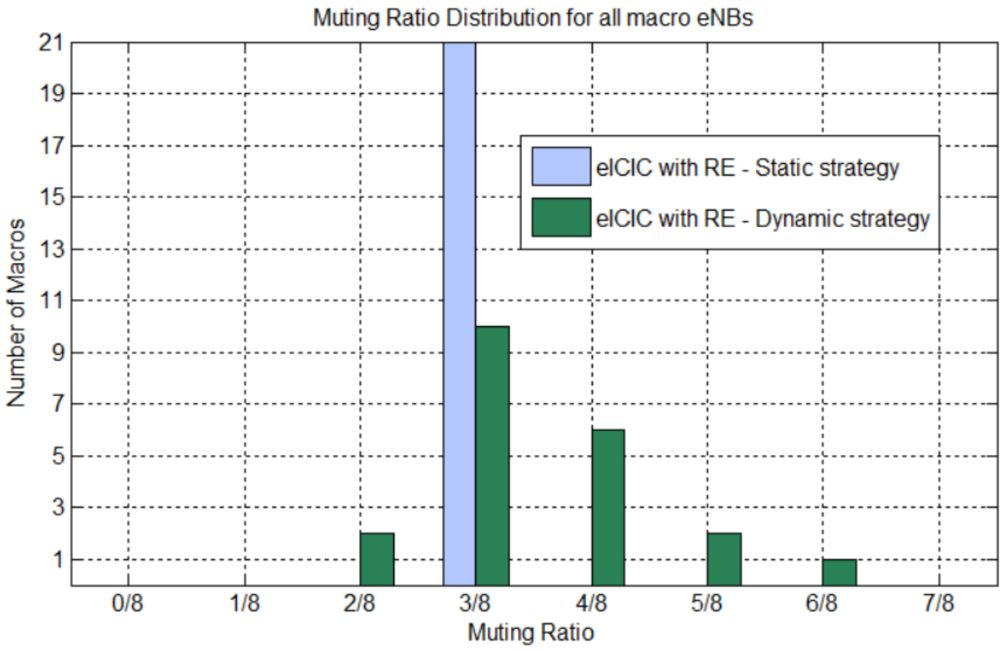

Figure 5.7: Muting Ratio distribution for the static and dynamic strategy

Finite Buffer UEs

In this section, UEs with a finite buffer are considered, meaning that now UEs have a certain time life in the network. The various simulation parameters regarding this type of UEs were shown in Table 5.1.

Unlike it was explained for the full buffer case, here the number of UEs in the network is not fixed, thus the settings for the RE at the LPN or muting ratio at the macro eNB varies depending on the load conditions (i.e. number of UEs in the network). For the dynamic strategy, 6 optional subframes are again used regardless the load in the network, which was demonstrated to be the optimal configuration. In order to analyze the results for the different investigated eICIC techniques, the 5^{th} and 50^{th} percentile UE throughput (i.e. coverage and median) are depicted in Figure 5.8. The UE throughput when neither RE nor eICIC techniques are performed is also plotted so as to fully cover the analysis for the different load conditions.

Moreover, the settings of RE for the dynamic case as well as the RE and number of mandatory ABS for the static case are shown for each offered load in Figure 5.8 (right graphic), which have been selected as the best configuration that maximizes the 5^{th} percentile of the UE throughput through simulations, similarly as how it was done for the full buffer case.

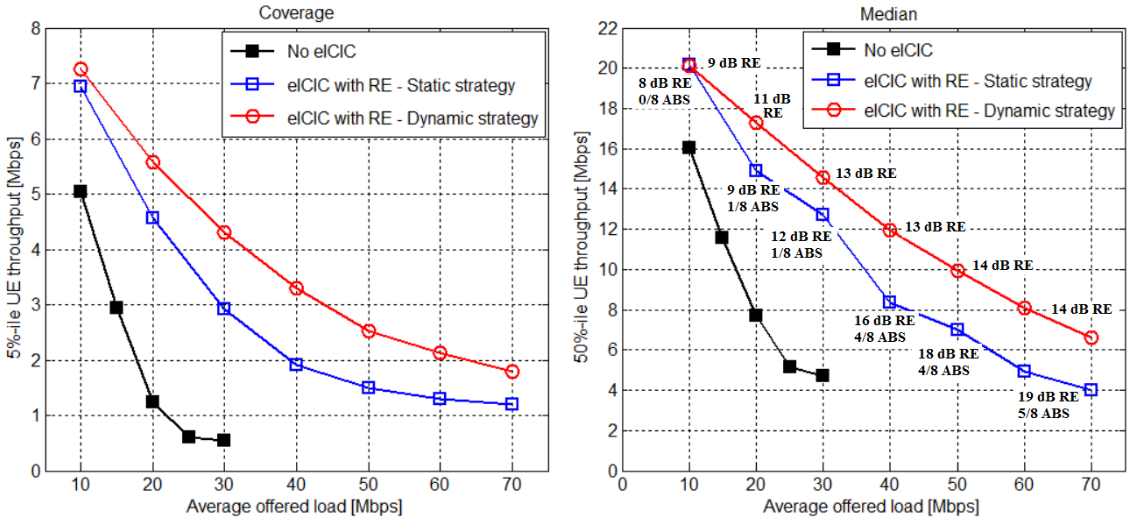

Figure 5.8: UE Throughput performance with/without eICIC versus the average offered load per macro-cell area.

Regarding the static strategy, at low offered load, there are very few UEs in the network and, therefore, only marginal inter-cell interference, so the system converges to not using ABS at the macro layer as illustrated in Figure 5.8. As the number of UEs in the network increases, the system converges to using more mandatory ABS at the macro eNBs and higher RE at the pico eNBs so as to get a higher offloading and inter-cell interference coordination. On the other hand, for the dynamic strategy only the optimal RE is chosen depending on the load, since the number of subframes to be used as normal or mandatory ABS are dynamically adjusted through the Fast Load Balancing algorithm explained in Chapter 4.

First, it can be observed from Figure 5.8 that, for the three depicted cases, when the offered load increases the UE throughput decreases for both the coverage and median. This result is completely coherent, since when the load in the network increases, there are more UEs sharing the same amount of resources and, therefore, the achieved throughput is lower.

Furthermore, such a remarkable improvement in the UE throughput is appreciated when using eICIC techniques compared to the case without eICIC. When RE and eICIC techniques are not enabled, once the number of UEs in the network increases (under medium or high load conditions) and both macro and pico eNBs start to have higher probability of transmitting, more interference is also generated for other cells, resulting in an important decadence in the UE performance. Enabling RE and eICIC techniques, relevant gains in the overall performance are achieved, especially with high offered load in the system and, therefore, more interference has to be managed.

Focusing on the 5^{th} percentile of the UE throughput, the achieved relative gains when using eICIC over no-eICIC are shown in Table 5.5. As illustrated, higher gains are obtained when the number of UEs in the network increases (i.e. lower UE throughput is achieved) in line with the explanation given above. Basically, Table 5.5 presents the percentage of extra load that the network can support when using eICIC, being able to achieve the same data rate that could be obtained without using eICIC. For instance, compared to the case with no-eICIC techniques, the 5^{th} percentile of the UEs could be served with a data rate equal to 5 Mbps even with around 80% and 140% (using the static and dynamic strategy, respectively) higher offered load in the network. In the same way, at high offered traffic, the gain from applying eICIC enables on the order of 120% - 250% higher offered load when using the static and dynamic strategy respectively, while still being able to serve the UEs with the same data rate.

Achieved UE Throughput	**Relative Gain 5^{th} percentile UE Throughput**	
	eICIC (static) vs. no-eICIC	eICIC (dynamic) vs. no-eICIC
5 Mbps	78%	140%
4 Mbps	88%	164%
3 Mbps	97%	190%
2 Mbps	117%	253%

Table 5.5: Relative gain of the 5^{th} percentile UE throughput with/without eICIC for different achieved UEs throughput

Once it has been explained the need of using interference management techniques to get a better system performance, the two studied ways of using eICIC are compared, trying to give an explanation of the higher UE throughput achieved with the dynamic strategy with respect to the static one as was illustrated in Figure 5.8. For this analysis, special focus is done on the worst condition UEs, which are represented by the 5^{th} percentile of the UEs.

From the left graphic in Figure 5.8, a higher UE throughput for all UEs is always obtained when using eICIC with the dynamic strategy over the static one. The relative gains for all UEs for different UE data rates are shown in Table 5.6. As depicted, the UE coverage gain is again higher as the offered load increases. For high load traffic in the network, the gain from using eICIC techniques with the dynamic strategy enables on the order of 50 - 60% higher offered load compared to the static one, while being able to serve the UEs with the same data rate, resulting in a notable improvement. In this case, the improvement of the dynamic case over the static one is higher than in the case with full buffer UEs. Effectively, when the number of UEs in the system is not fixed but varies depending on the offered traffic, it is still more important to do as fast ABS adaptation as possible to self-adjust to load conditions and fully benefit from eICIC techniques.

Achieved UE Throughput	**Relative Gain 5^{th} percentile UE Throughput**
	eICIC (dynamic) vs. eICIC (static)
7 Mbps	18%
6 Mbps	25%
5 Mbps	35%
4 Mbps	40%
3 Mbps	48%
2 Mbps	63%

Table 5.6: Relative gain of the 5^{th} percentile UE throughput with eICIC techniques for different achieved UEs throughput: static and dynamic strategies

Since now the number of UEs in the network is not constant, it is also interesting to analyze the muting ratio at the different macro eNBs for both strategies. For that purpose, the muting ratio distribution of two different macro eNBs for various offered loads varying from 10Mbps to 70Mbps per macro-cell area is shown in Figure 5.9 and Figure 5.10 for the static and dynamic strategies, respectively. From Figure 5.9, it can be appreciated that, with the static strategy, the macro eNB use the same muting ratio for a certain offered load, which is appropriately chosen as it was already depicted in Figure 5.8 (right graphic). Hence, since UEs arrive following a Poisson distribution and different macro eNBs may have different number of macro and RE pico UEs within its cluster, some macro eNBs may use more (or less) mandatory ABS than needed, resulting in a degradation of the overall performance. On the other hand, using the dynamic strategy each macro eNB makes use of a different muting ratio distribution as illustrated in Figure 5.10. It can be seen that, for a same average offered load, the macro eNB uses different number of mandatory ABS, achieving a fast adjustment of the muting ratio depending on the number of macro and RE RRH UEs in the macro-cell area.

In addition, the number of active macro and LPN UEs per cell is depicted in Figure 5.11. For the muting ratio distribution used in the dynamic case, the macro eNBs are applying most of the time the minimum muting ratio (1 over 8 mandatory ABS). In order to explain this fact, two different cases are distinguished:

- For low load conditions, both macro and RRH layers are empty most of the time as observed in Figure 5.11. Hence, the dynamic algorithm tends to use a small muting ratio.

- For high load conditions, there are more active UEs in the macro layers compared with the number of RE RRH UEs. Hence, the algorithm also tends to use a small muting ratio most of the time so that macro UEs can be scheduled.

Sometimes, however, it can be appreciated how the algorithm self-adapts and uses a higher muting ratio, meaning that for those cases the percentage of RE RRH UEs is higher than the percentage of macro UEs in the macro-cell area. This way, an efficient manner to allocate resources and schedule RE RRH UEs or macro/center RRH UEs only when needed is possible, bringing a remarkable improvement as a consequence.

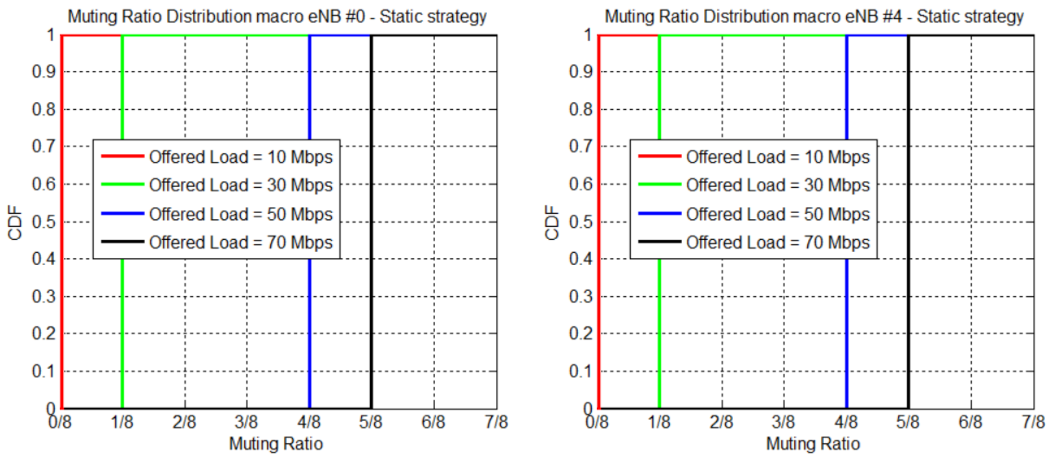

Figure 5.9: Muting Ratio Distribution for two different macro eNBs - Static Strategy

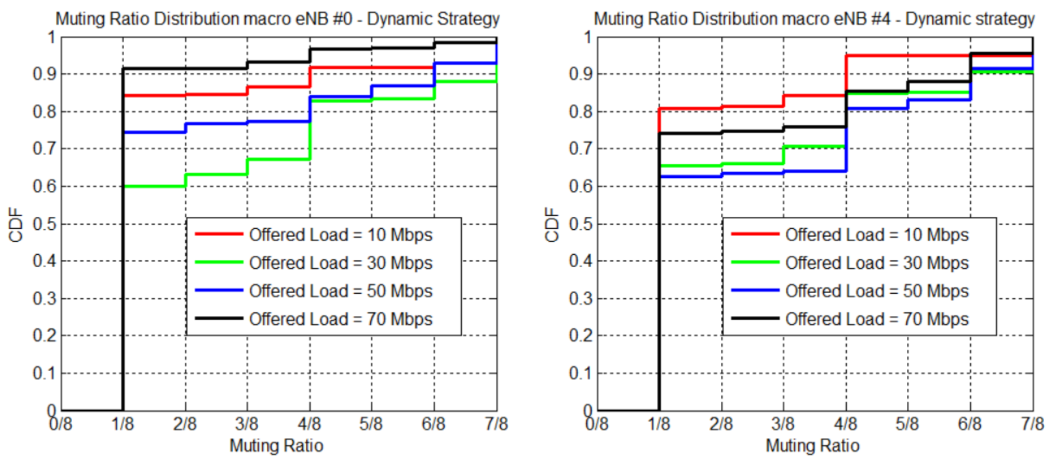

Figure 5.10: Muting Ratio Distribution for two different macro eNBs - Dynamic Strategy

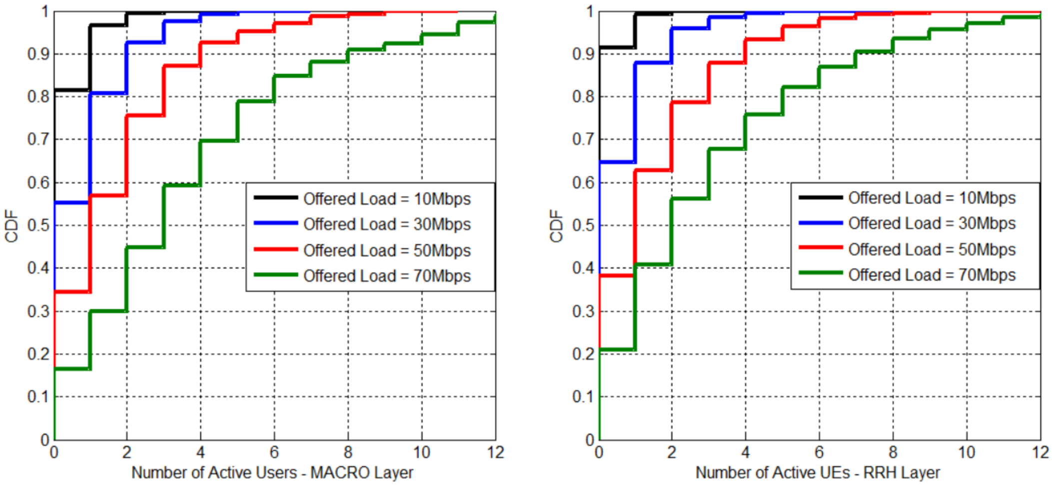

Figure 5.11: Number of Active UEs per cell - Macro and RRH Layer

5.3 GBR Traffic Results

In this section, the analysis of the results for UEs having certain GBR requirements is done. Since there are not former studies regarding GBR traffic in HetNets as mentioned in Chapter 1, a deep analysis is presented to notice the challenges that having UEs requiring a specific GBR put in HetNets scenarios, concretely in the macro - pico scenario. Now, it is important to observe whether the packet scheduler is able to operate properly and UEs can achieve the desired GBR or, on the other hand, there are some constraints to be considered. For the rest of the section, the FD PF Barrier Function (PF - B) scheduling metric explained in Chapter 4 is used.

Firstly, a simple macro - pico scenario with only one pico eNB per macro-cell area is considered for the analysis. Hence, the whole network is made up by 21 macro and 21 pico eNBs. Furthermore, eICIC techniques are carried out using the static strategy (i.e. fixed muting ratio at the macro eNB). In order to properly understand how the PF - B works, a distribution of only 2 UEs per macro eNB and 2 UEs per pico eNB is simulated (i.e. the minimum amount of UEs such that the eNB has a scheduling decision to take). For the study to be done correctly, both macro and pico layers will be analysed separately.

Based on simulations and analysing different clusters of the whole network individually, it has been noticed that, in order to fully cover how the PF - B operates, different cases has to be differentiated especially in the pico layer, depending on whether the UEs are in good or poor conditions[2] i.e. they are placed in the RE extended area or in the pico coverage area without RE:

a) Both UEs are in good conditions (i.e. both UEs are center pico UEs).

b) There is one UE in good conditions and one UE in poor conditions (i.e. one center pico UE and one RE pico UE).

c) Both UEs are in poor conditions (i.e. both UEs are RE pico UEs).

These three different cases are clearer illustrated in Figure 5.12.

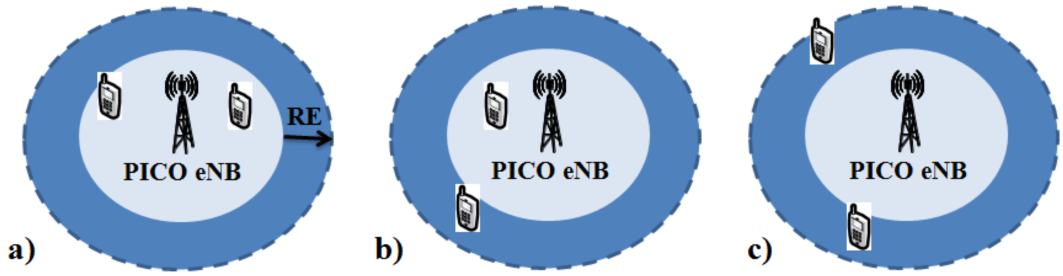

Figure 5.12: Different UEs distribution in the pico eNB: a) Both UEs in the pico coverage area, b) One UE in the pico coverage area and one UE in the extended area, c) Both UEs in the extended area

In summary, the procedure that has been followed in both macro and pico layers for the study of the PF - B when having GBR requirements is:

1) A simulation with a non-GBR aware scheduler (PF for the case) is run in order to get the values of throughput achieved by the two UEs connected to the macro and pico layer (e.g. TP_1 and TP_2, with $TP_1 > TP_2$).

2) Based on that, a certain GBR such that $TP_2 < GBR < TP_1$ is fixed for both UEs.

3) A simulation with the PF - B is run (i.e. GBR-aware scheduler) and it is analysed if the UE throughput for both UEs achieve the required GBR (i.e. $TP_1 \geq GBR$ and $TP_2 \geq GBR$). The parameters α and β of the PF - B have been accordingly chosen for the different GBR values, calculated as explained in Chapter 4.

[2]When talking about conditions of the UE, both radio condition and interference suffered from other cells are included. For simplicity, the G-factor of the UE is taken into account as estimation of the UE condition in this analysis.

In addition, the muting ratio at the macro eNB has also been selected to maximize the UE throughput depending on the number of macro and RE pico UEs in the cluster as illustrated in Table 5.7:

Case	**User Distribution within a cluster (4 total UEs per macro-cell area)**			**Muting Ratio Settings at the macro eNB**
	Macro eNB	Pico eNB		
	Number of Macro UE	**Number of Center pico UE**	**Number of RE pico UE**	
a	2	2	0	0 ABS
b	2	1	1	2 ABS
c	2	0	2	4 ABS

Table 5.7: Muting ratio settings for the different cases to be analysed

For the mentioned scenario, Tables 5.8, 5.9 and 5.10 illustrate the operation of the PF - B for the different cases in Table 5.7 and with UEs having certain GBR requirements[3] . Moreover, the GBR has been accordingly chosen depending on the difference between the throughputs of the UEs connected to the eNB. Besides the UE throughput, some relevant information is also shown such as the average PRB allocation and G-factor of both UEs, since it will be useful in order to clarify the PF - B operation for different UEs conditions.

CASE a)

MACRO LAYER						
User ID	G-factor (dB)	PF		GBR (Mbps)	PF - B	
		Throughput (Mbps)	Avg. PRB Allocation		Throughput (Mbps)	Avg. PRB Allocation
UE_1 (Macro UE)	12.91	16.11	25.4	12	13.23	21.28
UE_2 (Macro UE)	7.62	10.38	24.6		12.09	28.72

PICO LAYER						
User ID	G-factor (dB)	PF		GBR (Mbps)	PF - B	
		Throughput (Mbps)	Avg. PRB Allocation		Throughput (Mbps)	Avg. PRB Allocation
UE_3 (Center UE)	5.16	10.20	26.02	7.5	8.74	20.2
UE_4 (Center UE)	2.20	5.76	23.98		7.59	29.8

Table 5.8: PF - B operation for the macro and pico layer separately - Case (a): 2 macro UEs, 2 center pico UEs

[3]For the different tables, grey shaded cells make reference to UEs who have been able to fulfill the GBR.

CASE b)

MACRO LAYER						
User ID	G-factor (dB)	PF		GBR (Mbps)	PF - B	
		Throughput (Mbps)	Avg. PRB Allocation		Throughput (Mbps)	Avg. PRB Allocation
UE_1 (Macro UE)	6.62	8.18	24.56	10	10.11	31.19
UE_2 (Macro UE)	16.71	18.53	25.44		13.57	18.81

PICO LAYER						
User ID	G-factor (dB)	PF		GBR (Mbps)	PF - B	
		Throughput (Mbps)	Avg. PRB Allocation		Throughput (Mbps)	Avg. PRB Allocation
UE_3 (Center UE)	13.12	23.1	33.58	7	11.45	17.6
UE_4 (RE UE)	-5.02	4.92	16.42		7.15	32.4

Table 5.9: PF - B operation for the macro and pico layer separately - Case (b): 2 macro UEs, 1 center pico UEs and 1 RE pico UE

CASE c)

MACRO LAYER						
User ID	G-factor (dB)	PF		GBR (Mbps)	PF - B	
		Throughput (Mbps)	Avg. PRB Allocation		Throughput (Mbps)	Avg. PRB Allocation
UE_1 (Macro UE)	18.67	12.78	27.58	6	7.88	11.41
UE_2 (Macro UE)	-2.31	2.27	22.42		5.24	38.59
UE_1 (Macro UE)	18.67	12.78	27.58	4.5	9.85	14.91
UE_2 (Macro UE)	-2.31	2.27	22.42		4.93	35.09

PICO LAYER						
User ID	G-factor (dB)	PF		GBR (Mbps)	PF - B	
		Throughput (Mbps)	Avg. PRB Allocation		Throughput (Mbps)	Avg. PRB Allocation
UE_3 (RE UE)	-6.80	12.44	33.68	6	6.72	25.42
UE_4 (RE UE)	-9.67	3.87	16.32		5.08	24.58
UE_3 (RE UE)	-6.80	12.44	33.68	4.5	7.09	26.05
UE_4 (RE UE)	-9.67	3.87	16.32		5.01	23.95

Table 5.10: PF - B operation for the macro and pico layer separately - Case (c): 2 macro UEs, 2 RE pico UEs

In relation with the above obtained results, the analysis of the PF - B for the macro and pico layer can be done as follows:

Macro Layer
According to Tables 5.9 and 5.10, a proper behaviour of the PF - B can be observed, which corresponds to what it was explained in Chapter 4. Basically, both macro UEs are able to fulfill the required GBR. As illustrated, the UE who had a throughput lower than the GBR when PF metric was used is able to get a higher throughput when applying the PF - B scheduling metric and fulfill the GBR, at the expense of the UE who already fulfilled the GBR, who is also able to accomplish it.

Moreover, an important fact to be noticed is the column regarding the number of average PRBs allocated to each UE: the UE with TP $<$ GBR is allocated more resources than the one with TP $>$ GBR, in higher or lower scale depending on how far from achieving the GBR the UE is. For instance, in Table 5.9, UE_1 was allocated in average 24.56 PRBs using the PF metric, while it increased up to 31.19 when using the PF - B metric, allowing him to fulfill the GBR.

On the other hand, fulfilling the GBR is not always possible. As shown in Table 5.10, macro UE_2 is not able to achieve $TP_2 \geq GBR$ when GBR = 6Mbps. This fact is not surprising if we realise that the UE is in quite bad channel conditions (G-factor $<$ 0). Indeed, the PF - B behaves as expected, since the UE is allocated in average around 4 times more PRBs with respect to the UE who already fulfilled the GBR, but the UE is not able to get a higher throughput under those poor conditions. When a lower GBR is required (e.g. 4Mbps in Table 5.10) both UEs are again able to reach the required GBR.

Pico Layer
In this case, for the three cases depicted in Figure 5.12, some conclusions can be extracted according to the results in Table 5.8, 5.9 and 5.10. First, when both pico UEs are center pico UEs or there is one center pico UE and one RE pico UE (Tables 5.9 and 5.10 respectively), the explanation given above for the macro layer is also applicable here. The UEs with TP $<$ GBR are not in such bad conditions so that they are able to get higher throughput and fulfill the GBR at the expense of the UEs who already accomplished the GBR, finally both of them achieving TP $\geq$ GBR. Once again, the average PRB allocation column shows the desired behaviour of the barrier function.

Furthermore, when both UEs are RE pico UEs (i.e. they both are in poor conditions), the

UE with poorer conditions is only able to achieve up to a certain throughput (e.g. around 5Mbps in Table 5.10). If the GBR is set above that value, the UE is not capable of being allocated more PRBs and, consequently, the required GBR is not accomplished either.

In order to give consistence to the aforementioned comments and explain deeper the cases where the GBR could not be fulfilled (i.e. when UE conditions were poor), a cluster with 3 macro UEs and 3 RE pico UEs is simulated. Table 5.11 depicts the results for both macro and pico layer individually:

MACRO LAYER						
User ID	G-factor (dB)	PF		GBR (Mbps)	PF - B	
		Throughput (Mbps)	Avg. PRB Allocation		Throughput (Mbps)	Avg. PRB Allocation
UE_1 (Macro UE)	1.86	4.70	17.43	4	4.51	16.82
UE_2 (Macro UE)	-1.01	3.47	14.52		4.24	19.29
UE_3 (Macro UE)	5.51	6.09	18.06		4.74	13.89
UE_1 (Macro UE)	1.86	4.70	17.43	5	4.52	17.06
UE_2 (Macro UE)	-1.01	3.47	14.52		4.20	19.20
UE_3 (Macro UE)	5.51	6.09	18.06		4.80	13.74
PICO LAYER						
User ID	G-factor (dB)	PF		GBR (Mbps)	PF - B	
		Throughput (Mbps)	Avg. PRB Allocation		Throughput (Mbps)	Avg. PRB Allocation
UE_4 (RE UE)	-12.07	1.94	8.32	2	2.21	11.71
UE_5 (RE UE)	-8.60	3.52	23.74		3.47	23.43
UE_6 (RE UE)	-10.62	8.06	17.94		6.49	14.86
UE_4 (RE UE)	-12.07	1.94	8.32	3	2.04	11.73
UE_5 (RE UE)	-8.60	3.52	23.74		3.86	25.79
UE_6 (RE UE)	-10.62	8.06	17.94		5.10	12.48

Table 5.11: PF - B operation for the macro and pico layer separately - 3 macro UEs, 3 RE pico UEs

From Table 5.11, regarding the macro layer, it is appreciated that the UE conditions limit the UE throughput that can be achieved to 4 and 5 Mbps. Further, when the GBR is not too high and most UEs already fulfilled it using PF, then the PF - B allocates resources properly according to the UE throughputs and all of them can finally fulfill the GBR.

However, if the GBR is increased, it is observed how none of the UEs can achieve the GBR, even though the PRBs are properly allocated depending on the UEs conditions in line with the barrier function operation (i.e. the poorer conditions, the higher allocated PRBs). On the other hand, similar explanation can be done for the pico layer when all UEs are in poor conditions (i.e. placed in the RE area). Again, UE conditions determine the highest GBR that UEs are able to fulfill.

Therefore, the general conclusions that can be extracted when a greater number of UEs per macro-cell area is considered for the case with 1 macro and 1 pico eNB per cluster are:

- For the macro layer, considering the GBR is accordingly chosen depending on the number of UEs below or above the GBR, the PF - B scheduling metric allow all UEs to fulfill the required GBR, except for those UEs which are incapable of achieving more than a certain throughput due to their poor conditions.
- For the pico layer, same reasoning can be done. Basically, pico UEs are able to fulfill the GBR unless those UEs suffering from very strong interference (i.e. UEs placed in the RE extended area) which sometimes may not be able to fulfill it because of their poor channel conditions.

Finally, once the study of the PF - B has been fully explained for the macro - pico scenario with 1 macro and 1 pico eNB per cluster, we have tried to extend the case to the whole network with 4 pico eNB per macro-cell area, with a total number of 30 full buffer UEs per macro-cell area distributed as commented in Table 5.2. In this case, results cannot be given numerically as it has been made when having only 2 or 3 UEs per eNB. Due to the different behavior when applying the PF - B metric depending on the situation as demonstrated above (e.g. the behavior can be different for UEs in one cluster in relation with UEs from another cluster with different conditions), the results for this network cannot be analyzed as a whole. However, looking at different clusters separately, the same behavior of the PF - B operation has been appreciated. Even though all UEs are not capable of achieving the desired GBR because of their channel conditions, the PF - B metric assign more resources to those UEs which are further from fulfilling the GBR (i.e. UEs in worst conditions). This fact can be seen in Figure 5.13, where the average PRB allocation versus the G-factor for the different UEs according to the PF and PF - B scheduling metric when requiring a certain GBR is illustrated. Only the macro layer is represented, and same behavior has been observed for the pico layer. As depicted, while PF allocates in average similar amount of PRBs for all UEs, PF - B allocates more PRBs to those UEs in worst conditions (i.e. lower G-factor) in order to make them achieve a higher throughput and try to accomplish the required GBR.

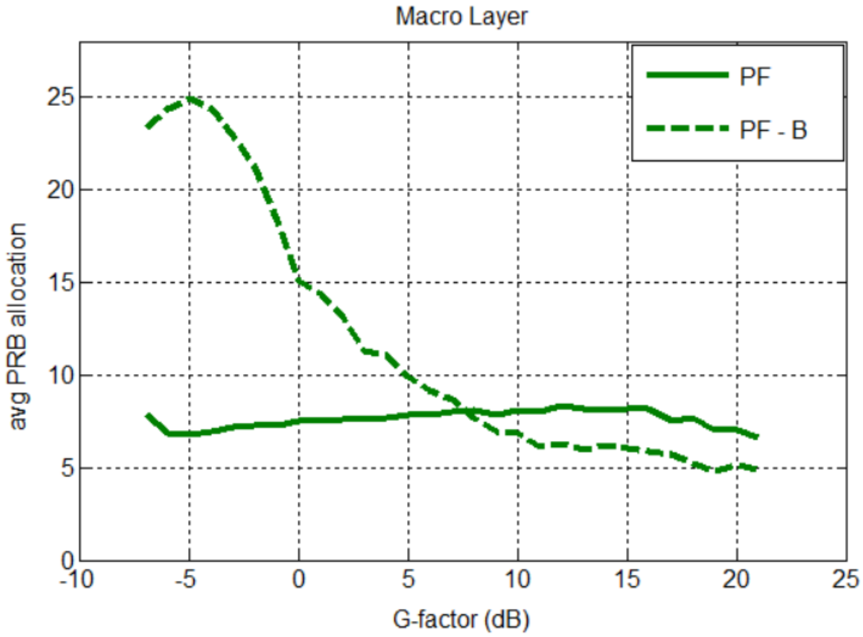

Figure 5.13: Average PRB Allocation versus G-Factor - Macro Layer

Chapter 6

Conclusions

The increasing demand for mobile data traffic is bringing new challenges on cellular networks deployment. In order to increase the average user capacity and coverage and fulfill these demands, the use of small cells has come up as a promising solution. These new networks should coexist with the former deployment and, therefore, their impact must be carefully studied. For this work, pico eNBs and RRHs have been considered as small cells embedded in macro cells deployment.

Moreover, with the evolution of mobile networks as well as the important popularity of smartphones, new multimedia applications having certain minimum QoS requirements are becoming more and more present. To cover this challenge, the study of users under GBR requirements has been done.

When having a HetNet deployment, interference between the different base stations may become a problem for their successful operation. Concretely, co-channel inter-cell interference from the macro eNB to the users connected to the small cell has been addressed in this thesis through the use of eICIC techniques.

Former investigations present a solution regarding eICIC techniques by means of slight coordination between the different eNBs via X2 interface in a macro - pico scenario (i.e. static strategy to perform eICIC). Nevertheless, it has been noticed that a more efficient way of managing inter-cell interference could be done, achieving great advantages in the system performance. Therefore, one of the main purposes of this project is to evaluate a method so as to manage inter-cell interference in a more efficient manner compared to the existing studies. This evaluation is based on a fast coordination between eNBs by means of fronthaul in a macro - RRH scenario i.e. eICIC through a dynamic strategy. Also, these both eICIC solutions have been compared with the case when no eICIC is carried out.

First, considering a fixed number of Best Effort users with an infinite buffer in the network, the results show the need of using inter-cell interference management techniques, resulting in a remarkable improvement in the overall system performance. In fact, a gain up to a factor 2.5 is achieved in terms of user throughput when using eICIC by means of the proposed dynamic strategy. Even the static case provides a user throughput two times higher than the case without eICIC. In addition, regarding the static and dynamic strategies studied to perform eICIC, a relative UE throughput gain of around 25% is obtained when using the dynamic case over the static one, which mainly comes from the Low Power Node - layer due to a more efficient allocation of the available resources.

Similar conclusions can be extracted when the number of Best Effort users in the network is not constant, but changing according to different average offered loads per macro-cell area. In this case, the UE throughput gain increases when the load in the system gets higher (i.e. there are more users in the network), since more interference is generated and, therefore, more need to be managed. At high traffic, an important relative gain in the coverage up to around 120% and 250% is achieved for the static and dynamic strategy respectively over the case without using eICIC techniques. Further, the gain from using eICIC with the dynamic strategy enables on the order of 50 - 60% higher offered load over the static one, while being able to serve the users with the same data rate.

On the other hand, in the case of users having GBR requirements, no former studies have been found for HetNets deployments, but only for conventional networks. For this purpose, the use of a GBR-aware FDPS (PF - Barrier Function for the case) is proposed as solution for the study of GBR traffic on HetNets (concretely, for the macro - pico scenario commented above).

According to Chapter 5 results when having GBR traffic, the proposed PF Barrier Function scheduling metric has been seen as a positive solution. Some general conclusions have been drawn regarding the PF - B operation:

- The resources allocation is properly done depending on how far from achieving the GBR the user is. Hence, users in worst conditions (i.e. their throughput is lower), are allocated more resources than those in good conditions.
- Users' conditions have an influence on the maximum throughput that they can achieve. Given an appropriated GBR, users in good channel conditions are able to fulfill the GBR, while users under very poor conditions may not be able to achieve it in case that the GBR is higher than the maximum commented throughput.

After the last point mentioned above, it can be therefore concluded that there are some future work to be done for the optimal operation when having GBR requirements. In this case, the Fast Load Balancing algorithm could be enhanced so that, for those users having GBR requirements, it does not adjust the number of mandatory ABS or normal subframes according only to the number of users, but also to the users' conditions.

Finally, it is worth emphasizing that both the proposed dynamic algorithm to perform eICIC techniques as well as the PF - Barrier Function scheduling metric are simple solutions and do not have high complexity, so they can be easily implemented.

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Appendix A

System Level Simulator

The results of the different simulations shown along this thesis have been obtained through a Nokia Siemens Networks proprietary LTE System Level Simulator. It mainly provided the framework where the ideas and algorithms proposed in this investigation have been developed.

The employed LTE Simulator is a quasi static system level simulator, i.e. it has fast fading, but UE positions are not updated. It is basically implemented in C++, with some related tools implemented in bash, octave, matlab and perl.

Indeed, the LTE system simulator consists of two simulators for both uplink and downlink support, but being in the same repository with a growing common code base.

The most important LTE system simulator features are listed below, even though some of them have not been used for this work:

- Possibility of simulating 3GPP and ITU-R channel models.
- Support for both homogeneous conventional networks as well as heterogeneous networks.
- Many different traffic models, including full buffer, finite buffer or VoIP. Moreover, traffic mix is also supported.
- Schedulers in both time and frequency domain with various available scheduling metrics.
- Support for several transmission schemes (MIMO).
- Capability to simulate with single or multiple carriers (channel bonding or carrier aggregation).

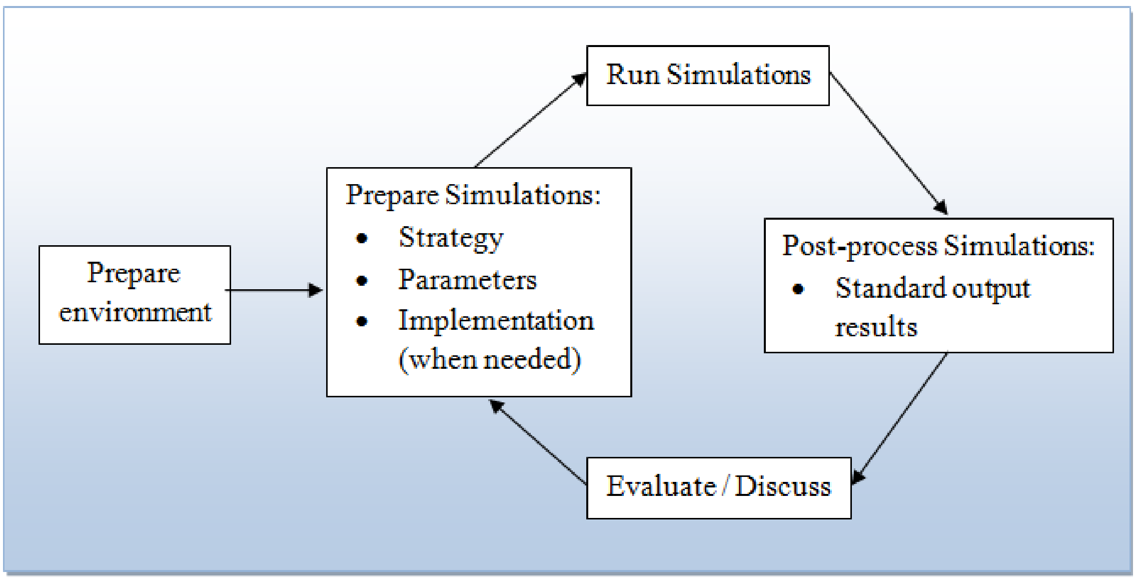
- Support for multiflow operation.
- Support for Coordinated MultiPoint (CoMP) transmission/reception.

Furthermore, some other important features which are not telecommunication specific but are worth mentioning are:

- Parameters interpreted with unmodifiable C++ variables (type safe and easy to use).
- Multiple independent random number generators. Hence, confident results can be extracted.
- Advanced statistical variables, where an assignment is a sample. Each variable must be given a name and a list of attributes, identifying the associated UE, base station, carrier, etc. as applicable. By default, a standard output of mean values per UE, descriptive statistics and histograms are obtained. Hence, it is easy to use as well as highly configurable when needed (histogram subsets, time traces, etc.).

In conclusion, it can be deduced how many strengths the simulator has. Besides all the features mentioned above, it is continuously tested to be improved and it has a detailed modeling and uniform formatting. Also, it is a mature system simulator. On the other hand, to mention some possible reasons not to use this simulator, it is slow (detailed models as mentioned), which makes the cycles of iterative work too long. Moreover, it is complex, making it hard to develop since a lot of features have to be maintained.

Finally, the whole working cycle of the simulator can be summarized in the following diagram:



A.1 Contributions to the Simulator

The simulated scenario and the rest of features (e.g. traffic models, call arrivals, etc.) used to extract the results shown along this thesis have been implemented in the simulator. Due to its huge potential, most of the features were already implemented, and it has only been necessary to carefully analyze the code and perceive that there were not bugs to be corrected on it. On the other hand, an extra contribution in the code has been done for the study of GBR traffic. In this case, the proposed PF - Barrier Function has been implemented in the frequency domain, since it was not included in the previous version of the code.

Appendix B

Optimal Setting for the Fast ABS Adaptation Algorithm

As explained in Chapter 4, the macro - RRH scenario with fast ABS adaptation is proposed in this investigation. Moreover, this is achieved by means of the addition of optional subframes and the Fast Load Balancing algorithm to decide whether to use these subframes as normal or mandatory ABS. However, different number of optional subframes and RE values can be used, being convenient to choose the configuration which makes possible a better system performance. Moreover, BE traffic with a fixed number of full buffer UEs is considered for the simulations. The simulated scenario and the rest of parameters are the same that were used in Chapter 5 and illustrated in Table 5.1 and Table 5.2.

First, in order to find the optimal settings for the number of optional subframes to be used, the coverage and median are depicted in Figure B.1 for the different possibilities. Since the algorithm has been used in an 8-basis frame, the different options range from 1 up to 6 optional subframes (at least one normal and one mandatory ABS have to be used to properly configure CQI measurements at the UE). The RE is now fixed and equal to 12 dB for all simulations.

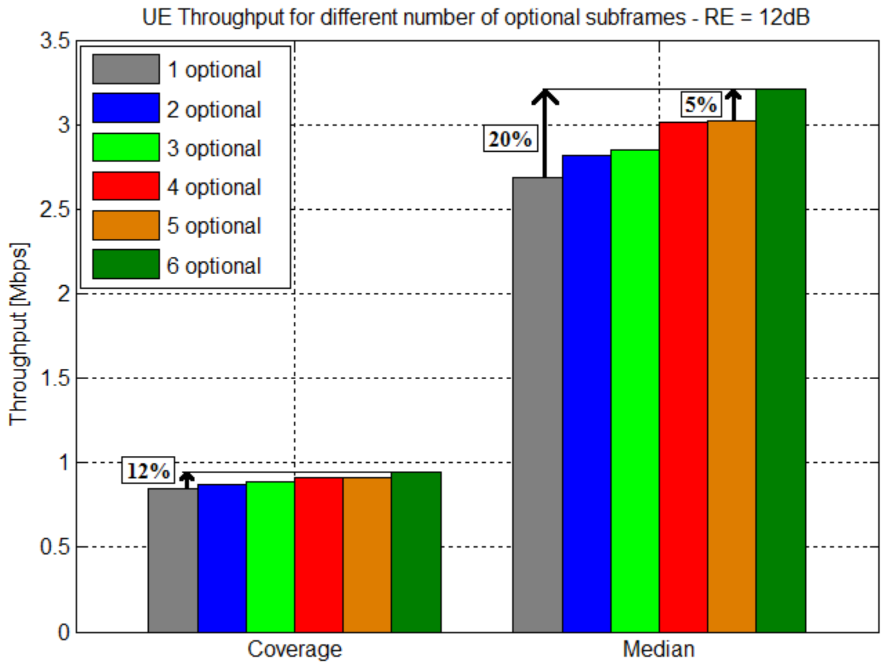


Figure B.1: Coverage and Median for different number of optional subframes - RE = 12dB

From Figure B.1, it can be observed that the UE throughput increases when more subframes are configured as optional subframes, even though with 4, 5 and 6 optional subframes there is not great improvement in the performance. Therefore, 6 optional subframes seem to be the configuration which best overall performance achieves and, therefore, the one considered for the simulations when using the dynamic ABS adaptation. Effectively, it is easy to deduce that, when more optional subframes are used, the dynamic ABS adaptation can be further exploited and more effectiveness in the resources allocation will be achieved. The average PRB allocation is illustrated in Figure B.2, where it can be seen how the resources are slightly better allocated (i.e. lower PRB utilization is achieved) when the number of optional subframes increases.

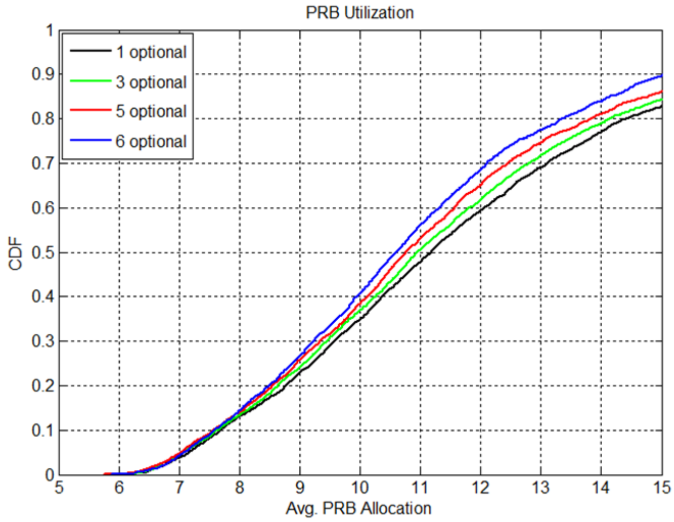


Figure B.2: Average PRB Allocation for different number of optional subframes - RE = 12dB

Once the number of optional subframes has been appropriately found, it is also needed to notice the impact of the RE in the system performance. Figure B.3 illustrates the coverage and median for different RE values and a fixed number of 6 optional subframes:

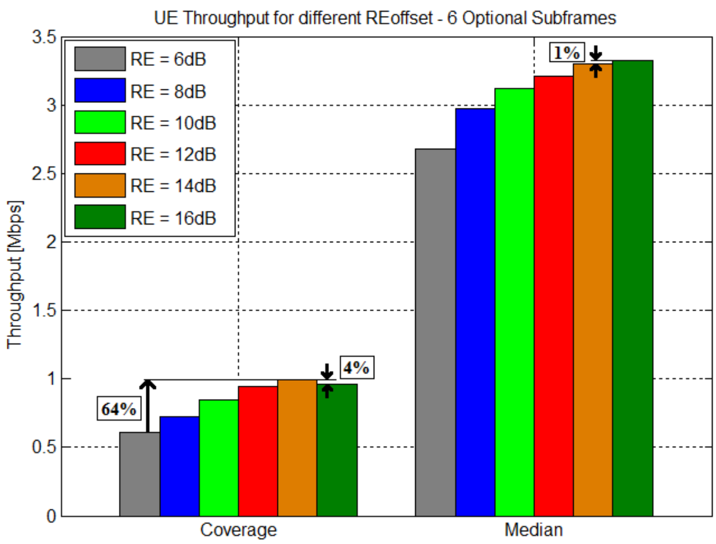


Figure B.3: Coverage and median for different values of RE - 6 optional subframes

As depicted, in general the coverage and median increases when higher values of RE are considered. However, there is a certain value where the coverage starts decreasing again even though the median gets a slight improvement.

In principal, increasing the RE implies a higher offloading from the macro eNB to the

LNP. Table B.1 represents the number of macro and RRH UEs as well as the offloading rate for the different RE values. Moreover, Figure B.4 shows the different types of UEs in the considered scenario depending on the coverage area they are placed. As illustrated in Table B.1, it can be deduced that when the RE increases more UEs are pushed to the RE extended area and connect to the RRH, achieving a higher offloading from the macro eNB, thus improving the performance. Nevertheless, when the RE is high in excess (from RE = 14dB in advance in this case), there are excessive number of UEs in the coverage extended area (i.e. UEs in worst conditions) compared with the UEs in the RRH coverage area without RE. In that case, more interference has to be managed, resulting in a degradation of the performance for those UEs. Since special focus is done on improving the performance of the worst conditions UEs in this study, RE = 14dB which maximizes the coverage is chosen for the simulations.

RE (dB)	Total Number of UEs	Macro eNB	RRH			Offloading
		Macro UEs	RRH UEs	Center RRH UEs	RE RRH UEs	
6	630	270	360	241	119	57%
8	630	231	399	241	158	63%
10	630	196	434	241	193	69%
12	630	166	464	241	223	74%
14	630	136	494	241	253	78%
16	630	111	519	241	278	82%

Table B.1: Number of Macro UEs, RRH UEs and Offloading rate for different RE values

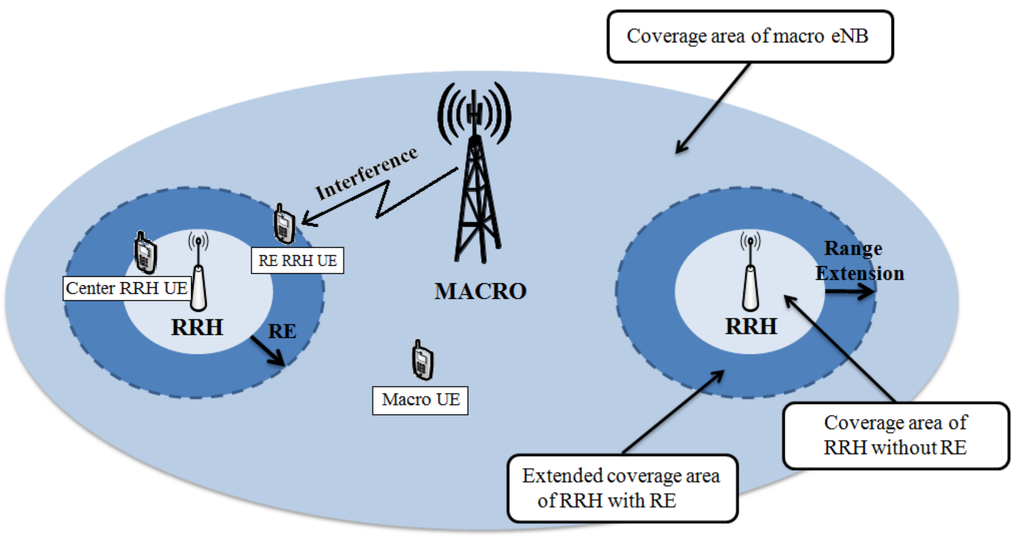


Figure B.4: Macro - RRH scenario with increased RE extended area