Master's Thesis

LTE-Advanced HetNet Investigations Under Realistic Conditions

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Abstract

With the exponential growth in traffic demands during past years, Heterogeneous Networks (HetNets) are envisioned as the major capacity and performance enhancement enablers by means of increasing the spectral efficiency per unit area. Several multi-cell cooperation techniques have been developed in order to improve the performance of HetNets, such as Range Extension (RE) and enhanced Inter-Cell Interference Coordination (eICIC) for co-channel deployments and inter-site carrier aggregation (CA) for dedicated deployments.

The main objective of this study is to analyze the performance of different multi-cell cooperation techniques in a site-specific scenario (central London area) as compared to the case without multi-cell cooperation. The performance of these multi-cell cooperation techniques has been well studied in 3GPP scenarios. But in the site-specific scenario, both the traffic distribution and network layout are far more irregular than in 3GPP scenarios, which calls for a deeper study considering local characteristics.

For co-channel deployment, dynamic algorithms used for cell selection and interference management are proposed in order to adaptively adjust the configurations (RE + eICIC) according to the local characteristics (such as the load and interference conditions). The results show that the performance with dynamic algorithms is much better than with static algorithms, achieving an overall user throughput gain up to 120% and 47% over the static configuration for the 5^{th} and 50^{th} percentile respectively.

For dedicated carrier deployment, inter-site CA proves to have good performance in the site-specific scenario, providing an overall user throughput gain up to 100% and 28% for the 5^{th} and 50^{th} percentile respectively, compared to the case without CA. The gain of inter-site CA depends on the UE's channel quality to both layers (macro layer and small cell layer) and the density of the eNBs of the site-specific scenario.

Preface

This Long Master's Thesis has been written by Guillermo Andrés Pocovi Gerardino and Sonia Barcos Sánchez, during the period from September 2013 to June 2014.

The project was developed for the Radio Access Technology Section (RATE) of Aalborg University, in close collaboration with Nokia Solutions and Networks.

This report consists of six chapters and eight appendices. The study is based on simulations performed using a Nokia Solutions Networks proprietary LTE System Level Simulator. Simulation results are post-processed and analyzed using MATLAB.

The references used thorough the document follow IEEE recommended style and nomenclature.

Aalborg University, 27th May, 2014

Guillermo Pocovi Sonia Barcos

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Guillermo´s Acknowledgements

First of all, I would like to express my gratitude to my supervisors Hua Wang and Klaus Pedersen for their continuous guidance and support that made possible the development of this master's thesis. Their infinite patience, encouragement and technical knowledge have definitely been important for the achievement of our goals.

I am also very thankful to all the people in NSN/RATE for the pleasant and unique working environment. It's been 9 months since I arrived in Aalborg and I would confidently say that every single day I spent here has helped me to develop lot of personal and professional skills. Although it might seem meaningless, I really enjoyed the fact that you could stablish a nice conversation with anybody, at any time, and in any place in NSN office.

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Besides, many thanks to all the people and friends I have met in Aalborg that has made these 9 months truly unforgettable. Especial thanks to those with whom I shared in a daily basis: my flatmates, Laura, Marta, Carmen, Derejee, Lucas, Isa and Nacho. Not to mention Sonia from whom I learnt endless things. Especially her organizational skills that were essential for writing this project and, with no doubt, will be very valuable in my future activities.

Besides, my warmest thanks to my friends in Venezuela with whom I had the opportunity to share amazing experiences back there: especially Juan J. Rodriguez, Giselle Arrioja and Fabiana Romero. I am grateful to them for their support and friendship.

Finally, I want to express my biggest gratitude to the most influential people in my life: my family. I feel privileged to have such an amazing family whom I owe every piece of success I've achieved. Despite the distance, their unconditional support and encouragement have definitely been essential for achieving my goals.

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De mis casi 24 años de vida, he pasado 23 en España, así que me parece justo empezar estos agradecimientos en español, para mi gente de España. Hay muchas personas a las que debo agradecer, y es difícil recordarlas a todas como se merecen en tan pocas líneas, pero haré lo posible. Sé que no puedo nombraros a todos, pero sabed que os quiero y os tengo en mente.

A lo largo de mi carrera como estudiante he conocido a profesores maravillosos, que no sólo me han dado conocimiento sobre Lengua o Matemáticas, sino también consejos y enseñanzas de gran valor para mi vida. Gracias a todos. En especial, a mi maestro de primaria, Don Fernando, al que recuerdo con grandísimo cariño, y que nos animaba diciendo: "Adelante, mis valientes, con las garras y con los dientes". También quisiera mencionar a mi profesor de matemáticas en Bachillerato, Don Antonio, que no sólo es el profesor con el que aprendí matemáticas de verdad, si no también una persona maravillosa, que me apoyó mucho cuando más lo necesitaba. Sin olvidar a, una vez más, otro Don Antonio, en este caso profesor de Señales en la universidad, que me animó y acompañó durante toda la carrera, y al que tengo gran cariño. Mención aparte merece también Pablo, mi coordinador de Erasmus en Granada, sin el que no hubiera sido posible para mí tener esta oportunidad.

Gracias a todos mis amigos, por animarme y aceptarme como soy, haciéndome sentir especial. Os quiero muchísimo, Isa y Encar, sois las mejores amigas que podría desear. A Caro, Moya, Fer, Leo, Juanchu, Fran y a todos mis Chanclis, gracias también. Gracias también a Sagrario, por su ayuda y apoyo, y enseñarme que la vida no es blanca o negra, va en escalas de gris. Eres alguien a quien tengo cariño y respeto mucho.

Por supuesto, tengo mucho que agradecer a mi familia. A mis padres, por quererme y estar siempre ahí, a mis abuelos, los mejores del mundo, por estar convencidos de que su nieta es la mejor, y a mis tíos y primos, que han hecho mi vida plena y especial. A mi hermano, al que quiero con toda mi alma, y a mi prima Laura, gran amiga y a la que considero como una hermana. Y por supuesto mi Lolo, no pienses que me olvido de ti.

Since I came to Aalborg in August 2013, I have met lots of wonderful people. I cannot name all of them, but I thank them all, because staying here and meeting them has changed me and I have grown, not only in a professional level, but also as a person.

First, many thanks to my supervisor Hua, who is a truly wonderful and nice person. He always answers me with a smile, always tries his best to be helpful, and always gives me good advice. Also thanks to Klaus, my other supervisor, for showing me ways to improve my work, and helping me give my best. Besides, I need to thank Beatriz, for listening to me and giving me advice about many things. Last, but no less, thanks to my project partner, Guille. Without him, this would not have been possible. He has being my partner and my friend. It has been a great experience working with him, from which I have learned a lot.

Thanks to all the people in the office. They are truly amazing people. To Jens and Mads, for enduring and helping me thorough all the year. To Carmen, Isa, Laura, Germán, Nacho, Dereje and Martha, for accompany me and making me feel welcome. Without forgetting Lucas, whose contagious laughing makes the office brighter, and who has being a friend to me.

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List of Abbreviations and Symbols

3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
ABS	Almost Blank Subframe
ACK	Positive Acknowledgement
AMC	Adaptive Modulation and Coding
ARQ	Automatic Repeat Request
BBU	Base-Band Unit
BLER	Block Error Rate
CA	Carrier Aggregation
CC	Component Carrier
CoMP	Coordinated MultiPoint
CP	Cyclic Prefix
CQI	Channel Quality Indicator
C-RAN	Centralized/Cloud RAN
CRC	Cyclic Redundancy Check
CRS IC	Common Reference Signals Interference Cancellation
CRS	Common Reference Signals
CSG	Closed Subscriber Group
DFT	Discrete Fourier Transform
DL	Downlink
DOE	Design of Experiments
DSL	Digital Subscriber Line
eICIC	enhanced Inter-Cell Interference Coordination
eNB	enhanced NodeB
EPC	Evolved Packet Core
EPS	Evolved Packet System
FDD	Frequency-Division Duplexing
FDPS	Frequency-Domain Packet Scheduler
FEC	Forward Error Coding
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat Request
HeNB	Home enhanced NodeB
HetNet	Heterogeneous Network
IE	Information Element
IMT-A	International Mobile Telecommunications-Advanced
IP	Internet Protocol
IRC	Interference Rejection Combining
ISD	Inter-Site Distance
ISI	Inter-Symbol Interference
ITU	International Telecommunications Union
ITU-R	ITU Radiocommunication Sector

KPI	Key Performance Indicator
LA	Link Adaptation
LPN	Low-Power Node
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
MME	Mobility Management Entity
MMSE	Minimum Mean Square Error
MU-MIMO	Multiuser MIMO
NAK	Negative Acknowledgment
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PAPR	Peak-to-Average Power Ratio
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PF	Proportional Fair
P-GW	Packet Data Network Gateway
PRB	Physical Resource Block
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RAN	Radio Access Network
RE	Range Extension
RI	Rank Indicator
RLF	Radio Link Failure
RNC	Radio Network Controller
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
SAE	System Architecture Evolution
SC-FDMA	Single-Carrier Frequency Division Multiple Access
S-GW	Serving Gateway
SINR	Signal-to-Interference-and-Noise Ratio
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SON	Self-Organizing Networks
TDD	Time-Division Duplexing
TDPS	Time-Domain Packet Scheduler
TTI	Time Transmission Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System

Chapter 1

1 Introduction

In this chapter the background and motivation of this Master's Thesis are introduced, as well as the problem statement and the objective of this study.

1.1 Background and Motivation

In recent years, the development of wireless communications has experienced a huge revolution. While just a couple of decades ago mobile phones were mostly used for making calls and sending messages via SMS, the introduction of 3G, which allowed the use of broadband data granting access to browse the internet, and later 4G, which gets higher speeds, marked the development of mobile broadband and data oriented devices such as smartphones and USB modems. These devices are responsible for a fast growth in mobile data traffic [1]. In 2012, global mobile data traffic grew 70 percent and it is expected to increase 13-fold between 2012 and 2017. Moreover, the number of laptops and tablets mobile-connected is increasing exponentially too, meaning even more growth in mobile data traffic. By 2017, mobile data traffic generated by mobile-connected tablets will be 1.5 times higher than the traffic generated by the whole global mobile network in 2012 [1].

Mobile networks have to deal with the increase of the number of devices and also the demands of users for higher speeds to allow diversions like real time video streaming and online games. Therefore, mobile networks have to evolve in order to fulfill these demands. In the past years the required increase in capacity would have been achieved by adding more macro nodes in the network. However, the high costs and the space needed for such an approach represent an important problem for the operators [2]. Moreover, spectral efficiency per link is reaching theoretical limits [3].

At the sight of this, LTE-Advanced (LTE-A) in conjunction with Heterogeneous Networks (HetNets) are seen as the keys for further enhance the performance in mobile networks by improving spectral efficiency per unit area.

LTE-A is a technology that was designed to meet the demands of the growing traffic. It includes several advanced techniques such as carrier aggregation, multiple-input multiple-output (MIMO), and the introduction of HetNets.

A traditional homogeneous cellular network consists of a group of high-power nodes (macro nodes). Heterogeneous networks instead include not only macro but also low-power nodes. This deployment allows to improve the spectral efficiency per unit area, as the low-power cells make possible to remove coverage holes in the macro-only network and increase the capacity in zones with very high traffic volume [4]. The main characteristic of HetNets is the great disparity between the transmit power used by the high-power and the low-power nodes [2]. This makes necessary the usage of interference management techniques as low-power nodes can suffer great interference from macro ones. Other challenges that these networks might face are:

- Sharing resources (time and frequency) between the different types of nodes in the best way possible so as to avoid coverage holes [2].
- Load balancing amongst nodes.

Two kinds of deployments have been proposed for HetNets: co-channel, where all nodes share the same carrier frequency and dedicated carrier, with different frequency carriers for the macro and low-power layer. Each one presents technical challenges as well as advantages. A brief description can be seen in [2]. A great number of works can be seen addressing the problems of these deployments and trying to find solutions for them, as well as showing the performance obtained when applying those HetNet techniques in generic 3GPP scenarios. Some references are shown below.

State of the Art

In a co-channel deployment, it is necessary to balance the load between the different layers. This can be achieved using the Range Extension (RE). Several studies have been conducted about how to get the best RE configuration for a network, as well as a great amount of other studies trying different techniques and algorithms to reach an optimal user association. Extensive information can be found in [5] [6] [7] [8].

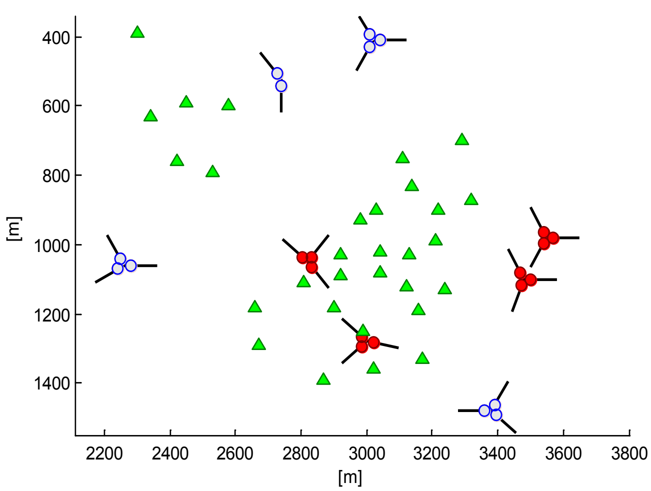
The usage of Range Extension leads to interference problems as the carrier frequency is shared between the high-power and the low-power layers. A strong control and management of the inter-layer interference is needed to protect the users in the RE area. For this purpose, the technique known as enhanced Inter-Cell Interference Coordination (eICIC) has been studied and showed promising results. Some of these studies are [3] [9]. The authors in [10] [11] introduce the Fast Muting Adaptation, a dynamic version of eICIC.

In the case of a dedicated carrier deployment, the inter-layer interference is not a problem as macro and low-power nodes are deployed at different frequency carriers. The problem in this scenario lays on the bandwidth fragmentation between the layers, which prevents a better performance of the network. To avoid this and therefore improve the performance collaborative inter-site carrier aggregation (CA) has been proposed as the best solution so far. The idea is allowing some user equipments (UEs) to simultaneously connect to a macro cell and a small cell, thus benefiting from larger transmission bandwidth from the two layers. The references [12] and [13] will enlighten the reader about this technique.

1.2 Problem Statement and Objective of the Study

There is extensive literature concerning the study of HetNets performance in generic 3GPP scenarios. 3GPP scenarios consist of guidelines and standard models for simulations allowing the comparison of different mobile technologies and features across the industry and academia. The goal is to reproduce the most common effects in real networks using generic statistical models that are obtained from observations of typical situations in reality. Figure 1.1 (right) shows an example network layout in a typical 3GPP scenario.

However, according to the authors' knowledge, not many studies analyze HetNet performance in a site-specific scenario. The objective of this study is to analyze the performance of multi-cell cooperation techniques in HetNet considering a site-specific scenario for which is available real operator information. The investigated area corresponds to a zone in central London with intensive mobile data usage. Figure 1.1 (left) illustrates the network layout used in this study. Red circles and white circles represent macro sectors that are pointing according to the black line direction. Green triangles represent pico base stations.



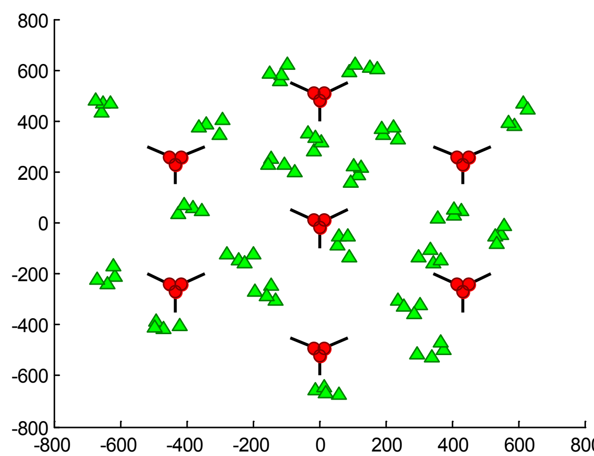


Figure 1.1: Site-specific operator scenario (left) and 3GPP scenario (right) network layout

From the observation of Figure 1.1, it is obvious that there are many differences between a generic 3GPP scenario and our site-specific scenario. Some of those differences are:

- Macro sites are not hexagonally located.

- The macro inter-site distance (ISD) is very irregular across the network, while it remains constant in 3GPP scenarios.
- UE distribution is more irregular.
- Propagation maps are far more irregular than in a generic 3GPP scenario, varying significantly from one base station to another.

These variations may change the behavior and gain numbers when analyzing different multi-cell cooperation techniques in real operator scenarios as compared to 3GPP scenarios. Thus, the main objectives of this project are:

1. Study in depth the differences between a specific case scenario versus 3GPP scenarios.
2. Analyze the behavior of multi-cell cooperation techniques in HetNet such as eICIC and inter-site CA in this specific case scenario, using 3GPP scenarios results as a reference.
3. Examine and develop new algorithms to improve network performance for the specific case scenario, especially focusing on 5%-ile UE throughput performance.

The study will be conducted assuming a co-channel deployment first, and considering a dedicated deployment afterwards. It is worth saying that, as the greatest part of the traffic volume flows in the downlink (DL), this report will focus on improving the performance on this link.

In the case of co-channel deployment, the approach followed in this study is:

- The operator scenario under study is much more irregular (both network layout and user traffic density) than 3GPP scenarios. Thus it is useful to separate the network in different regions and study the performance in each one.
- First, we study traditional RE and eICIC techniques, applying the same configuration to the whole network (this will be called static configuration). The analysis of these results shows that the best configuration changes from zone to zone due to the irregularity of the network.
- From the results it is expected that larger gains can be achieved when different configurations are applied in each area. Therefore, we propose dynamic algorithms for eICIC and cell selection. These algorithms target to adjust to the particular conditions in each region, hence increasing the overall network performance and also allowing the flexibility of being used in other scenarios as well.

For dedicated deployment, the study also takes into account the different regions in the area of interest. In this case the focus will be on the application of inter-site CA.

In order to successfully achieve these goals, this is the methodology followed:

- To get a deep understanding of the present situation, it is necessary a research of techniques and algorithms that are currently been developed for managing interference and load balancing amongst cells in HetNets.
- The implemented techniques and algorithms are tested by simulating in a Nokia Solutions and Networks proprietary LTE System Level Simulator.
- Several simulations are run under different assumptions.
- The results are post-processed, analyzed and compared using MATLAB.
- Conclusions are obtained from the results, along with guides on what could be done in future work.

1.3 Thesis Outline

This report is structured as follows:

- **Chapter 1: Introduction**
  This chapter outlines the motivation of this study, the related work, and explains the problem and the objective of the study.
- **Chapter 2: LTE and Advanced Heterogeneous Networks**
  Definition of the main features of LTE-Advanced, especially those related to this study. Besides, description of key design features for Heterogeneous Networks: UE cell selection and interference management for co-channel deployment, and inter-site CA for dedicated deployment.
- **Chapter 3: System Model and Simulation Assumptions**
  Description of 3GPP scenarios related to this work, and references to relevant results, as well as detailed description of the site-specific operator scenario used in this study. This chapter includes also the simulation assumptions, and a description of the traffic models employed and the key performance indicators considered.
- **Chapter 4: Algorithms and Performance for Co-Channel Deployment**
  Performance results for the whole network and also in each area for a co-channel deployment, explaining how is separated the network in regions. First results using a static RE + eICIC configuration, and second, results using dynamic configurations. Besides, the dynamic techniques used for this study are explained: Fast muting adaptation for interference management, and Throughput-based and Load-based cell selection.
- **Chapter 5: Inter-Site CA and Performance for Dedicated Deployment**
  Performance results for the whole network and also in each area for a dedicated deployment, studying inter-site CA. This chapter includes also an explanation of how Throughput-based cell selection is applied in a dedicated deployment.

- **Chapter 6: Conclusions, Contributions and Future Work**
  Summary of the main ideas and conclusions presented in this study, along with the considerations for the study and what could be done in the future.

Some appendices are also included to provide further information:

- **Appendix A: Macro and Small Cell Description**
  This appendix describes the main characteristics of macro cells and the different types of small cells.
- **Appendix B: Examples of Optimal Cell Selection Algorithms and Comparative Table**
  Brief explanation of some algorithms proposed in other studies to achieve an optimal cell selection. It also includes a comparative summary table of techniques for optimal cell selection.
- **Appendix C: Base Station ID Map**
  Map containing the IDs assigned to the base stations in the area of study (site-specific operator scenario, London).
- **Appendix D: Normalization for Fast ABS**
  This appendix describes the different normalization factors that can be applied to the number of victim users in Fast muting adaptation, and how these normalization factors affect the results.
- **Appendix E: Pseudo-code for Throughput-based Cell Selection**
  It includes the pseudo-code for throughput-based cell selection algorithm.
- **Appendix F: Pseudo-code and Load Threshold for Load-based Cell Selection**
  It includes the pseudo-code for load-based cell selection algorithm. Besides, this appendix explains different approaches to set the Load Threshold for Load-based cell selection algorithm, and how these approaches affect performance.
- **Appendix G: Full-Buffer Results for Co-Channel Deployment**
  This appendix shows detailed results using full-buffer traffic model in co-channel deployment, applying a static configuration. It includes both overall network and regional performance results.
- **Appendix H: Finite-Buffer Regional Study for Co-Channel Deployment**
  This appendix shows the settings that obtain the best 5%-ile UE throughput in each region for co-channel deployment, both in cases of static and dynamic configuration, considering full-buffer traffic model.

Chapter 2

2 LTE and Advanced Heterogeneous Networks

This chapter focuses first on describing LTE-Advanced, explaining its architecture and most relevant features. After that, Heterogeneous Network concept is depicted, along with an explanation of main challenges and techniques used in co-channel and dedicated carrier deployments.

2.1 LTE - Advanced Overview

As mentioned before, mobile data traffic is growing fast. This is mainly due to the introduction of new devices that are capable of providing a variety of data-oriented services such as web browsing, video and audio streaming, online gaming, etc. This represents a huge challenge for the operators since they are responsible for carrying most of this data.

In order to fulfill these demands, the 3rd Generation Partnership Project (3GPP) developed a new mobile broadband technology called Long Term Evolution (LTE). The first version of LTE (called LTE Release 8) was completed in March 2009 with the purpose of satisfying the current and future demands. LTE introduces new features, such as flexible spectrum and a flat network architecture, which help to achieve much higher performance over previous 3GPP standards (e.g. HSPA), especially in terms of DL and UL peak data rates, spectral efficiency and latency [14].

However, these improvements do not meet the needs of the expected demands, and, for that reason, at the end of 2010, the 3GPP submitted a major enhancement of the existing LTE standard called LTE Release 10 or LTE-Advanced[1] (LTE-A) as a proposal to fulfill the International Mobile Telecommunications-Advanced (IMT-A) requirements issued in 2008. As seen in [15], some of these requirements are:

- 100 Mbps peak data rate support for high mobility and up to 1 Gbps peak data rate for low mobility case;
- Allow inter-working with other radio access systems;

[1] The 11^{th} and 12^{th} releases of the LTE technology are also referred as LTE-Advanced.

- Cell spectral efficiency, ranging from the 3 bits/Hz/cell in the indoor downlink scenario, to the 0.7 bits/Hz/cell in the high speed uplink scenario;
- Peak spectral efficiency, ranging up to 15 bits/s/Hz;
- Bandwidth scalability up to and including 40MHz, up to 100 MHz should also be considered;
- Latency requirements for control plane to achieve 100 ms transition time between idle and active state, and respectively to enable 10 ms user plane latency (in unloaded conditions)
- Mobility support up to 350 km/h

Many of these demands were already met by LTE Release 8. For that reason, 3GPP also defined its own requirements for LTE-Advanced that, in some areas, exceed the ones issued by the ITU-R, especially in terms of peak and cell-edge spectral efficiency [16]. This ensures an incremental step of performance and capabilities between the successive releases. More detailed information about LTE-A requirements can be found in [17].

The performance improvement brought by LTE-A is mainly achieved thanks to the introduction of new features. As seen in [18], some of these are:

- Intra and Inter-band Carrier aggregation (CA)
- Enhanced MIMO
- Coordinated multipoint transmission and reception (CoMP)

Apart from these, LTE-A also introduces the eICIC functionality for co-channel deployment of HetNets and also, relay nodes for backhauling the base stations via LTE radio interface. These two features aim at enhancing the network capacity and coverage.

The most relevant features that are related to this work will be further described along this chapter. More detailed information can be found in [18].

2.1.1 Network Architecture

Both the Radio-Access Network (RAN) and the core network were modified in order to obtain a much more simplified network. This process led to what is called System Architecture Evolution (SAE) which consists of a flat architecture that comprises a new core network referred as the Evolved Packet Core (EPC), as well as a new RAN named Evolved-Universal Terrestrial Radio Access Network (E-UTRAN). Figure 2.1 depicts a simple LTE architecture example including the main standardized interfaces.

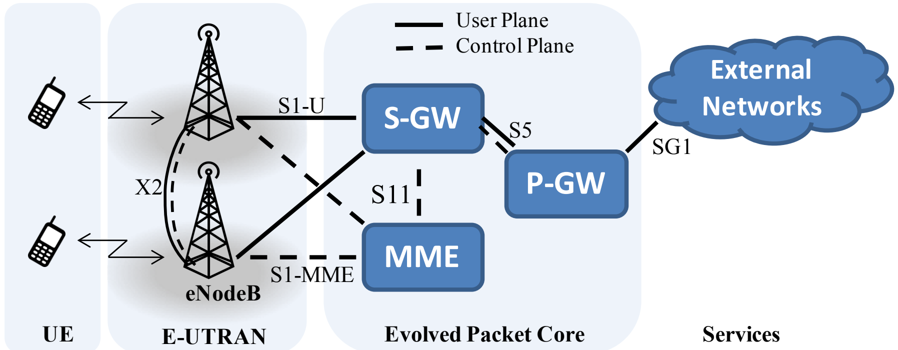


Figure 2.1: LTE Network Architecture [19]

Evolved Packet Core Overview

LTE packet core network assumes a full Internet Protocol (IP) network architecture and is designed to support voice in the packet domain. It includes support for multiple access networks, including 3GPP legacy e.g. GSM and UMTS, and some others non-3GPP systems (for example WiMAX or cdma2000).

The main components and functionalities of the EPC are the following:

- **Mobility Management Entity (MME):** is the main control element in the EPC. The MME is in charge of user mobility, bearer set-up, and some security functions such as authentication and temporary identification of the user.
- **Serving Gateway (S-GW):** is responsible for routing and forwarding user data packets among different LTE nodes. It is also a key part in inter-eNodeB mobility events.
- **Packet Data Network Gateway (P-GW):** is the termination node of the EPC and provides to the UE access to external packet data networks (e.g. Internet).

E-UTRAN Overview [20]

The E-UTRAN consists of base stations (called evolved Node B in LTE) that are interconnected with each other via the X2 interface.

The LTE evolved Node B (**eNodeB)** is the only node in the E-UTRAN and is in control of all Layer 1 and Layer 2 radio related functionalities. The eNodeB acts as a bridge between UE and the EPC, relaying data between the radio interface and the EPC through the S1 interface. Other functionalities of the eNodeB are:

- Channel coding and de-coding.
- Radio Resource Control: this relates to the allocation, modification and release of resources for the transmission over the radio interface between the user terminal and the eNodeB.

- Radio Mobility management: this refers to a measurement processing and handover decision.
- Radio Resource Management (RRM): administrates the usage of the radio resources.

Additionally, the **X2 interface** is also a new element introduced in the E-UTRAN that gives the possibility to connect eNodeBs with each other. The main purpose of this interface is to allow the exchange of signaling information [21] making possible some of the features described above, especially those related to user mobility and RRM. The X2 interface is a logical interface, this means that the eNodeB are not necessarily connected together with a physical direct connection, in fact, it is usually routed in the same transport connection as the S1 interface [19].

Since most of the contributions of this project are closely related to E-UTRAN functionalities, a special emphasis will be put on the E-UTRAN functions that are most relevant in this study. These include some of the layer 1 to layer 3 features such as: MIMO, RRM algorithms, carrier aggregation, among others.

2.1.2 Physical Layer

LTE physical layer modifications over WCDMA are one of the key elements that ensure high performance in terms of both data rates and latency. First, the radio access technology has significantly changed to a multiple carrier transmission that offers several advantages that increase the spectral efficiency. Second, the modified radio frame structure makes possible the dynamic allocation of shared resources hence increasing the flexibility of the system.

2.1.2.1 Radio Access

In the downlink (DL) direction, Orthogonal Frequency Division Multiple Access (OFDMA) is used, whereas Single-Carrier Frequency Division Multiple Access (SC-FDMA) is used in the uplink (UL).

OFDMA is a multiple access technique that consists on assigning a subset of multiple orthogonal carriers to individual users. OFDMA has many advantages: it is robust to multipath fading and interference, offers opportunities to exploit multi-user diversity, can be easily adapted to different bandwidths, and also, is very simple to implement thanks to digital signal processing techniques.

In the specific case of LTE, the subcarriers are spaced 15 kHz from each other, which corresponds to a symbol rate of 66.7 μs. A guard period - called cyclic prefix (CP) - is inserted between each symbol which is used to overcome the inter-symbol interference (ISI) that results from multipath delays.

On the other hand, SC-FDMA is used in the UL direction. The SC-FDMA transmission scheme is very similar to the one used in the DL, with the main difference being the inclusion of a Discrete Fourier Transform (DFT) pre-coding. This assures a lower Peak to Average Power Ratio (PAPR) which helps to save the UE battery energy while keeping some of the most important features of OFDMA like the multipath interference robustness and the frequency domain orthogonality among intra-cell users.

More detailed information about the LTE multiple access technologies and transmission schemes can be found in [19].

2.1.2.2 Frame Structure

In time domain, the transmission structure consists of radio frames of 10 ms long. As depicted in Figure 2.2, every frame has 10 subframes of 1 ms each. Each subframe contains 2 slots (with duration of 0.5 ms) that are filled with either 6 or 7 OFDM symbols depending on whether extend or short cyclic prefix is used.

Each DL subframe contains reference signals, control information, and data transmission. The control part can be 1-3 symbols located at the beginning of each subframe and is provided by the Physical Downlink Control Channel (PDCCH), among others. The rest of the subframe is filled with data which corresponds to the Physical Downlink Shared Channel (PDSCH).

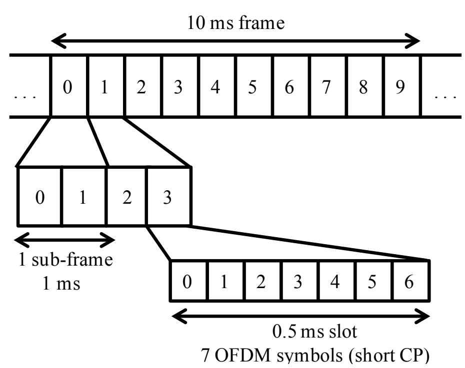


Figure 2.2: LTE Downlink Frame Structure [19]

These OFDM symbols are allocated in the time-frequency domain in form of resource blocks (RB). A RB is the minimum resource element that can be assigned to a UE for data transmission and consists of 12 subcarriers having a total bandwidth of 180 kHz in the frequency domain and 14 OFDM symbols (with normal cyclic prefix), i.e. 1 subframe, in the time domain. An example of a physical resource block is illustrated in Figure 2.3.

LTE supports different bandwidths up to 20MHz, covering 1.4 MHz, 3 MHz, 5 MHz, 10 MHz and 15 MHz. The amount of RBs in each bandwidth varies from 6 RBs for 1.4 MHz to 100 RBs in a 20 MHz bandwidth.

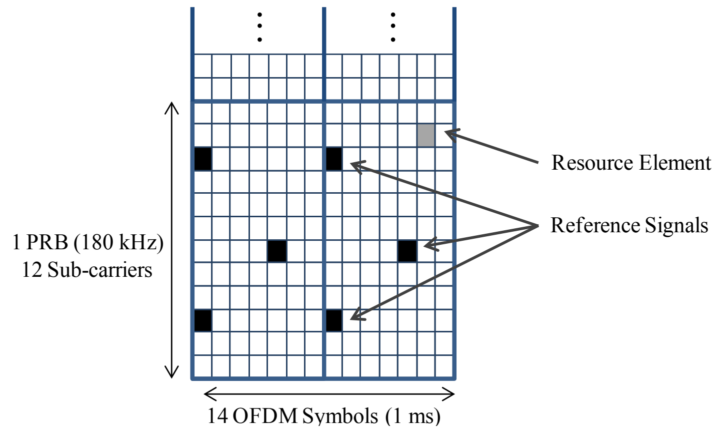


Figure 2.3: Example of Downlink Resource Block for short cyclic prefix [19]

2.1.3 Multiple Input –Multiple Output

Multiple Input-Multiple Output (MIMO) is one of the new features in the first LTE Release. MIMO consists on having multiple antennas at both the transmitter and receiver to provide higher data rates without the need of additional time-frequency resources.

A successful MIMO operation requires reasonably high SNR. Therefore, the introduction of OFDMA is very beneficial for MIMO operation due to the fact that this system can now get advantage from the locally (in the frequency/time domain) high SNR that is achievable.

The increase in performance in MIMO is achieved through two different techniques that exploit the spatial domain of the radio channel: first, *transmission diversity* which corresponds to send a single stream from multiple antennas in order to take advantage of the gains from independent fading between the antennas [19]. Second, if the channel conditions are good enough, different data streams can be transmitted in parallel using *spatial multiplexing* hence linearly increasing the peak data rates.

This decision, referred as *rank adaptation*, is based on a UE channel information report called *Rank Indicator* (RI) which corresponds to the UE recommendation of the number of layers to be used in spatial multiplexing. For example, in a 2x2 antenna configuration, the RI can have values 1 (transmission diversity mode) or 2 (MIMO mode) which mainly depends on the experienced SINR and spatial correlation among the layers.

Additionally, a pre-coding operation can be executed by the transmitter which consists on weighting the signals that are sent from the different antennas in order to maximize the received Signal to Noise Ratio (SNR). This pre-coding can be either deterministic (open-loop MIMO) or based on the pre-coding matrix indicator reported by the UE (closed-loop MIMO) [19].

LTE Release 10 supply new enhancements to the MIMO functionality such as: 8x8 and 4x4 antennas configuration support for DL and UL respectively, and enhanced multiuser MIMO (MU-MIMO) [16]. In this study a 2x2 MIMO configuration is considered. Figure 2.4 illustrates a basic scheme of a 2x2 MIMO operation.

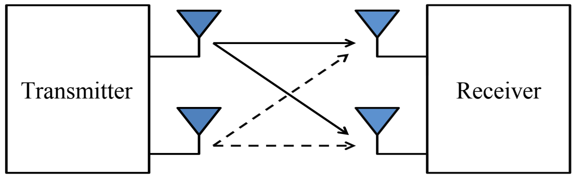


Figure 2.4: Example of 2x2 MIMO Configuration

In order to be able to separate the multiple spatial streams at the receiver, different reference symbols are added to each spatial layer at the transmitter side. Figure 2.5 shows this principle for a 2x2 MIMO case. This concept can be also extended for the case with more than two antennas.

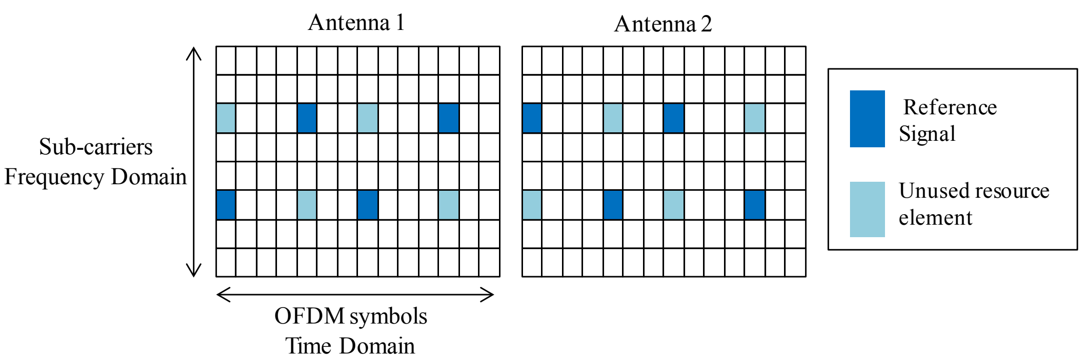


Figure 2.5: Example of OFDMA Reference Symbols in 2x2 MIMO [19]

2.1.4 Radio Resource Management

The introduction of a new radio access technology, as well as an evolved network architecture in LTE, provides new opportunities to further increase the system capacity.

The objective of Radio Resource Management (RRM) in LTE-A is to utilize the radio resources as efficiently as possible and to serve users according to their Quality of Service (QoS) [19] [22].

This is achieved by applying different strategies and algorithms for controlling various mechanisms such as link adaptation, hybrid automatic repeat request, time and frequency domain packet scheduling, etc. Figure 2.6 shows the main RRM functionalities as well as its corresponding layer.

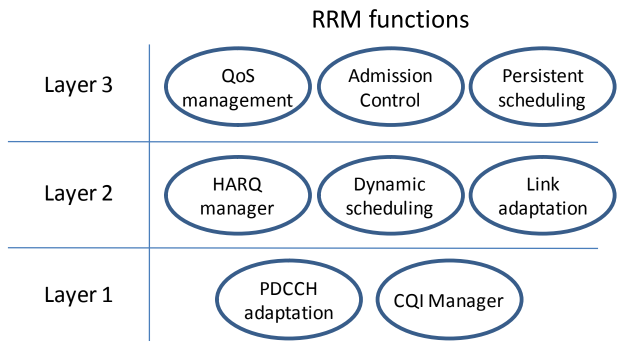


Figure 2.6: Overview of the RRM functionalities in each layer [19]

The Admission Control algorithm is the RRM functionality that decides whether to grant permission or reject the creation of a new data bearer. To take this decision, Admission Control takes into account the current resource situation of the cell, the QoS Requirements of the new data bearer, and its priority. A new request is granted only if the cell estimates that the requested QoS can be fulfilled without jeopardizing current sessions with equal or higher priority.

Layer 3 RRM functionalities are performed mostly during the setup of new data flows. For that reason, they are considered semi-dynamic mechanisms.

Layer 2 functionalities will be explained more in depth since they have a big importance in this work. These are: Link Adaptation (LA), dynamic scheduling and HARQ manager. These features are characterized as *fast dynamic* due to the fact that they are executed every Transmission Time Interval (TTI), which is 1 ms in LTE.

2.1.4.1 Hybrid Automatic Repeat Request

Every communication channel is subject to transmission errors due to unpredictable variations of the channel. For this reason, LTE employs an error correction mechanism called *Hybrid Automatic Repeat Request* (HARQ). This consists of a forward error-correction coding (FEC) and Automatic Repeat Request (ARQ). The former's principle is to introduce redundancy in the transmitted signal (typically convolutional or turbo code) that helps to correct a subset of errors that may occur, whereas the ARQ method is used to detect uncorrectable errors. If an error is detected, the transmitter will be notified by the receiver by sending a negative acknowledgement (NAK) and the same information will be retransmitted.

The HARQ in LTE is based on the use of a stop-and-wait HARQ procedure [19]. For negative acknowledgement the UE will not discard the packet, instead it will be combined with the retransmitted block and will be decoded again. When the decoding is successful (based on CRC check) the UE will send a positive acknowledgement (ACK) to the eNodeB.

There are two HARQ methods in LTE: Chase combining and the use of incremental redundancy. In Chase combining, that retransmission contains exactly the same information. For incremental redundancy, a different coded version of the message is retransmitted.

2.1.4.2 Link Adaptation

Link adaptation (LA) is a technique that consists of adjusting dynamically the modulation scheme and the coding rate in order to adapt to the variation of the channel quality. This means that, in situations with favorable channel conditions, the data rates might increase compared to a case with poor channel quality. The selected modulation and coding scheme (MCS) are signaled to the users on the PDCCH channel.

Channel Quality Indicator

The link adaptation parameters are primarily defined based on the Channel Quality Indicator (CQI) feedback from the UE. The CQI is a channel information report that provides information about the MCS that the UE is able to support at the time [19]. This information, which is based on the UE capabilities and the current channel condition, is used by the base station not only for link adaptation but also for scheduling decisions. Moreover, when outer loop link adaptation is used, the link adaptation unit can also take information from the HARQ acknowledgements from past transmissions in order to obtain more accurate results [23].

Reporting a CQI for every PRB will lead to excessive uplink signaling. For this reason, an LTE terminal can be configured to report information on specific sub-bands. It is important to mention that, the more detailed the report is, the bigger the gains that can be achieved from a frequency-domain scheduler. Therefore, several CQI report types have been defined in LTE that represents different tradeoffs between system performance and amount of signaling overhead. More detailed information about the CQI report configurations can be found in [19].

2.1.4.3 Packet Scheduling

The Packet Scheduler is the functionality that controls, in time and frequency domain, the allocation of the PRBs among users. This entity has a significant importance in wireless communication systems due to the fast changing nature of the channel and the diversity of the channel quality among users.

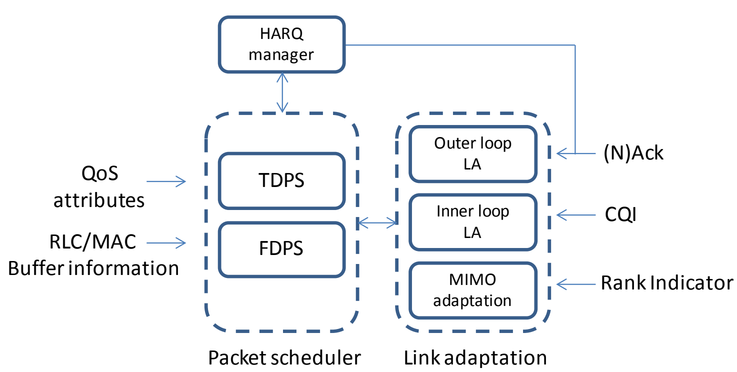


Figure 2.7: Layer 2 RRM Functionalities [22]

The Packet Scheduler is the main entity of Layer 2 and hence interacts very close with the Link Adaptation and HARQ units (see Figure 2.7). In fact, every TTI, the packet scheduler has to decide whether to send a new transmission or to perform an HARQ transmission. For each user, the LA chooses a modulation scheme and coding rate that will depend on the selected set of PRBs.

LTE is highly standardized by 3GPP; however, some of the network algorithms including link adaptation, power control and packet scheduling are vendor-specific [19] [24].

In this work, one of several packet scheduling implementation techniques is explained. As proposed in [23], it is a two step algorithm: first, a time-domain packet scheduler (TDPS) selects up to N potential users to be scheduled in the next TTI. The selection criterion is based mostly on QoS parameters. Second, a frequency-domain packet scheduler (FDPS) allocates the available PRB among the N selected users.

The FDPS takes advantage of the frequency-selective-fading channel and the multi-user frequency domain diversity; therefore, users are likely to be scheduled on PRBs where they experience a good channel quality. As mentioned previously, channel quality estimation is based on the CQI feedback from the UE, meaning that, the gains that can be obtained from a FDPS will depend on the accuracy of the CQI report, channel coherence time[2] and carrier bandwidth.

Scheduling Metrics – Proportional Fair

The scheduling decisions of the TDPS are primarily based on QoS requirement of the UEs whereas the FDPS is designed to benefit from radio channel multiuser frequency diversity. To accomplish the latter, several scheduling algorithms can be used hence offering different objectives such as: maximum cell throughput, equal resources scheduling, equal throughput, etc. In this study we consider a well-known scheduling algorithm called *Proportional Fair* (PF) which is in charge of assigning a numerical value (i.e. scheduling metric) to every UE according to the following expression:

$$M_{k,n} = \frac{\hat{r}_{k,b}[n]}{T_k[n]} \tag{2.1}$$

where $\hat{r}_{k,b}[n]$ is the instantaneous achievable throughput of user k on PRB b over the scheduling interval n, and $T_k[n]$ is the average delivered throughput in the past.

Proportional fair aims at maximizing the utility function expressed as the sum of $\log(R_i)$ over all users, where R_i denotes the throughput of user i; hence providing an attractive balance between total cell throughput and resource fairness among the users [25].

[2] The coherence time is the time duration over which the channel impulse response is considered to be not varying.

2.1.5 Carrier Aggregation

To satisfy the peak data rates required by IMT-Advanced, LTE must support wider bandwidths. That is why in LTE-Advanced a new feature is introduced: Carrier Aggregation (CA). This consists of the aggregation of multiple component carriers (CCs) of smaller bandwidth making possible the transmission of data in larger bandwidths.

The fact that large portions of continuous spectrum is rarely available, makes carrier aggregation a very appealing feature since it does not only provide an efficient and flexible way to deploy the spectrum, but also keeps backwards compatibility with older LTE terminals.

In the specific case of LTE-Advanced, up to 5 CCs of 20 MHz can be used simultaneously which leads to a substantial increase in the data rates [26]. There are three possible carrier aggregation scenarios: contiguous aggregation of carriers in a single band, non-contiguous aggregation of carriers in a single band and non-contiguous aggregation of components in multiple bands which, in principle, can have different bandwidths [13].

The implementation of Carrier Aggregation is not straightforward and requires some modifications in the UE and base station protocol stack. In the uplink direction, the UE physical layer must incorporate *N* parallels SC-FDMA transmitters in order to support non-contiguous aggregation of carriers. However, as shown in [16] [27], the use of multiple carriers in the uplink has several implications in the UE transmission power (power backoff issues); therefore, allocating more CCs to a UE in UL direction might not always result in a higher throughput due to transmission power limitations.

In layer 2, a single scheduling entity at the Medium Access Control (MAC) layer manages the separate data streams of each CC. As illustrated in Figure 2.8, each CC has its corresponding HARQ and LA unit meaning that link adaptation and HARQ retransmissions are performed independently in each CC hence matching the modulation, coding scheme and MIMO pre-coding according to the channel conditions of each carrier.

At higher layers, the user-plane architecture remains the same as previous LTE releases in order to maintain backward compatibility with previous LTE releases.

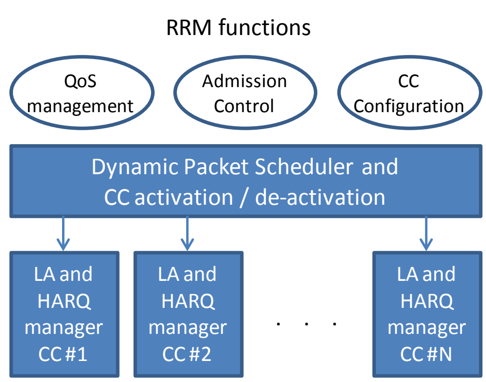


Figure 2.8: RRM algorithms with Carrier Aggregation [13]

Apart from the RRM functionalities mentioned above, a new mechanism is introduced with LTE-Advanced called *Component Carrier configuration* (see Figure 2.8). This new layer-three functionality is in charge of the configuration of the CC set for each UE [13]. The CC are assigned according to a series of parameters including QoS requirements, terminal capabilities, radio bearer configuration, cell load, among others; hence facilitating some techniques such as load balancing, interference coordination and QoS management techniques among the CCs. For example, CC configuration will make sure that a user with a low guaranteed bit rate requirement will be assigned a single carrier in order to not to unnecessarily increase the UE power consumption [16].

2.2 Heterogeneous Networks

Traditionally, mobile broadband networks are deployed as homogeneous networks consisting of macro cells. The placement of the macro base stations is carefully planned in order to allow the maximum coverage and manage the interference amongst them. In these networks all the base stations have similar transmit power levels, antenna patterns, backhaul connectivity and receive noise limit. Besides, all cells grant unrestricted access to the UEs in the network [4]. An example of a traditional network deployment can be seen in Figure 2.9.

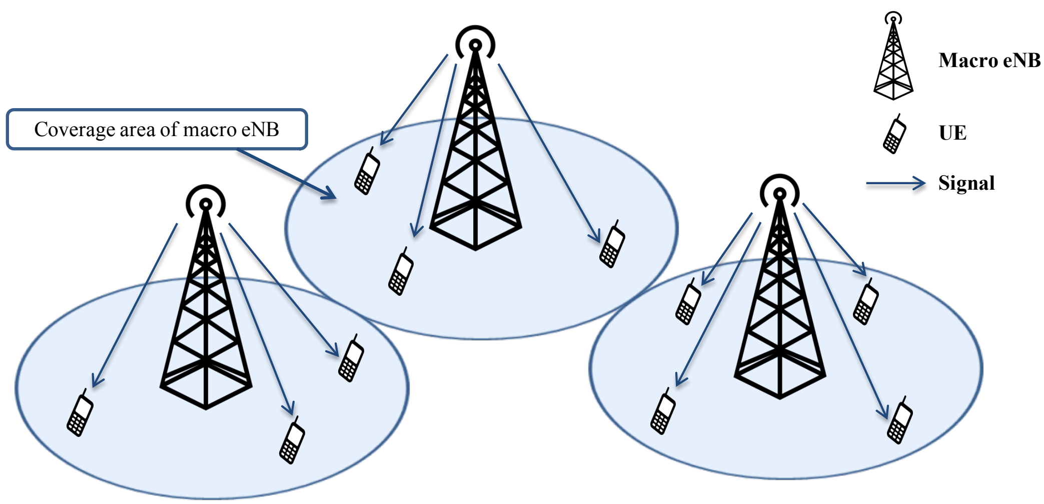


Figure 2.9: Traditional Network Deployment

A Heterogeneous Network (HetNet) consists of a series of low-power nodes that are distributed throughout the existing macro cell network. The LPNs (also called small cells) transmit at significantly lower power levels. This deployment allows to improve the spectral efficiency per unit area, as the low-power cells make possible to remove coverage holes in the macro-only network and increase the capacity in zones with very high traffic volume (usually called hotspots) [4]. Therefore, Heterogeneous Networks are envisioned as the major performance improvement enablers of LTE-Advanced [28]. A possible HetNet deployment is shown in Figure 2.10.

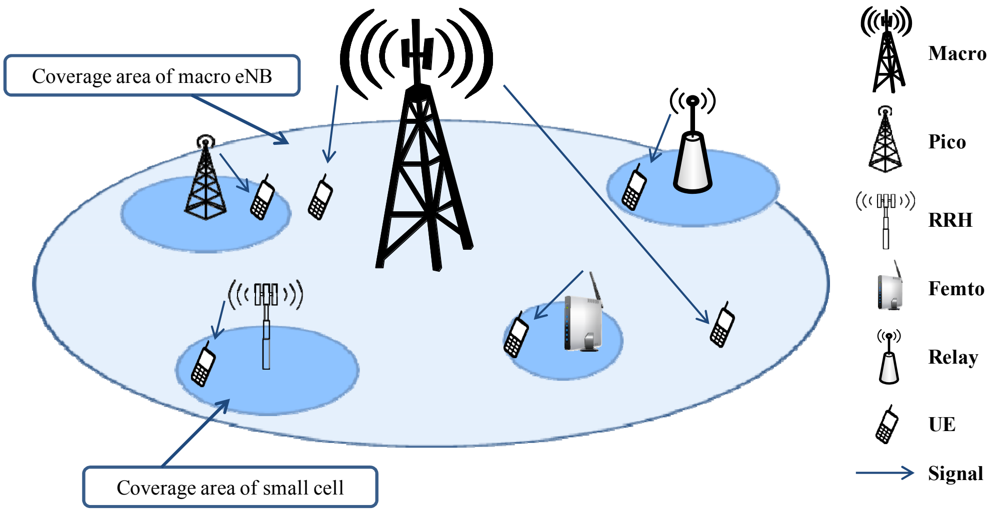


Figure 2.10: Heterogeneous Network Deployment using different low-power nodes

There are different types of small cells that can be deployed in a HetNet. Small cells can not only be operator deployed as macro cells, but also user deployed. Some of them can be coexisting in the same area. A summary of macro and small cells characteristics can be seen in Table 2.1 [16] [28]. A detailed description of the different small cell types can be found in [2] [4] [28], and a brief description is explained in Appendix A.

Types of nodes	Transmit power	Coverage	Placement	Access
Macrocell	46 dBm	Few km	Outdoors	Open to all UEs
Microcell	30 - 37 dBm	< 2 km	Outdoors	Open to all UEs
Picocell	23 - 30 dBm	< 300 m	Indoors or outdoors	Open to all UEs
Femtocell	< 23 dBm	< 50 m	Indoors	Open or restricted (CSG)
Relay	30 dBm	300 m	Outdoors	Open to all UEs
RRH	30 dBm	300 m	Indoors or outdoors	Open to all UEs

Table 2.1: Characteristics of macro and low-power nodes

Macro cells and most small cells are connected via S1 or X2 interface. These interfaces introduce some delay in the transmission. On the other hand, RRH nodes use a fiber fronthaul, which has nearly zero delay and, therefore, it can be considered as an ideal backhaul.

It is worth noticing that an ideal backhaul is considered thorough this study. However, for the sake of simplicity, we will refer to the small cells as pico cells.

Two different kinds of deployments can be used in a HetNet, as explained in [2]: co-channel deployment and dedicated carrier deployment. Following sections explain the main design features of each one.

2.2.1 Co-Channel Deployment: Key Design Features

In a co-channel deployment both macro and small cells share the same frequency carrier. This may be the only option if the available spectrum is limited. The key features to take into account for the design of the network are UE cell selection and interference management. These features will be studied in detail in the following subsections.

2.2.1.1 UE Cell Selection

In traditional homogeneous networks, the way of selecting cell for an arriving UE is based on the UE measurement of the received signal strength. The serving cell selected is the one with the highest signal. There are different signal strength indicators. In LTE the measurements carried on are [19] [29] [30]:

- ***Reference Signal Received Power (RSRP)***, which measures for each cell the average of the power of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth. This indicator reflects the received power from each cell.
- ***Reference Signal Received Quality (RSRQ)***, which is calculated dividing RSRP by the total received power, thus including the channel quality of the resources. This indicator provides additional information useful in cases when RSRP is not reliable enough for doing the cell selection or a handover.

Usually in co-channel deployments the cell selection is done based on the RSRP level. This will be also the approach used thorough this study. However, it is worth noticing that macro cells have much larger coverage areas than the small cells due to the large transmit power disparity between the macro and small cells, resulting in few users served by the small cells. It is desirable for the network to balance the load between the macro and pico layers to harvest the gain from cell splitting [31]. The most commonly used technique is the Range Extension offset [4] . Besides, researchers have also been proposing other algorithms for selecting the serving cell [32] [33] [34] [5] [6] .

Range Extension

A positive bias factor is added to the RSRP level of each pico cell, thus expanding their coverage area. This offset is called *Range Extension (RE)* [4]. A typical deployment using RE can be seen in Figure 2.11.

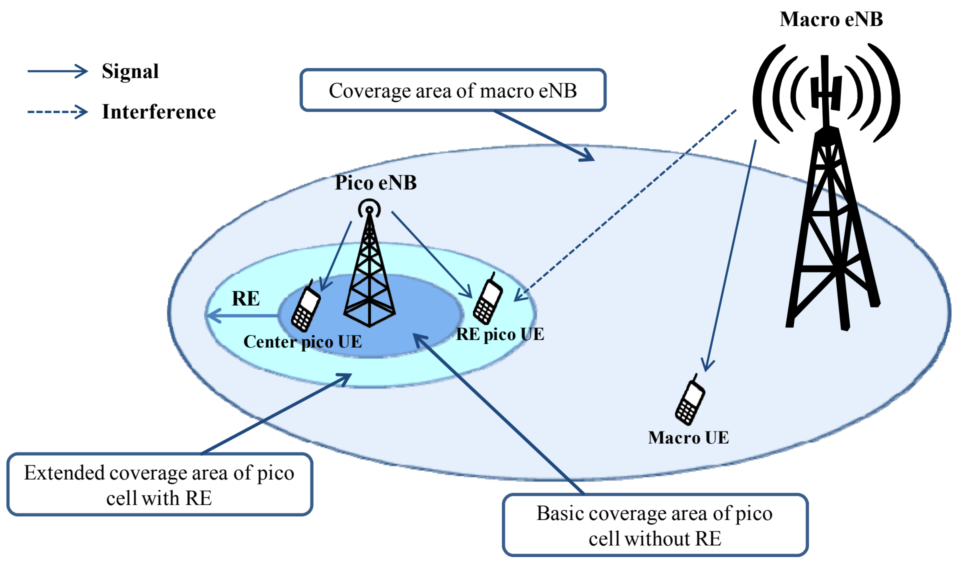


Figure 2.11: HetNet topology using RE in the pico layer

Adding this Range Extension offset, the cell selection is calculated as follows:

$$Selected\ cell = \arg max \left\{ RSRP_{macro}, RSRP_{pico} + RE \right\} \tag{2.2}$$

The selected cell is either the strongest macro signal or the strongest pico signal plus range extension. This gives some advantage to pico cells, pushing more users to them.

The value of the RE offset is signaled to the users using the Radio Resource Control (RRC) protocol [32]. The users in the network can now be categorized into three types:

- *Macro UEs*, those users that are connected to a macro cell.
- *Center pico UEs*, those users that are in the coverage area of the pico and are connected to the pico.
- *RE pico UEs*, users connected to a pico cell but positioned in the extended coverage area of the pico.

These types of users can be observed in Figure 2.11.

Although the RE technique allows to balance the load between the macro and small cells, thus improving the overall performance of the network, the selection of RE offset has to be done carefully:

- The users in the extended area of a pico cell may suffer strong interference from the macro. Thus, for these users in the RE area techniques of interference management and/or cancellation are of vital importance. These techniques will be studied in Section 2.2.1.2.

- It is recommended not to use large RE offsets without any interference management because that can increase the occurrence of Radio Link Failures (RLF) due to the poor channel quality experienced by users in the range extension area [35].
- It is not straightforward to obtain the optimal settings of the RE for different networks as it depends on several things like the load of the network, the number of macro and pico cells, the positions of the base stations, the inter-site distance, etc. It is needed to study each situation, and this creates a scalability problem.

A great amount of studies can be found solving the problem of obtaining the optimal cell selection, i.e., the cell selection that balances the load maximizing the network performance. It is interesting for this study to give an overview of some of the existing ideas and techniques.

Studies for Optimal Cell Selection

The previous approach with RE typically works in a slow basis, adjusting the range extension according to the traffic conditions using SON-based load-balancing algorithms [32]. Some cell selection techniques take into account instantaneous information from the network (e.g. specific BS load and channel quality) hence offering nearly optimal cell association.

Some of the most common algorithms are **load-based**. These algorithms focus on the load in each cell as decision criterion. In [32] the authors propose the number of users divided by the capacity of each layer as load measurement. This approach has the disadvantage of not taking into account the channel quality in each cell.

Other studies concentrate in the **SINR**, like in [33], where the authors propose to select the cell with highest SINR, measuring it during normal transmission subframes for macro cells and during ABS subframes for pico cells. In this case the load in each cell is not considered.

Besides, another option is implementing **throughput-based** algorithms. These kinds of algorithms aim to balance the load among the cells by selecting the one which offers best throughput, thus taking into account both the load in each cell and the channel quality. The throughput in each cell can be estimated based on a function of SINR and number of users, as proposed in [32]. This algorithm depends strongly on the current condition of the network when choosing the serving cell.

In recent years it is gaining popularity the logic approach known as **fuzzy logic**. The idea is to translate the operator experience in linguistic terms into several rules with IF-THEN syntax. The algorithm in itself it is flexible, as the designer can choose whatever KPIs depending on what it is desired to achieve, and the rules are also made for each case. This technique is usually used as part of SON (Self-Organizing Networks). The fuzzy logic approach has proved to be useful for different kinds of problems as it has many advantages: translation of the human knowledge into basic rules, dynamic adjustment to network conditions, possibility of implementing self-learning, and low computational complexity. As an example, the authors in [34] use this approach for the optimization of handover processes, obtaining good results. However, it is worth saying that this technique requires experienced human knowledge in order to get the best settings for optimizing the network performance.

For the interested reader, some examples of studies [5] [6] which implement algorithms for optimal cell selection are briefly explained in Appendix B. In said appendix there is also a comparative summary table of techniques for optimal cell selection.

In this study, we focus on studying cell selection based first on a Range Extension offset, and second, on load-based and throughput-based cell selection, comparing the performance of these approaches in an operator-specific scenario.

2.2.1.2 Time-Domain Interference Management

As both layers share the same frequency carrier in case of co-channel deployment, techniques with the objective of managing and minimizing the interference between layers are needed. The technique typically used in LTE is known as enhanced inter-cell interference coordination (eICIC).

TDM eICIC: Basic Principle [9]

The main principal of eICIC is that the macro cells mute transmission on certain subframes, allowing the pico users suffering from macro interference to be scheduled with better signal quality. In order to work properly, eICIC requires synchronization in time and phase among all the base stations in the same geographical area.

The muted subframes are called ABS (Almost Blank Subframes). During an almost blank subframe, the macro base station only transmits the strictly necessary information, such as common reference signals (CRS). Thus, although the interference to the pico users in the range extension area is far lower than during a normal subframe, it is not completely zero. Usually the remaining signal power is around 9% of the power in normal transmission mode, assuming a 2x2 MIMO configuration [36]. Only advanced UE terminals with the ability of cancelling CRS interference will experience nearly zero interference during ABS. This new feature included in 3GPP Release 11 is called CRS interference cancellation (CRS IC) [2].

As RE users are more affected by the macro interference, they are the ones getting greater advantage from ABS. It indicates that in order to get gains from eICIC the pico cells should schedule RE users mainly in subframes where the macro cells are using ABS, while the center pico users can be scheduled in any subframes. In order to do this, it is necessary for the packet scheduler and link adaptation of the base station to be aware of the muting pattern used in macro cells.

The muting pattern is the number of subframes configured with ABS in the macro layer. This pattern must be adjusted adaptively according to the traffic and interference conditions to get the best overall performance in the network, as using ABS has a negative effect in the macro layer capacity [3]. However, most studies have been focused in a slow muting adaptation, assuming an update in the ABS muting pattern each few seconds, due to the fact that this update relies on the information exchange through X2 signaling, and this signaling suffers from delays.

The study conducted in [10] proposes a way of performing a fast muting adaptation adjusting the muting pattern independently at each macro cell. The authors first evaluated the performance with a centralized RRM architecture, assuming that the small cells are implemented as RRHs. Therefore all necessary information is available at the macro and it offers opportunities for the macro to decide whether or not to mute a subframe based on the available network information. Besides, the authors also demonstrate the possibility of implementing the fast muting adaptation in a distributed architecture based on X2 signaling, although in that case the rate of adaptation limits the gain obtained.

Subframe Classification [10]

<u>*Slow Muting Adaptation*</u>

In traditional cases of slow or semi-static muting adaptation, two kinds of subframes are defined: normal subframe or ABS. The type of subframe limits which kind of users can be scheduled during it. Center pico UEs can be scheduled in any subframe as they are not very affected by macro interference. However, RE pico UEs are preferably scheduled during subframes when macro is muting, as they are more affected by the macro layer interference. Therefore RE pico users have higher scheduling priority than center pico UEs in muted subframes. Macro UEs cannot be scheduled in muted subframes as there is no data transmission in those subframes. Subframe classification and UE scheduling for slow muting adaptation are depicted in Figure 2.12.

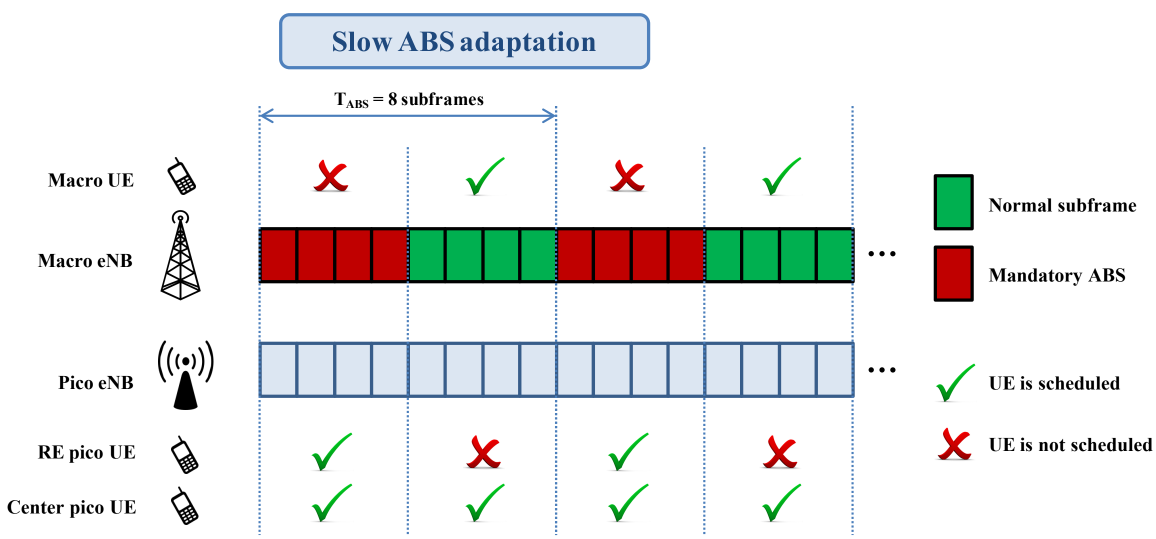


Figure 2.12: Subframe classification and UE scheduling for slow ABS adaptation [10]

Fast Muting Adaptation

Fast muting adaptation needs a new subframe, called optional ABS. This subframe can be used as a normal subframe or muted subframe, as needed. Again in this case center pico UEs can be scheduled in any subframe, but the scheduling preference is given to RE pico UEs in mandatory ABS or optional ABS used as ABS in order to fully benefit from muting. Figure 2.13 shows subframe classification and UE scheduling for fast muting adaptation.

It is important to notice that at least one normal and one mandatory ABS subframe must be defined for UE measurement purposes, as will be explained later. The number of optional ABS subframes can be configured according to the needs and the degree of adaptation. Generally speaking, the higher the number of optional ABS, the more dynamic the adaptation will be.

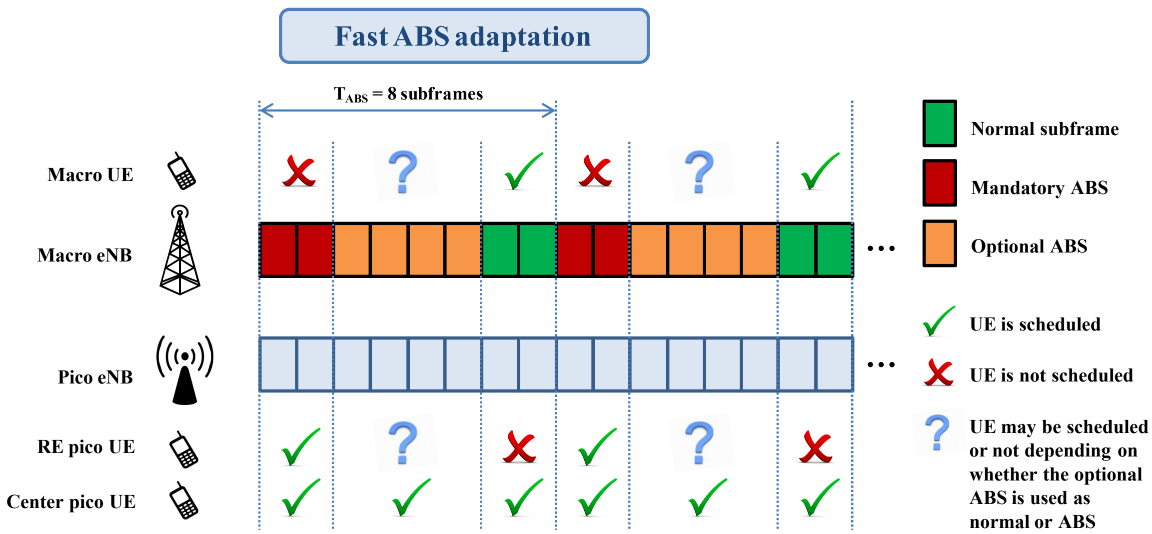


Figure 2.13: Subframe classification and UE scheduling for fast ABS adaptation [10]

Network Configuration of ABS Muting Patterns [9]

The ABS muting pattern is periodical with 40 subframes for FDD. This periodicity was selected to protect as much as possible the common channels. For TDD mode the periodicity changes depending on the UL/DL configuration.

The specifications of Release 10 include mechanisms to configure the ABS muting patterns in a dynamic and distributed way. The idea is to exchange ABS-related information between macro and pico cells in its coverage area using the X2 interface. Based on that information the macro cell can decide whether or not to change its ABS muting pattern, with the objective of maximizing the overall network performance. An example of this exchange of information through X2 signaling is illustrated in Figure 2.14.

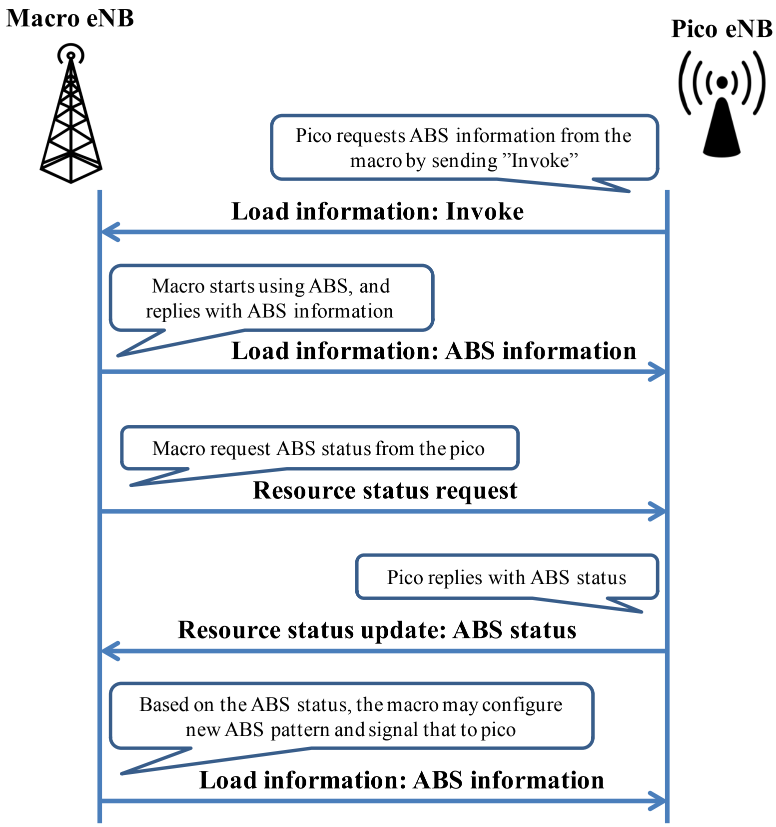


Figure 2.14: Example of X2 signaling for distributed coordinated adaptation of ABS muting pattern [3]

A pico eNB can request from the macro about the ABS muting pattern being used. The pico eNB needs this information to know in which subframes it should schedule RE users, as explained before. The way of asking for that information is sending to the macro a Load Information X2 message, with an Information Element (IE) Invoke, as shown in Figure 2.14. The macro eNB replies using a message with IE ABS information of its current ABS muting pattern. Besides, it is also possible for the macro to send a message of resource status request. This message asks the pico for information about the usage of the ABS resource. The pico eNB reports back the required information using a message with IE ABS status. From this the macro gets knowledge about how much of the ABS resource is blocked in the pico because RE users are scheduled or for other reasons. Not only that, pico can also inform which part of the ABS resource is not usable due to for instance to interference from other macro eNBs in the vicinity. With all that information the macro can decide whether to change the ABS muting pattern or not. If so, it informs the pico about the new ABS muting pattern by sending a message.

It is worth noticing that macro eNBs can also use this X2 signaling to inform each other about their ABS muting patterns. This is important because macro eNBs in the same area should use the same or overlapping patterns in order to get the maximum benefit from eICIC.

UE measurements [9] [10]

Using muting patterns causes variations in the network interference and it is necessary to restrict CQI measurements for Release 10 users so that two different CQI measurements are reported: one for normal subframes and the other for ABS [9].

In the case of fast muting adaptation optional ABS can be muted or not, so the solution is to configure UEs to measure CQI only in subframes that are semi-statically configured as mandatory ABS or normal subframes [10]. UEs will not measure CQI in optional ABS.

Fast Muting Adaptation: Algorithms

Two different algorithms for fast muting adaptation are proposed in [10]: one based on instantaneous load, and one based on proportional fair (PF) metrics.

Instantaneous Load Based Algorithm (IL-ABS)

This algorithm is based on the instantaneous load and number of muted subframes. The following notations are used:

- **Load:**
  - Number of macro users: u_{macro}
  - Number of pico RE users: u_{RE}
  - Total number of users in the cluster[3]: U
- **ABS subframes:**
  - Number of normal subframes: n
  - Number of ABS subframes: z
  - ABS period: T_{ABS} (typically 8 subframes)

For each optional ABS subframe, the algorithm works as follows:

1. Ensure first the service of macro users, as the coverage area of the macro is bigger and, moreover, macro cell-edge users cannot be served with reduced interference.

$$\frac{u_{macro}}{U} < \frac{n}{T_{ABS}} \tag{2.3}$$

2. If (2.3) is fulfilled, check ABS subframes assigned to RE users and mute current subframe if those users do not have enough ABS resources assigned:

$$\frac{u_{RE}}{U} > \frac{z}{T_{ABS}} \tag{2.4}$$

[3] Cluster is defined in 3GPP scenarios as the group of picos within the coverage area of a certain macro.

Proportional Fair Based Algorithm (PF-ABS)

This algorithm is based on the PF metrics at the macro and pico layer. The information used for the PF metrics is:

- Estimated throughput for each user at a certain PRB group and time.
- Estimated long-term average throughput for that user at a certain time.
- Total number of users at the macro and the pico cell.

A detailed explanation about how to calculate the PF metrics can be found in Section 2.1.4.3. The idea is to capture the average user throughput as well as the instantaneous channel quality. The averaged PF metrics at the macro and pico layer provide information about if the layer throughput is improving or deteriorating. With this information the algorithm decides how to change the muting pattern at the beginning of each ABS period as follows:

1. If the pico layer is deteriorating and, at the same time, the macro layer is improving, then increase the muting ratio[4].
2. If the previous condition is not fulfilled, check if the macro layer is deteriorating and, if that is true, decrease the muting ratio.

This algorithm is fairer to the users than IL-ABS as it takes into account the instantaneous channel condition. However, it is more computationally complicated.

It is worth mentioning that in this study we focus on the IL-ABS algorithm.

These algorithms are focused in resource partitioning, and resources are fairly distributed between the macro and pico layer. Performance could be further improved by using an appropriate algorithm for the cell selection in conjunction with fast muting adaptation.

Some studies propose techniques for solving cell selection and interference management simultaneously with the same algorithm. So far those techniques are theoretical analysis. It is quite hard to implement them in real networks as they are very complex and require a lot of computation. This study will not be focused on that kind of techniques, but for the interested reader, an example can be found in [7].

[4] Muting ratio is the number of muted subframes in each ABS period.

2.2.2 Dedicated Deployment: Key Design Features

In a dedicated deployment there is no interference between the macro and pico layer. However, the spectrum is segmented. To solve this problem the feature known as inter-site Carrier Aggregation (CA) is included in LTE Release 10. This technique allows a certain UE the possibility of connecting to both the macro and the pico layer, thus fully utilizing the spectrum resources. UE connection in CA mode is depicted in Figure 2.15.

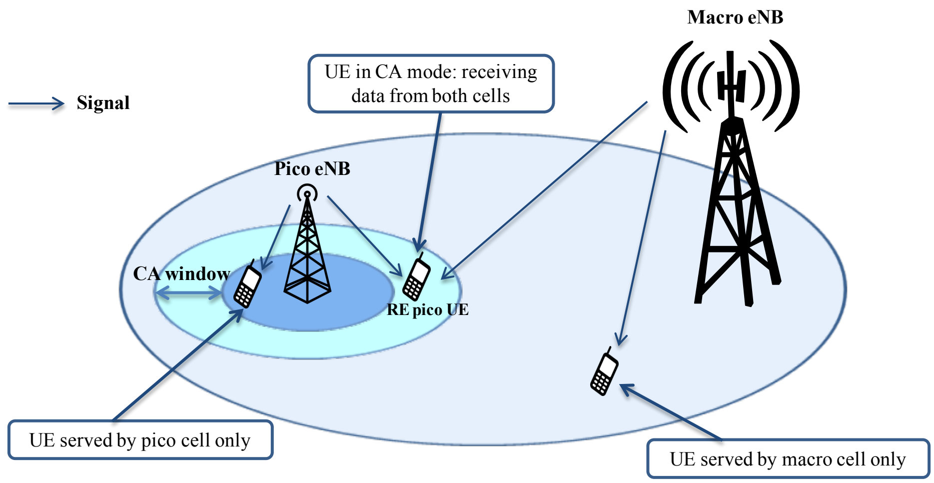


Figure 2.15: Diagram of connection in CA mode showing CA window concept

For legacy UEs not supporting inter-site CA, they can only be served by one serving cell and the corresponding cell association algorithm is explained in Section 2.2.2.1. For CA capable UEs, they have the possibility to be served by a macro cell and a small cell simultaneously, hence benefitting from the availability of ideally double transmission bandwidth. . However, some users may have a very bad signal quality to one of the layers. In those cases, it is not beneficial to operate with inter-site CA, as it costs more to the network and UE in terms of signaling and power consumption than the gains that could be obtained from CA [27]. Two different conditions can be used to determine whether CA capable UEs should operate with inter-site CA or not, and these conditions are explained in Section 2.2.2.2.

2.2.2.1 RSRQ + RE

In cases where inter-site CA is not supported, the cell selection is done in a similar way as in a co-channel deployment. However, in this case the metric chosen is RSRQ instead of RSRP, as it captures the channel quality of the respective resources. This signal indicator is more representative in a dedicated case because the macro and pico layer are deployed at different frequency carriers, which means that now the interference in each layer will be quite different. It is usually assumed that the macro layer is deployed at a lower frequency than the pico layer to ensure a wide coverage area for the macro layer, as pathloss is smaller at lower frequencies [37].

In a dedicated deployment the coverage area of the two layers may vary depending on the frequency in which they are deployed. Also, the interference is different in each layer. This means that load conditions in each layer can vary a lot depending on the deployment. For cases with unbalanced load between the layers, it is used the same concept of Range Extension offset explained in co-channel deployments. The cell selection is done as follows:

$$Selected\ cell = \arg max \left\{ RSRQ_{macro}, RSRQ_{pico} + \ RE \right\} \tag{2.5}$$

This means the serving cell selected is either the strongest macro signal or the strongest pico signal plus range extension. The RE operation is referred to in Figure 2.11. It is worth noticing that in this case RE can be either a positive or a negative value, depending on whether the macro layer is over loaded or under loaded as compared to the pico layer. Typically the macro layer is more loaded as macro coverage areas are usually larger, indicating that in most cases the RE will be a positive value.

The values of RE offsets have to be carefully set in order to optimize the network performance. This can be nearly non-relevant in cases where most of the users are operating with CA, but should be carefully taken into account if a considerable amount of users are not in CA mode.

It is also found that the load balancing techniques proposed in Section 2.2.1.1 can be adapted and applied in the dedicated case.

2.2.2.2 CA Conditions

The techniques used to determine if a certain CA capable UE should operate in CA mode are: CA window and RSRQ threshold.

CA Window [12]

The CA window limits the maximum RSRQ difference between the two candidate cells in the two layers. The operation works as follows:

$$\left| RSRQ_{macro} - \ RSRQ_{pico} \right| < CA_{window} \qquad \text{(2.6) } \textbf{[12]}$$

If (2.6) is fulfilled, the UE connects to both macro and pico. Otherwise, UE connects to the cell with the best RSRQ plus RE offset, as described in the previous section without inter-site CA. Figure 2.15 shows the concept of CA window.

The study conducted in [12] showed that the best performance was achieved when all the users are in CA mode (assuming all UEs to be CA capable), which means that the CA window is set to be infinity to allow all users to connect to both layers. However, these results are ideal. In real conditions, the CA window cannot be set arbitrarily large, because allowing users to connect to a layer with very bad channel quality does not bring any gains but costs the additional resource consumption in the network, as explained previously.

RSRQ Threshold [38] [39]

For UEs configured with inter-site CA, the assumption is that users have their Primary Cell (PCell) configured on the best macro cell, with the option of also having a small cell configured as their Secondary Cell (SCell) when feasible. RSRQ threshold limits the minimum RSRQ level for the secondary cell.

If the pico cell has a RSRQ level above the RSRQ threshold, then the UE will be allowed to operate with inter-site CA, connecting to both layers. Otherwise, the UE connects to the best macro cell.

The lower the RSRQ threshold, the more users are allowed to operate with CA mode. However, similar to CA window, too low level of the threshold is not recommended due to the bad channel quality at small cells.

Chapter 3

3 System Model and Simulation Assumptions

This study focuses on investigating the performance of some of most popular HetNet techniques applied to an operator-specific scenario; however, the performance obtained when using these techniques in generic 3GPP scenarios will be often used as a reference (see references in Chapter 1). For this reason, in this chapter, a description of both the 3GPP standard scenarios and the operator-specific scenario to be used in this study is presented, making special emphasis in the most relevant differences between these two cases. Finally, specific simulation assumptions and methodology are also described throughout this chapter.

3.1 Generic 3GPP Scenarios

To facilitate the evaluation and comparison of different mobile technologies and features across the industry and academia, the 3rd Generation Partnership Project (3GPP) proposes several deployment scenarios for both homogeneous and heterogeneous networks (see [40] [41] for more information) as well as system simulation baseline parameters (e.g. channel and traffic models) and the recommended key performance indicators (KPIs) for evaluating the performance.

A typical 3GPP HetNet model consists of a regular hexagonal grid of 3-sector macro sites, placed with a fixed inter-site distance (ISD) of 500 m. A fixed amount of small cells are randomly deployed at each macro cell area with a minimum ISD of 20 m. Regarding the user distribution, several spatial distributions are proposed, ranging from uniform distribution to hotspot distribution in which 66% of the UEs are placed in the vicinity of the small cells.

Figure 3.1 shows an example 3GPP scenario network layout in which 4 small cells are deployed in each macro sector area in form of a cluster (i.e. small cell scenario #1-#2a [41]). Red circles represent macro sectors pointing according to the black line direction. Green triangles represent the pico base stations.

Additionally, 3GPP also defines some assumptions such as pathloss models, antenna patterns and gains, etc. Pathloss is modeled according to commonly accepted stochastic models that reproduce typical observations from dense urban environments. Two propagation models are defined: 3GPP and ITU pathloss model. The former consists of a deterministic distance dependent component plus two independent stochastic components for shadow fading and fast fading. The latter is a more advanced model that includes separate models for line-of-sight (LOS) and non-LOS (NLOS) links, spatial correlated models for shadow fading, among other assumptions explained in [42]. Regarding the antennas, a directional 3D antenna pattern with down-tilt is modeled for the macro cells, while small cells are simply equipped with omni-directional antennas.

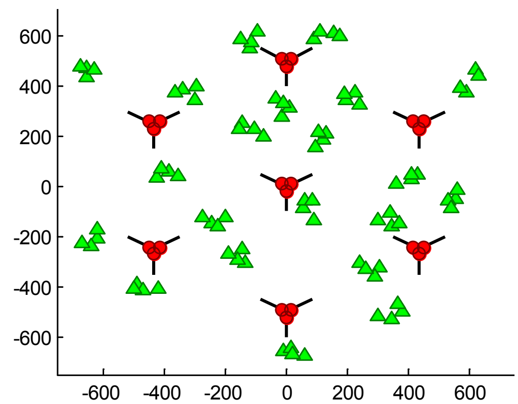


Figure 3.1: Example of 3GPP Scenario network layout

3.2 Operator-Specific Scenario

In this section the case-specific network scenario to be used in this study is presented. This scenario is very irregular and, therefore, a detailed description of the main elements is given. The layout corresponds to a real network deployment located in London city. Real macro site locations as well as realistic user traffic information and pathloss prediction from ray-tracing tool are available in order to be able to reproduce, as accurate as possible, the entire network environment.

3.2.1 Network Layout Description

The investigated area, which covers approximately 1.2 km^2, consists of four 3-sector macro sites (inner BSs) and 30 pico cells. Additionally, 221 macro sectors from 80 sites (outer BSs) located outside the examined area are used for generating interference (transmitting with full power) in order to avoid border effects.

The area of interest can be regarded as a “Hotzone” i.e. an area with intensive mobile data usage. Macro site locations, antenna heights and tilts, etc are from real network deployment and correspond to already existing 3G macro sites in the operator-specific network which, in this specific study, are considered to be reused for LTE deployment. On the other hand, pico cells are not provided; instead, they are deployed according to a criterion later explained.

Figure 3.2 illustrates the network layout used in this study. Red circles and white circles represent inner and (some) outer macro sectors respectively that are pointing according to the black line direction. Green triangles represent the pico base stations.

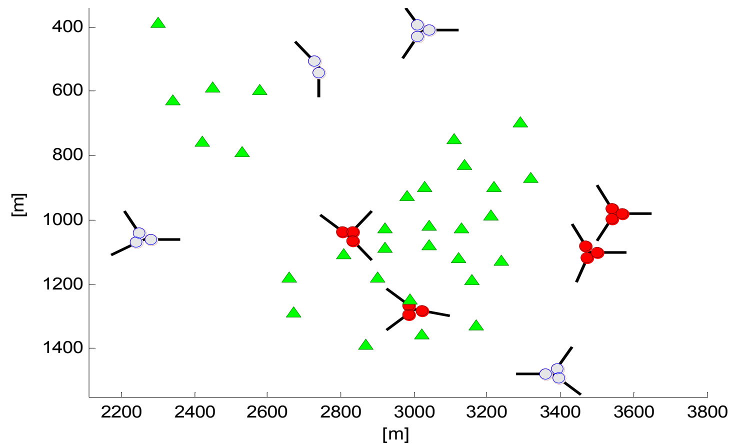


Figure 3.2: Operator-specific network layout

In this scenario, the ISD between 2 neighbor macro sites is 365 meters on average. However, as is shown in the CDF in Figure 3.3, the ISD is very irregular across the network and varies from 92 meters to 740 meters.

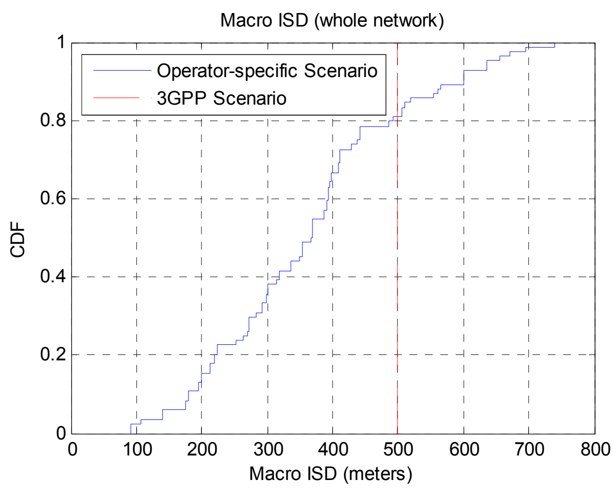


Figure 3.3: Inter-site distance CDF of macro base stations.

Table 3.1 summarize ISD statistics for both macro and pico cells. It is observed that, in the scenario under study, the ISD of the macro sites is generally smaller and much more irregular than standard 3GPP scenarios, in which the macro sites are placed in a hexagonal grid with a fixed ISD of 500 m.

Inter-site distance (meters)			
	Min	Mean	Max
Macro (whole network)	92.20	364.68	740.41
Macro (area of interest)	138.92	215.49	292.06
Pico (area of interest)	58.31	103.91	243.31

Table 3.1 ISD statistics for the operator-specific scenario

Small Cells Deployment Strategy

The small cells were generated using a network planning tool. The main goal was to reduce the overall user outage probability, i.e. the percentage of users that experience a data rate below a predefined value. The optimal locations were found by executing an algorithm that iteratively shifts the position of the pico cells to new locations in the candidate area until the best outage level is achieved. In this particular case, the candidate area consisted of all the possible outdoor locations within the region. As shown in Figure 3.4, the small cells were finally placed in feasible locations such as along streets or adjacent to buildings. More information about the small cell placement algorithm and the deployment criterion can be found in [43] and [37] [44], respectively.

3.2.2 Traffic Distribution

Figure 3.4 shows the spatial traffic distribution in the operator-specific case. This traffic distribution is provided by the operator and corresponds to traffic measurement campaigns under busy hours. In this particular study, 80% of the traffic is assumed to be generated indoors locations whereas the remaining 20% corresponds to outdoor areas. This behavior can be observed in Figure 3.4 where each traffic hotspot takes the shape of the area where it is generated, e.g. office buildings, shopping malls, etc. Moreover, the indoor traffic has been further distributed among the various floors of the buildings; in this particular case, the distribution is uniform across all building floors. The consequences in terms of received power are explained in the following sub-section.

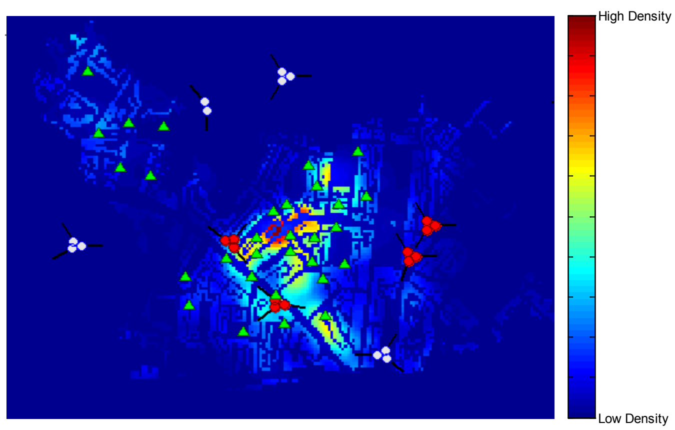


Figure 3.4: 2D spatial UE traffic distribution and cell layout for the operator-specific scenario. Base stations are represented similar to Figure 3.2. The rest of the map represents the traffic density.

The traffic density map illustrated in Figure 3.4 shows that there are some areas with a very high user density; whereas some others have nearly no traffic. In order to have a better understanding of the traffic density, Figure 3.5 shows the traffic distribution in terms of the amount of traffic that is generated in a certain percentage of the most active territory. The most common user distribution models defined by the 3GPP are also shown for comparison.

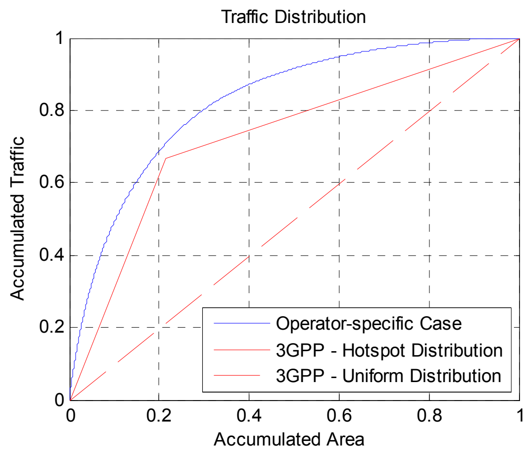


Figure 3.5: Traffic distribution in terms of the amount of traffic that is generated in a percentage of the most active territory. Operator-specific case and 3GPP generic distributions are shown.

From Figure 3.5 it is observed that the traffic distribution in this specific case is very irregular. For example, 10% of the most active territory accounts for 50% of the total offered traffic. The 3GPP hotspot distribution[5] also has very irregular traffic distribution; however, the traffic is assumed to be uniform in both the hotspot area and the rest of the macro coverage area, which clearly differs from the traffic distribution in the site-specific scenario.

In order to model this spatial traffic distribution, two traffic models will be used in this study: finite-buffer and full-buffer. These two traffic models are very different in terms of traffic density and interference variation.

Full-Buffer Traffic Model

This traffic model consists of a fixed amount of UEs that are placed in the network according to the traffic density map shown in Figure 3.4. These UEs are always active and have an infinite buffer in the eNB to download, hence staying in the network for the whole simulation. The full buffer traffic corresponds to high load conditions. In other words, in this traffic model the network conditions remain static and, for this reason, it is often considered to be non-realistic.

Finite-Buffer Traffic Model

In this model, the traffic has a bursty behavior meaning that the network conditions are continuously changing. In this study a dynamic birth-death traffic model is applied for generating user

[5] Hotspot distribution for 3GPP Small Cell Scenario #1-#2a in [41]: a 70 m – radius cluster with 66.6% of the total traffic is placed within each macro cell coverage area.

calls. The users arrive according to a Poisson process with arrival rate λ. The position of arrival is determined by the traffic density map shown in Figure 3.4, meaning that, the higher the traffic density in a certain area, the more probable is that a user arrives in that area.

Each user call has a finite payload size of B Mbits. Once the payload has been successfully received by the UE, the call is terminated and the UE is removed from the simulation. Thus, the average offered load in the network equals λ×B.

Since this traffic model is more similar to the traffic expected in a real network, this will be the one used in most of the performance evaluations in the network.

3.2.3 Pathloss Maps

To accurately estimate the propagation, a 3D ray-tracing tool was used to determine pathloss and antenna pattern effects of the radio links between the cells and users. A 3D topography map of the analyzed area provided realistic information about street and building sizes and positions.

For outdoor areas, which make up for approximately 60% of the analyzed region, the pathloss prediction was calculated using the *dominant path model* [45] [46]; for indoor locations, an outdoor-to-indoor penetration loss of 20 dB plus 0.6 dB per indoor meter is added to the highest received power among the external walls. Pathloss maps were generated at a height of 1.5 m, which corresponds to the assumed UE height of the outdoor/ground floor users; for users located at higher altitudes, a floor gain of 3.4 dB per floor is added to the received signal from the macro cells.

Figure 3.6 illustrates the dominance area of the 12 macro cells in the area of interest. It can be observed that, due to diffractions, the dominance areas of the cells are very irregularly shaped and, in some cases, take the shape of streets, parks, open squares, etc.

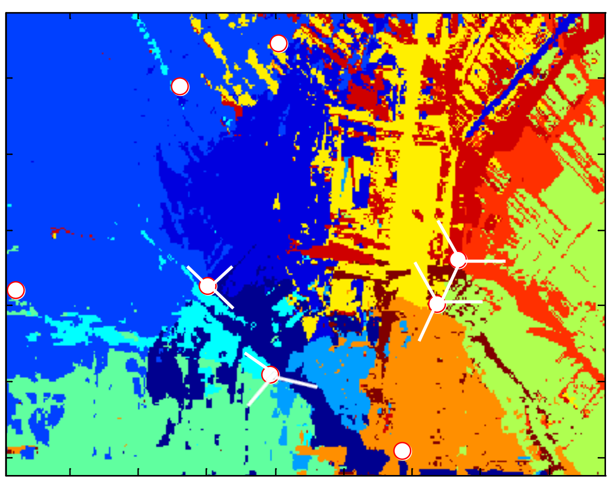


Figure 3.6: Dominance area of the 12 inner macro sectors at 2.6 GHz. Each color represents a different macro cell.

3.3 Simulation Assumptions

The network layout used in this study was described in the previous section. Table 3.2 shows a summary of the main network elements.

Parameter		Value
Macro eNodeB	**Macro eNodeB Position**	Network input data
	Supported Carrier Frequencies	2.6 GHz
	Antenna configuration	Realistic antenna pattern Gains, cable losses and vertical tilts: network input data
	Antenna height	Network input data. Average: 31 m
Pico eNodeB	**Pico eNodeB Position**	Outage-driven. Minimum ISD: 40 m.
	Carrier frequency	2.6 GHz
	Antenna configuration	Omni antenna pattern Gain: 5 dBi
	Antenna height	5 m
Scenario Topology	**Terrain height**	Digital Elevation Map
	Area	1.197 km²
	Radio Propagation	Ray-tracing tool. Dominant Path Model
	Prediction Height	1.5 m
	3D Building Map	Overall Indoor area percentage: 40 % Floor Height: 3.1 m Average Height: 12 m Number of Buildings: 715
	Floor Gain	3.4 dB/floor added to macro cell received power only
	Indoor Propagation	20 dB Penetration Loss plus 0.6 dB per indoor meter

Table 3.2: Macro eNodeB, pico eNodeB, and scenario topology description

3.3.1 System-level Simulator Assumptions

All the elements of the operator-specific scenario described throughout this chapter were imported into a system-level simulator. This simulator follows the LTE specifications, including detailed modeling of major RRM functionalities such as packet scheduling, hybrid ARQ and link adaptation explained in [22]. The simulation methodology follows the 3GPP guidelines: every TTI, the packet scheduler entity decides how to distribute the available resources (i.e. PRBs) among the active users. For the selected set of PRBs, the link adaptation functionality decides an appropriate modulation and coding scheme for the transmission which is determined by the frequency-selective CQI measurement reported by the UE. Next, a link-to-system-level mapping is applied to determine whether the transmission was successfully decoded; this is done taking into account the experienced SINR per subcarrier of each scheduled user. In case of transmission error, the packet is retransmitted by the HARQ unit using ideal chase combining.

Additionally, a closed loop 2x2 single-user MIMO with pre-coding and rank adaptation is assumed for each link and the UE receiver type is Minimum Mean Square Error (MMSE)-Interference Rejection Combining (IRC) [47]. The UEs are considered to be LTE-Advanced compliant meaning that CQI measurement restrictions and CRS IC cancellation are assumed. Table 3.3 contains an overview of the general simulation assumptions.

Parameter	Setting/Description
Network Layout	Operator Specific Scenario: 12 macro sectors (4 macro sites) and 30 small cells in the area of interest. 221 interfering macro sectors outside the area of interest.
Transmit power	Macro eNodeB: 46 dBm; Pico eNodeB: 30 dBm
Component Carrier Frequency	10 MHz at 2.6 GHz
Pathloss	Realistic pathloss maps from ray-tracing tool
Fast Fading Model	Typical Urban with 20 taps
Antenna Configuration	2 x 2 MIMO with rank adaptation
Antenna Gains:	Macro: network input data, Pico: 5 dBi, UE: 0 dBi
UE distribution	Realistic User distribution provided by operator
UE location	20% outdoor UEs, 80% Indoor UEs
Receiver type:	MMSE-IRC
HARQ	Ideal chase combining with maximum 4 transmissions
BLER target	10 % (first transmission)
Link Adaptation	Fast AMC
Available MCS	QPSK (1/5 to 3/4), 16QAM (2/5 to 5/6), 64QAM (3/5 to 9/10)
Packet Scheduler	Proportional Fair
CQI delay	6 ms

Table 3.3: Summary of simulation assumptions

The traffic models described in Section 3.2.2 are applied. The simulation assumptions used for these traffic models are summarized in Table 3.4.

Traffic Model	Parameter	Value
Full-Buffer	Number of runs[6]	5
	Simulation time per run	5 s
	Amount of UEs per run	610
Finite-Buffer	Average offered load per macro cell	10 – 60 Mbps
	Payload	4 Mbps
	Simulation time	Depending on the load: at least 2800 finished calls

Table 3.4: Simulation assumptions for full-buffer and finite-buffer traffic models

In both traffic models the traffic is regarded as *Best Effort*. The proportional fair scheduler assigns similar amount the resources among the users in the long term. Due to the adaptive modula-

[6] For each run, a different subset of UEs is simulated, in order to have more accurate results.

tion and coding, in finite buffer case, users having good channel conditions are likely to get a higher throughput and complete their payloads faster than those with poor conditions.

Finally, the following considerations regarding the system-level simulator are taken into account:

- The UEs are considered to remain static (no mobility) during the simulation. No handover procedure is considered, meaning that the serving cell(s) will remain the same during the simulation.
- Outer base stations are configured to transmit with full power in the whole band. When a static eICIC muting pattern is applied to the network, these base stations will also mute with the same muting pattern.
- An ideal backhaul is assumed between the eNBs.
- The offered load in the network is configured according to the traffic density map. This means that, for the same offered load, some regions of the network will experience a higher load than others. In order to maintain consistency with related works done in 3GPP scenarios, the offered load in the network is expressed in terms of average offered load per macro sector area, which is calculated as the division of the offered load in the network by the number of macro sectors in the area (12 sectors in this study).
- Statistics are only collected for UEs served by base stations in the area of interest. For this reason, the resultant average offered load in the network is not exactly the same as the configured.
- Each macro base station has a unique ID which is the one used when plotting specific statistics per cell. A map containing the IDs of each cell can be found in Appendix C.

3.3.2 Key Performance Indicators

In this study, the generated results from system-level simulations are post-processed and compared using statistical tools. The Cumulative Distribution Function (CDF) is used as the main function to analyze the results. The Key Performance Indicators (KPIs) used in this study are defined as:

- Median user throughput: corresponds to the 50^{th} percentile of the user throughput CDF.
- 5%-ile user throughput: this is the throughput achieved by the 5% worst users. This measure represents the throughput achieved by those UEs in very bad conditions, normally cell-edge users.

Besides, special attention is paid to some other metrics such as: cell load measured in terms number of active users, ratio of users offloaded to the small cells, and finally, the system capacity which is defined as the maximum offered load that the system can handle with a certain minimum 5%-ile user throughput (e.g. 2 Mbps).

Moreover, fairness in the achieved throughput among the users is studied through Jain's Fairness Index, which is calculated according to the following expression:

$$J(R_1; R_2; \dots; R_U) = \frac{\left(\sum_{u=1}^{U} R_u\right)^2}{U \sum_{u=1}^{U} R_u^2} \tag{3.1}$$

where R_u is the throughput of user u, and U is the total number of users. This index varies from $\frac{1}{U}$ (when all resources are given to a single user) to 1 (when all users obtain equal throughput).

It is worth mentioning that in this study, the goal is to maximize the overall system capacity. For this purpose, in co-channel deployment, the considered as "best configuration" will be the one that maximizes the 5%-ile user throughput.

All the KPIs that have been described in this section will be used to analyze the global performance of the network, i.e. statistics obtained from all the users and base stations in the area of interest; however, due to the irregularity of the scenario layout, the performance will also be studied in different "sub-areas" of the network which are shown in Figure 3.7.

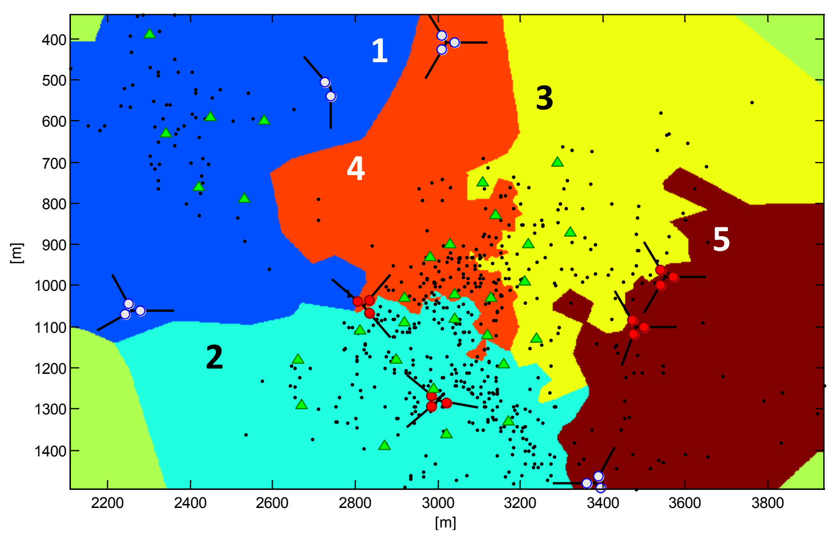


Figure 3.7: Sub-area division showing geographical UE distribution

For this local performance analysis, the statistics are separately collected from the users following the geographical division shown in Figure 3.7. These 5 areas were obtained by analyzing strongest-macro-interferer statistics of the users in each pico cell in order to create macro-pico associations. As depicted in the figure, some regions comprise multiple macro and pico base stations (e.g. area 2 and 3) due to the fact that, in some cases, it was not possible to determine a dominant macro aggressor for the users of a certain pico cell. In those cases, the region was separated containing all the macro cells with similar interference level to the pico cell users.

From Figure 3.7, it is observed that there are multiple differences between the areas, especially in terms of macro and pico cell density, user distribution, etc. These and other factors affect the potential benefit of the multi-cell cooperation techniques [48] [49]. For example, larger gains are likely to be obtained in areas with high small cell density (e.g. area 4); whereas, no benefit from eICIC/inter-site CA is expected in area 5, which is a macro-only sector.

The main characteristics of each area are summarized in Table 3.5.

Area	Characteristics			
	No. of Macros	No. of Picos	Picos per Macro	UEs (%)[7]
1	1	6	6	11.4
2	4	11	2.75	41.47
3	2	6	3	19.25
4	1	7	7	19.53
5	4	0	0	8.35

Table 3.5: Summary of characteristics for each region

[7] Percentage of users from all the network that are in each region

Chapter 4

4 Algorithms and Performance for Co-Channel Deployment

This chapter focuses on studying several cell selection and interference management techniques applied to the real operator scenario described in Chapter 3, and the performance obtained applying these techniques in the operator scenario for co-channel deployment.

4.1 Dynamic Configurations

This section focuses on explaining the different dynamic algorithms that will be studied in this project. As explained previously, the two main problems that need to be addressed in order to improve the network performance are: eICIC and cell selection.

The first item is eICIC, for which Fast Muting Adaptation algorithm (also known as Fast ABS) is proposed as dynamic solution.

The second item is cell selection. Typically a fixed RE is used in the whole network. This approach allows balancing the load between macro and pico while neglecting potential benefits of intra-layer load balancing. Besides, a fixed RE does not adapt to the varying conditions in the network. To further improve the performance, cell selection should also be configured in a dynamic way. For this, two different dynamic cell selection algorithms are proposed: Throughput-based Cell Selection and Load-based Cell Selection. Both of them will be used in combination with the Fast ABS algorithm, thus enabling dynamic cell selection and eICIC configuration.

4.1.1 Fast Muting Adaptation

All the details about how Fast ABS works were presented in Section 2.2.1.2. The idea is to dynamically change the number of muted subframes in each macro cell according to the number of victim users (RE pico UEs) affected by that macro, while ensuring enough resources for the users served by the macro.

As explained in the aforementioned section, the results in this study will use the IL-ABS algorithm, for the sake of simplicity. The pseudo-code for this algorithm can be found in [10].

The authors in [10] use the concept of "cluster", so that all users connected to the picos within a cluster will be reported to the macro. This approach works fine in 3GPP scenarios. However, when applying to the operator scenario the problem is that no clusters are defined in the operator scenario. It is necessary to find a solution so that Fast ABS can be applied to the operator scenario. In this study it is proposed to report information to the macro cells based on the UE measurements instead of using the clusters.

Report to macro cells based on UE measurements

The operator scenario is very irregular, which makes difficult to associate each pico cell to a certain macro cell. This was explained in Section 3.3.2, where the separation of the network in regions resulted in areas containing more than one macro cell because several macro cells were affecting the same pico cells.

The reason is that in some cases the coverage area of the pico is not in the dominance area of only one macro cell as in 3GPP scenarios. The operator scenario is more complex, and sometimes the users in some part of the coverage area may be affected by a different macro cell than users in other part of that same coverage area, as can be seen in Figure 4.1.

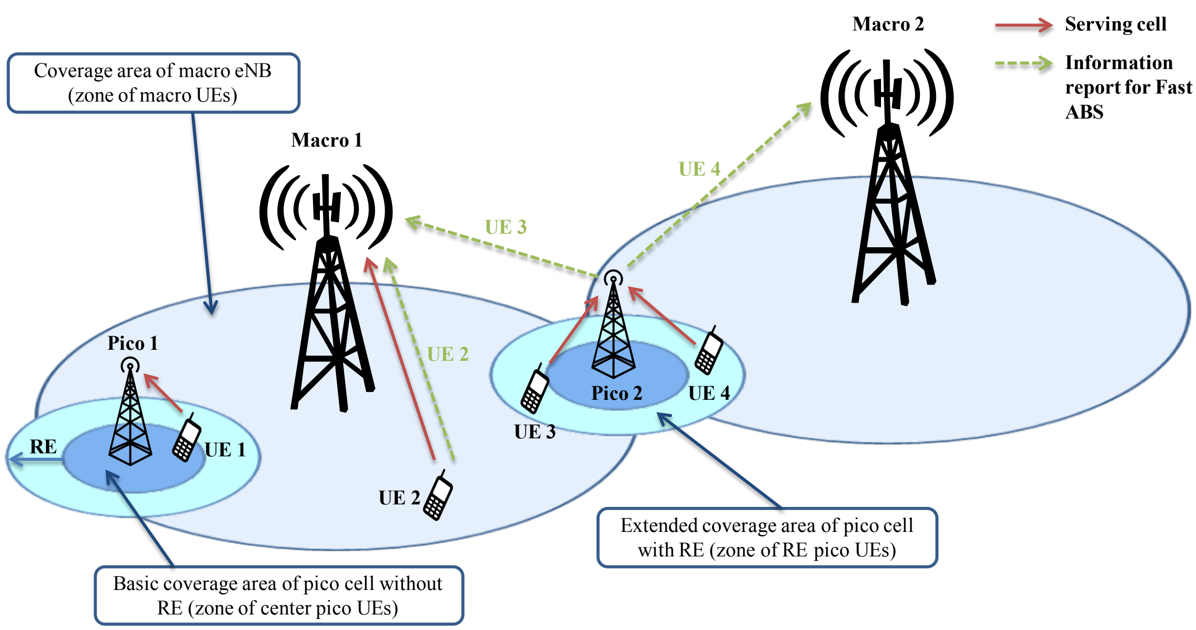


Figure 4.1: Report to macro cells based on UE information for the Fast ABS algorithm

Figure 4.1 also shows the proposed solution for the reporting of victim users to each macro cell. Instead of reporting all users in a pico cell to the same macro, the idea is reporting separately depending on the strongest interferer of each victim user. Thus, as depicted in Figure 4.1, Pico 2 will report to Macro 1 that UE 3 is a victim user, while UE 4 will be reported as victim to Macro 2.

Besides the victim users, it is necessary counting the macro users for the Fast ABS, like UE 2, which is counted as a Macro 1 user.

With this solution, the Fast ABS algorithm works exactly in the same way as before, but with different values of u_{RE} and U:

- u_{RE} is the total number of active victim users of the macro cell (which are the RE pico UEs reported to the macro as victim users, from whatever picos they are).
- U is the total number of users in the macro plus the victim users of that macro: $U = u_{macro} + u_{RE}$
  In this case center pico UEs are not taken into account, as anyway they are nearly not affected if the macro is muting or not. The ones really getting advantage from the muting are the RE users. Thus the number of center pico UEs is not reported to the macro cell.

A test is presented in order to evaluate the benefit of the proposed solution. The test consists of comparing the results obtained with the proposed UE-information based report with the results from the usual cluster-based report.

To do this, a manual configuration of clusters was done in the operator scenario under study. For each pico cell, the dominant macro cell is selected by choosing the macro that affects as the strongest interferer to most of the users in the pico. After defining the clusters, the Fast ABS can be applied in the traditional way.

Finite-buffer traffic model is considered. RE offset is applied for cell selection, and for each load the RE value that gives the best performance was chosen. Figure 4.2 shows the results of the test for 5th percentile and median UE throughput in the overall network with cluster-based and UE-information based report.

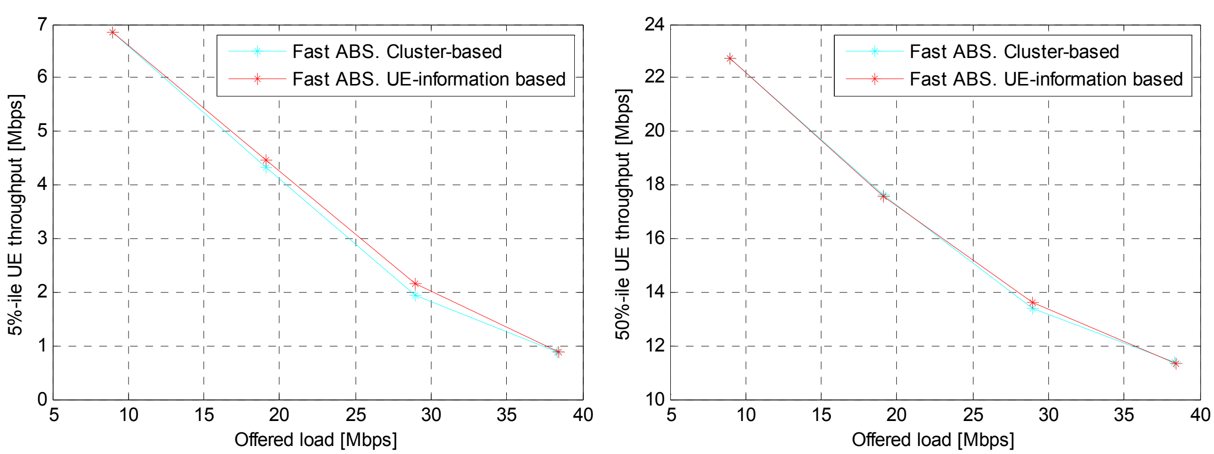


Figure 4.2: Cluster-based vs. UE-information based report for Fast ABS

It can be observed that the results are very similar, and actually the proposed solution performs a little better than the cluster-based approach for some loads. From now on, all the results using Fast ABS algorithms in this study will be generated using the UE-information based report. It is worth noticing that using this solution allows applying Fast ABS in any network, as no longer the predefinition of clusters is needed.

4.1.2 Throughput-based Cell Selection

This algorithm targets to optimize the throughput of each user. This is achieved by choosing the best cell according to the estimated user throughput that takes into account both the number of users and the signal quality of the candidate cell. This algorithm assumes that the PF scheduler is applied, thus sharing the resources fairly between all the users connected to a certain cell.

Every time an UE arrives to the network, the serving cell i^* is selected as follows:

$$i^* = \arg\max_{i \in F}\{\hat{R}_i\} \tag{4.1}$$

Where:

- $\hat{R}_i$ is the estimated throughput of the UE in cell *i*.
- F is the set of feasible candidate cells for the UE.

The estimated throughput the UE would get by connecting to a certain candidate base station "i" is calculated according to the following formula:

$$\hat{R}_i = \frac{1}{N_i + 1} \cdot BW_i \cdot \log_2(1 + \Gamma_i) \tag{4.2}$$

Where:

- N_i is the number of users in cell *i*.
- BW_i is the component carrier bandwidth of cell *i*.
- Γ_i is the conditional SINR of the UE in cell *i*.

The conditional SINR (Γ_i) is estimated as follows:

- For Macro BSs:

$$\Gamma_{Macro_i} = \frac{P_{Rx_{Macro_i}}}{Interference + Noise} \tag{4.3}$$

- For Pico BSs:

$$\Gamma_{Pico_i} = \frac{P_{Rx_{Pico_i}}}{Interference - \ P_{Rx_{Strongest\ Macro}} + Noise} \tag{4.4}$$

Where:

- $P_{Rx_{Macro_i}}$ is the power received by the UE from Macro "*i*".
- $P_{Rx_{Pico_i}}$ is the power received by the UE from Pico "*i*".
- $P_{Rx_{Strongest\ Macro}}$ is the power received by the UE corresponding to the strongest macro signal. This is the strongest interferer for the potential pico UE.
- *Interference* is the total interference the UE suffers assuming all BSs active.
- *Noise* is the thermal noise.

Γ_i estimates the SINR the UE would have by connecting to a certain base station with the assumption that the rest of base stations are transmitting at full power (that is, considering all BSs to be active). In the case of pico cells the conditional SINR is computed assuming that the dominant macro interferer is muted i.e. uses ABS all the time. Thus, this estimation is optimistic for the pico cells as it is subtracted the power of the strongest macro interferer. Besides, the estimation is also optimistic for the macro base stations as it is not considered that in muted subframes there is no transmission available from the macro.

This approach for the estimation of the throughput does not take into account the applied muting ratio in each cell. Therefore, the cell selection is based just on the number of users and the signal quality, which allows the algorithm to balance the load among the cells, leaving the Fast ABS to manage the resource partitioning.

The set of feasible candidate cells, *F*, is composed by every cell *i* which fulfills the following condition:

$$\frac{P_{Rx_{max}}}{P_{Rx_i}} < 10^{\frac{RE_{THRESHOLD}}{10}} \tag{4.5}$$

Where:

- P_{Rx_i} is the power received by the UE from cell i.
- $P_{Rx_{max}}$ is the maximum power received by the UE, corresponding to the strongest signal the UE receives i.e. $max\{P_{Rx_i}\}$.
- $RE_{THRESHOLD}$(dB) is the maximum threshold allowed between the maximum power received by the UE and P_{Rx_i}.

The parameter $RE_{THRESHOLD}$ sets a condition check for the selection of the candidate base stations. The objective of this parameter is preventing the connection of the UE to a base station with a very bad signal quality. This could happen in a case where the network is very loaded and then a BS with poor signal but with few users shows the best theoretical throughput. In practice, connecting to a BS with poor signal causes communication problems, and should be avoided.

The $RE_{THRESHOLD}$ value used in this study for the throughput-based cell selection algorithm is 15 dB.

The conditional SINR is stable, and this stability is important for the good performance of the throughput-based algorithm. However, the conditional SINR is something ideal that cannot be obtained in the real network. Each UE can measure the channel quality in a certain moment. At that moment, some BSs are transmitting and others are not. In some other moment, the BSs transmitting may be different. Thus, it is not possible for the UE to determine if all BSs are transmitting at full power in order to obtain the conditional SINR. It would be interesting to study in the future how to adapt this algorithm so that it can be applied to a real network.

The pseudo-code for this throughput-based algorithm is shown in Appendix E.

4.1.3 Load-based Cell Selection

The basic idea of this load-based algorithm is balancing the number of users among the cells. This algorithm is a more simplistic solution than throughput-based cell selection and can be an interesting option if it can achieve similar performance as throughput-based cell selection.

The **simplest version of this algorithm** selects the cell with the lowest load. Thus, every time an UE arrives to the network, the serving cell i^* is selected as follows:

$$i^* = \underset{i \in F}{\arg\min}\{N_i\} \tag{4.6}$$

Where:

- N_i is the number of users in cell i.
- F is the set of feasible candidate cells for the UE.

The set of feasible candidate cells, F, is determined in the same way showed in throughput-based cell selection (see Equation (4.5)). In the case of the load-based algorithm the setting of $RE_{THRESHOLD}$ has to be careful. A very high value of this parameter would possibly allow the connection of the UE to base stations with bad signal quality, which is not convenient. On the other hand, a too low value of $RE_{THRESHOLD}$ would not get enough candidates. For this study, the best value of the $RE_{THRESHOLD}$ for the load-based algorithm is 10 dB and all the results for this algorithm will be generated using this setting.

An **improvement of the load-based algorithm** considers the two cells with the lowest load and selects one of those two cells, depending on the number of users and the signal quality in each one. The two cells with the lowest load are:

$$i_1{}^* = \underset{i \in F}{\arg\min}\{N_i\} \ ; \ \ i_2{}^* = \underset{i \in [F - i_1{}^*]}{\arg\min}\{N_i\} \tag{4.7}$$

The load in the two cells is normalized by the total number of users in both of them:

$$n_{i_1^*} = \frac{N_{i_1^*}}{N_{i_1^*} + N_{i_2^*}} \; ; \; n_{i_2^*} = \frac{N_{i_2^*}}{N_{i_1^*} + N_{i_2^*}} \tag{4.8}$$

Where:

- $N_{i_1^*}$ and $N_{i_2^*}$ are the number of users in cells i_1^* and i_2^* respectively.
- $n_{i_1^*}$ and $n_{i_2^*}$ are the normalized number of users in cells i_1^* and i_2^* respectively.

By normalizing the load in the two cells we ensure that the difference between them is always a number between 0 and 1.

Two conditions are checked in the cell selection:

1. Check if the difference in the normalized number of users of the two cells is not higher than a certain threshold:

   $$n_{i_2^*} - n_{i_1^*} \leq Load_{THRESHOLD} \tag{4.9}$$

   Where $Load_{THRESHOLD}$ is the maximum difference allowed between the normalized load of the two cells. The value of this threshold can vary between 0 and 1.

2. Check if the received signal of the UE in cell i_2^* is higher that the power received by the UE in cell i_1^*:

   $$P_{Rx_{i_2^*}} > P_{Rx_{i_1^*}} \tag{4.10}$$

If both conditions (4.9) and (4.10) are fulfilled, then cell i_2^* is selected. Otherwise, cell i_1^* is chosen. To sum up, the idea of this improvement is that in situations where the two cells have nearly the same load, it is better for the UE to connect to the cell which offers better signal.

The results presented in this study use the load-based algorithm based on this improvement i.e. considering two cells for the selection.

At low load, it is more convenient to connect to the cell with the best signal, thus higher load difference should be allowed between the two candidates. As the load increases, it is more important to balance the load among the cells, thus the value of $Load_{THRESHOLD}$ should become more restrictive. Therefore, in this study we propose the $Load_{THRESHOLD}$ to be: $\frac{1}{N_{i_1^*}+N_{i_2^*}}$, hence varying from higher to lower values as the number of users in the two candidate cells increase. For this specific case, the condition (4.9) is simplified into:

$$N_{i_2^*} - N_{i_1^*} \leq 1 \tag{4.11}$$

Basically, the condition in (4.11) means that if there is a difference of one user between the number of users in the two candidate cells, the UE selects cell i_2^* in case that (4.10) is fulfilled. Otherwise, cell i_1^* is selected.

The approach proposed in Equation (4.11) obtains a gain of around 8% in the 5%-ile UE throughput of the overall network at high load, compared to the case depicted in condition (4.6) i.e. selecting always the cell with the lowest number of users.

For more information about how the $Load_{THRESHOLD}$ was selected and the corresponding performance gains, please refer to Appendix F. It is expected to obtain higher gains by determining the optimal value of this parameter according to the network conditions. However, it is out of the scope of this study to further investigate those possibilities.

The pseudo-code for this load-based algorithm is shown in Appendix F.

4.2 Performance Analysis Introduction: Full-Buffer Results

This part of the study will be conducted using full-buffer traffic model, as the results are easier to interpret. This section just outlines the main findings obtained from the full-buffer study. For more detailed results, please refer to Appendix G.

Overall Network Performance

The first step is studying a global and static configuration, which means that the same configuration will be applied to all base stations in the network (global), and the configuration will not change in time (static). The cell selection will be done applying the same RE offset to all pico cells, while static eICIC, that is, a fixed muting pattern in each macro cell, is used for interference management.

After studying the 5%-ile UE throughput for different RE + eICIC configurations, it is found that the gain obtained is not very large, just around 20% with the best RE + eICIC settings as compared to the reference case without RE and eICIC. This gain is quite low as compared to the results in 3GPP scenarios (references for 3GPP results can be found in Chapter 1).

Regional Performance

Previously the performance for different RE + eICIC configurations was studied in the whole network. But those results are not enough to study the network due to its irregularity. Thus we study the 5%-ile UE throughput obtained applying different configurations in each one of the regions (defined in Section 3.3.2). The main characteristics and results for each area are summarized in Table 4.1.

Area	Characteristics			Best RE + eICIC configuration		Performance	
	No. of Macros	No. of Picos	UEs (%)[8]	RE (dB)	Muting Ratio	5%-ile Gain (%)[9]	Offload (%)[10]
1	1	6	11.4	6	1/8	30	75
2	4	11	41.47	6	1/8	17	62
3	2	6	19.25	6 – 9	1/8	20	56
4	1	7	19.53	16	4/8	106	89
5	4	0	8.35	0	0/8	0	0

Table 4.1: Summary of characteristics and results for each region with full-buffer traffic model

The configurations which obtain the best user throughput performance are different in each area, as can be seen in Table 4.1. This explains why the overall performance of the network by having a global RE + eICIC configuration in the whole network does not obtain much gain, as for a certain configuration some regions are gaining but others are having losses. The reason for such a different behavior in each zone is that they are very different in several aspects: the number of pico cells per macro, user distribution in the network and pathloss. Those differences affect eICIC performance [49].

It is worth noticing that region number five does not have any pico cells, which obviously means that the best configuration for it implies not to mute the macro cells in region number five.

Conclusions from Full-Buffer Analysis

The results from applying a fixed RE + eICIC configuration in all the network show that the best configuration changes from zone to zone due to the fact that there are large differences from area to area in terms of the number of picos, traffic density, pathloss, etc.

From the results it is expected that larger gains can be achieved in the overall performance when different configurations are applied in each area according to its characteristics. Moreover, greater gains are expected when using non-static configurations, i.e. configurations which adapt to the changing conditions through time. Therefore, this study is mainly focused on applying **dynamic algorithms for eICIC and cell selection**, which target to adjust to the particular conditions in each region and to the changes they suffer through time, hence allowing the flexibility of being used in other scenarios as well.

[8] Percentage of users from all the network that are in each region
[9] 5%-ile UE throughput gain for the best configuration in the region respect the case with no RE and no eICIC
[10] Offload is the percentage of users that are connected to a pico cell

4.3 Performance Analysis: Finite-Buffer Results

This section analyses the performance results for a co-channel deployment applied to the operator scenario described in Chapter 3, using finite-buffer traffic model. The specific simulation assumptions used for this section are listed in Table 4.2.

Range Extension	0 - 15 dB
Cell Association Metric	1. RSRP + RE offset 2. Throughput-based Cell Selection 3. Load-based Cell Selection
ABS ratio	1. Static eICIC configuration for all macro sectors 2. Fast ABS with 6 optional subframes.
T_{ABS}	8 subframes
UE capabilities	Non-ideal CRS IC with 10 % of residual CRS interference. Different CQI reports for ABS and normal subframes.

Table 4.2: Simulation assumptions for co-channel deployment in operator-specific scenario

First, the overall network performance is studied. In this part, global configurations are used. Afterwards, some results focusing on different regions of the network are presented. For the regional study, the best configuration for each region is considered (the configuration that maximizes the 5%-ile UE throughput in the region).

4.3.1 Overall Network Performance

First we start our analysis by looking at the performance with global and static RE + eICIC configurations. Figure 4.3 shows the 5%-ile and 50%-ile UE throughput performance with different static configurations, i.e., without using any RE or eICIC, using just a RE offset, and using both RE and eICIC. The configuration used is the same for all the base stations in the network and is static.

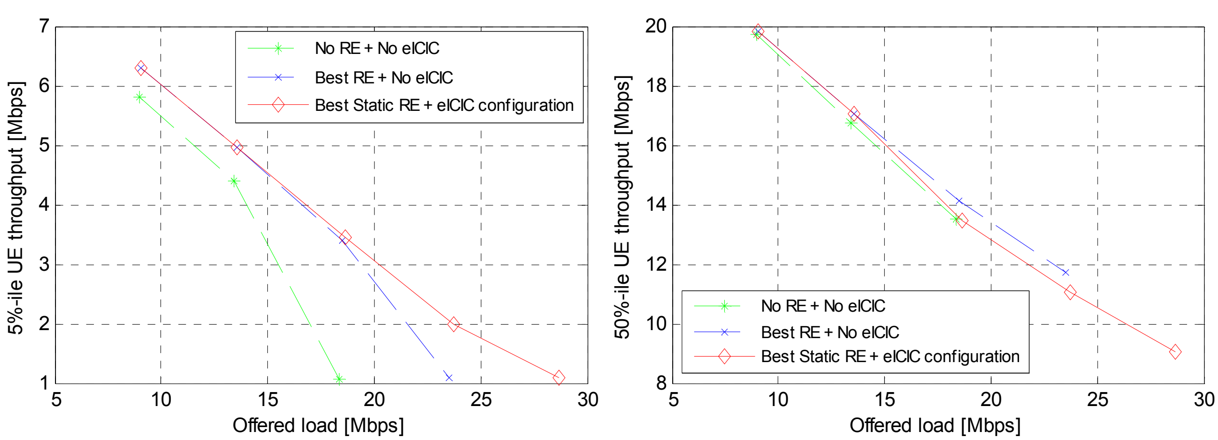


Figure 4.3: Comparison of UE throughput performance using RE + No eICIC and static RE + eICIC

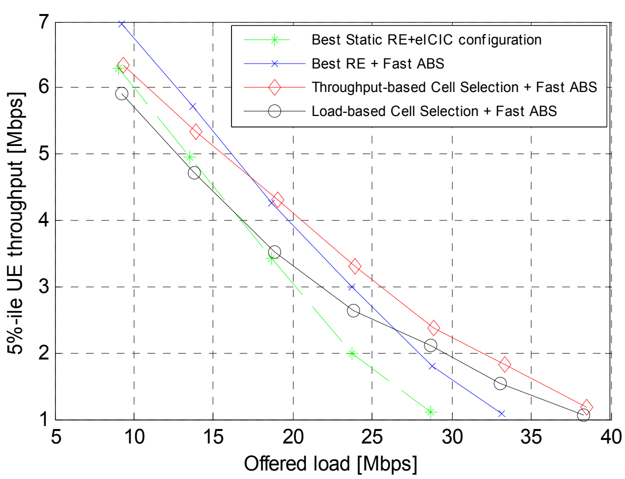
From the results shown in Figure 4.3 it is clear that applying a RE offset to the pico layer improves the 5%-ile performance. The gains with eICIC are mainly visible at high load, and these gains are smaller compared to 3GPP scenarios results (referenced in Chapter 1). This behavior was also observed in Section 4.2, using a full-buffer traffic model.

Offered Load (Mbps)	Best Configuration[11]			5%-ile Gain (%)[12]		50%-ile Gain (%)[12]	
	Best RE + No eICIC	Best Static RE + eICIC		Best RE + No eICIC	Best Static RE + eICIC	Best RE + No eICIC	Best Static RE + eICIC
	RE (dB)	RE (dB)	Muting Ratio				
10	2	2	0/8	9	9	0.5	0.5
15	3	3	0/8	12	12	1.6	1.6
20	3	6	1/8	216	220	5	0.6
25	3	8	1/8	-	-	-	-
30	-	10	1/8	-	-	-	-

Table 4.3: Best configuration and UE throughput gains for RE + No eICIC and static RE + eICIC

Table 4.3 includes the summary 5%-ile and 50%-ile UE throughput gains compared to the case without RE and eICIC, and the settings that obtained the best overall network. The results in Section 4.2 proved that the configuration obtaining the best performance in each region was different from one region to other. Thus, the gains from using eICIC are expected to improve by applying Fast ABS, which adapts to the traffic conditions in each region. Moreover, using dynamic cell selection techniques such as Throughput-based and Load-based cell selection may further enhance the performance.

Following, we analyze the performance when dynamic RE + eICIC settings are applied. Figure 4.4 shows the 5%-ile and 50%-ile UE throughput performance with different dynamic RE + eICIC configurations. The performance with optimal static RE + eICIC configuration obtained from Figure 4.3 is used as a reference case.



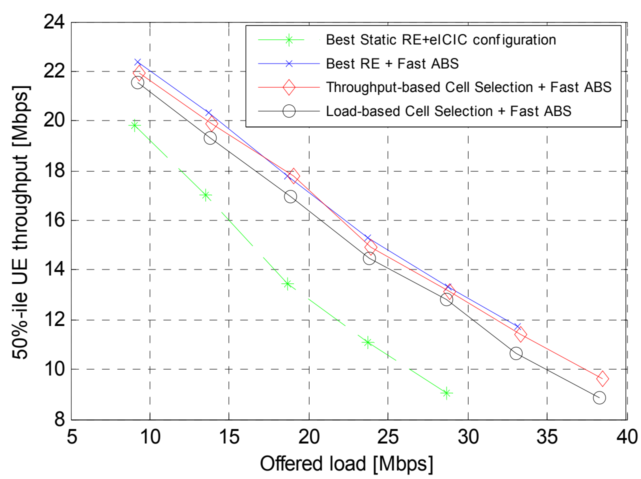


Figure 4.4: Comparison of UE throughput performance using different cell selection metrics + Fast ABS

[11] Global configuration that obtains optimal overall network performance (for 5%-ile UE throughput)
[12] UE throughput gain in the overall network performance compared to the case with no RE and no eICIC

Some interesting observations can be stated from Figure 4.4:

- Fast ABS gets good gains over static eICIC, both in the 5%-ile and median UE throughput.
- Dynamic cell selection techniques have good 5%-ile performance at high loads, but in low loads a global static RE offset performs better.
- Load-based cell selection has a similar performance to Throughput-based at high loads, although a bit lower.
- With dynamic cell selection, the network can handle an increase in the offered load of around 35 %.
- 95% of the UEs can be served:
    - With at least 2 Mbps supporting a 35 % load increase.
    - With at least 4 Mbps supporting a 23 % load increase.
- For an offered load of 35 Mbps, Throughput-based cell selection obtains a 70 % 5%-ile gain over the usage of the best RE offset.

To explain these observations, a detailed analysis of the gain mechanisms by using dynamic algorithms is performed in the following paragraphs.

Comparison of Fast ABS and Static eICIC

Best RE + Fast ABS			
Offered Load (Mbps)	**Best RE (dB)**[13]	**5%-ile Gain (%)**[14]	**50%-ile Gain (%)**[14]
10	7	11	13
15	8	15	19
20	7	24	32
25	10	51	38
30	10	64	47
35	10	-	-

Table 4.4: Best RE configuration and UE throughput gains for RE + Fast ABS

Table 4.4 shows the 5^{th} percentile and median UE throughput gain obtained by using Fast ABS compared with a global static eICIC configuration. It is observed that both 5%-ile and median throughput get a good performance improvement, and said improvement is higher with increasing load. These gains using Fast ABS prove that the muting pattern should be dynamically adjusted to the instantaneous conditions in order to fully benefit from eICIC.

Figure 4.5 shows the CDF of the muting pattern for low load conditions (left) and high load (right) in the different macro cells, applying Fast ABS and a fixed RE. For the interested reader, a map showing where each macro sector is located according to its ID can be found in Appendix C.

[13] Global RE offset that obtains optimal overall network performance (for 5%-ile UE throughput)
[14] UE throughput gain in the overall network performance compared to the best global and static RE + eICIC configuration

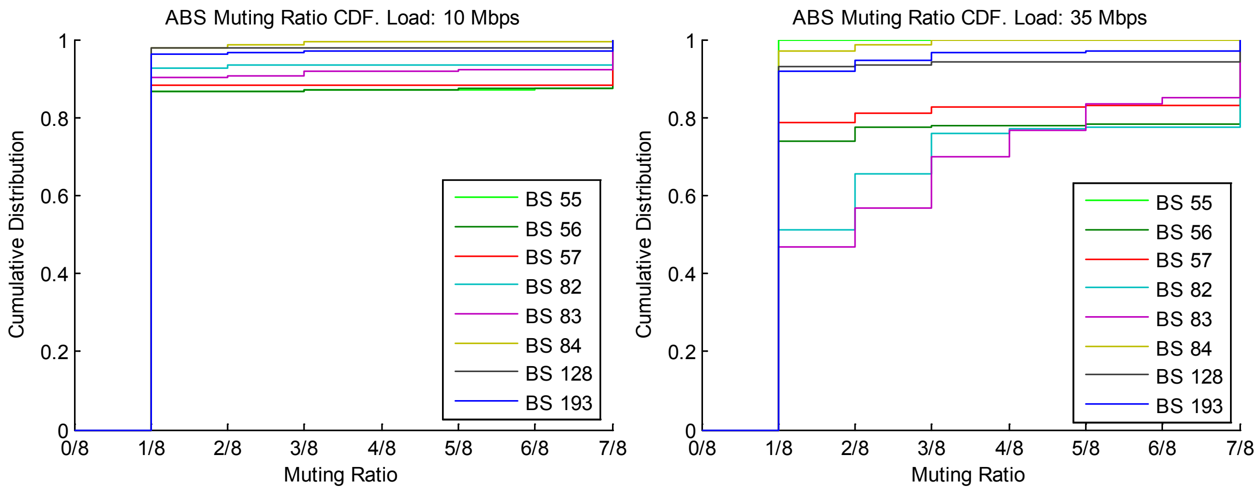


Figure 4.5: CDF of the muting ratio for Fast ABS in the different macro sectors[15]

Figure 4.5 shows that for low load conditions (left) the muting pattern tends to be the minimum 1/8 most of the time in all the macro sectors, as all the base stations in the network (macro and pico cells) are empty most of the time. When the load increases (right), the probability of having users in each base station increases. However the users are not evenly distributed among the cells. Some cells may have lots of users while others remain almost empty. Depending on the load conditions in each macro cell and its surrounding pico cells, the muting pattern will be adapted accordingly, resulting in very different muting patterns in each macro sector. For instance, in high load Macro no. 55 mutes the minimum (1/8) most of the time, while the muting pattern of Macro no. 83 changes a lot and is the maximum (7/8) nearly 20 % of the time. Both macro cells (55 and 83) are in area 2, but their load conditions are very different: Macro no. 55 has a lot of users, thus muting as less as possible in order to protect them; whereas Macro no. 83 has very few users and can mute much more in order to help the surrounding RE pico users.

From Figure 4.5 we can conclude that in the operator-specific scenario very different muting patterns are applied to each macro sector. This behavior differs from the one observed in 3GPP scenarios, where the muting pattern also changes over time but remains pretty similar among different macro sectors [10]. Besides, the results in [10] show that in 3GPP scenarios the muting pattern is low even for high load because the number of users is higher in the macro layer and the algorithm tends to serve first those users.

[15] The four macro sectors in Area 5 (see regions in Section 3.3.2) are not shown as that region does not have pico cells and thus the muting pattern is the minimum most of the time for any load.

Comparison of Dynamic Cell Selection Techniques and Range Extension Offset

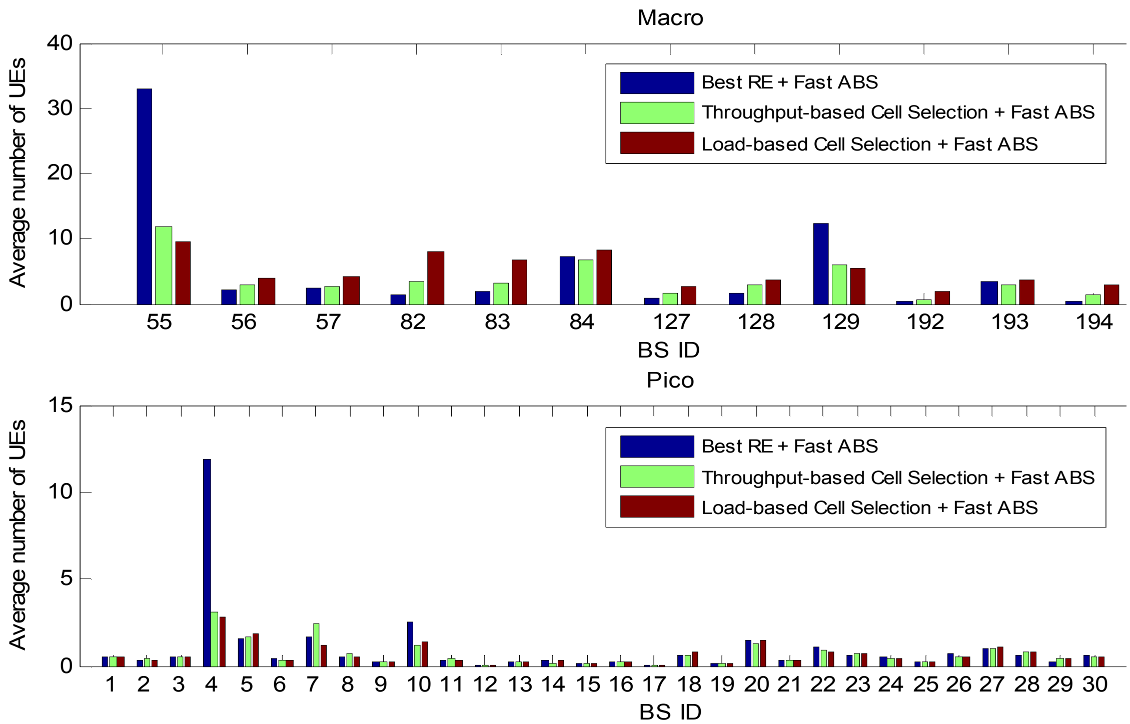


Figure 4.6: Average number of UEs being served by each Macro and Pico cell using different cell selection metrics + Fast ABS. Offered load of 35 Mbps

Figure 4.6 depicts the average UE distribution in each cell, separating between the macro and the pico layer, in a case of high offered load. By applying a fixed RE offset in the whole network, some base stations have a very high load compared to other cells as can be seen especially in Macro no. 55 and Pico no. 4 (both in region 2). UEs in those highly loaded cells experience poor throughput performance. Dynamic cell selection algorithms (Throughput-based or Load-based) try to balance the load among the base stations, resulting in a better distribution of users among the cells as shown in the figure. The load balancing is especially important at high load, offloading some of the users from highly loaded cell to less loaded cells, thus allowing for a more even distribution of the network resources among the users and preventing the cell overloading. Besides, while Throughput-based takes greatly into consideration the signal quality in the cell selection, Load-based is mainly focused in obtaining an even user distribution among the cells, which helps smoothing the saturation[16] when the offered load is very high.

[16] Saturation or overloading refers to the state that reaches a base station when the incoming load rate is lower than the output rate i.e. the BS cannot handle the incoming load fast enough and users begin to get stacked in the buffer.

Table 4.5 summarizes the UE throughput gains that can be obtained by using different cell selection techniques + Fast ABS, compared to the case with best global and static RE + eICIC configuration.

Offered Load (Mbps)	5%-ile Gain (%)[14]			50%-ile Gain (%)[14]		
	Best RE + Fast ABS	**Throughput-based + Fast ABS**	**Load-based + Fast ABS**	**Best RE + Fast ABS**	**Throughput-based + Fast ABS**	**Load-based + Fast ABS**
10	**11**	1	- 6	13	11	9
15	**15**	8	- 5	19	17	14
20	24	25	2	32	32	26
25	51	**66**	32	38	35	31
30	64	**116**	**91**	47	45	41

Table 4.5: UE throughput gains for different cell selection metrics + Fast ABS over the case with best global static RE + eICIC configuration

Concerning the 5%-ile UE throughput, at high load Throughput-based and Load-based cell selection get higher gains than a fixed RE offset, as the load balancing has a great importance at high load. However, at low load, it is more convenient for the users to connect to the cell with the best signal quality, as the average number of users in each cell is very low anyway. Although the performance with Load-based algorithm is not as good as Throughput-based algorithm, it is interesting for very high load as it smoothes the saturation level among the base stations and is a more simplistic solution than the Throughput-based algorithm.

In the case of median UE throughput, fixed RE offset and dynamic cell selection techniques have a similar behavior, getting good gains over the best static RE + eICIC configuration for any load.

Fairness

Figure 4.7 shows Jain's fairness index using different configurations: no RE + no eICIC, global static RE + eICIC, and different dynamic configurations (RE-based, Throughput-based or Load-based cell selection + Fast ABS).

Both for static and dynamic configurations the fairness is lower than the one showed by 3GPP scenarios (see [10] for results of slow and fast muting adaptation in 3GPP scenarios). The reason for this behavior is that the site-specific operator scenario is more irregular and the achieved throughput changes a lot for the different users across the network.

The tendency is the same showed in 3GPP scenarios: fairness decreases with the offered load, and the decrease is more pronounced for slow muting adaptation (static eICIC). Fast ABS adapts to the changes in the network, therefore being able to provide more fairness among the users.

RE-based and Throughput-based cell selection achieve approximately the same fairness, although for increasing load Throughput-based offers higher fairness. Load-based cell selection balances the number of users in all base stations, but offers lower fairness as it does not take much into account the channel quality, thus providing lower throughput to some users.

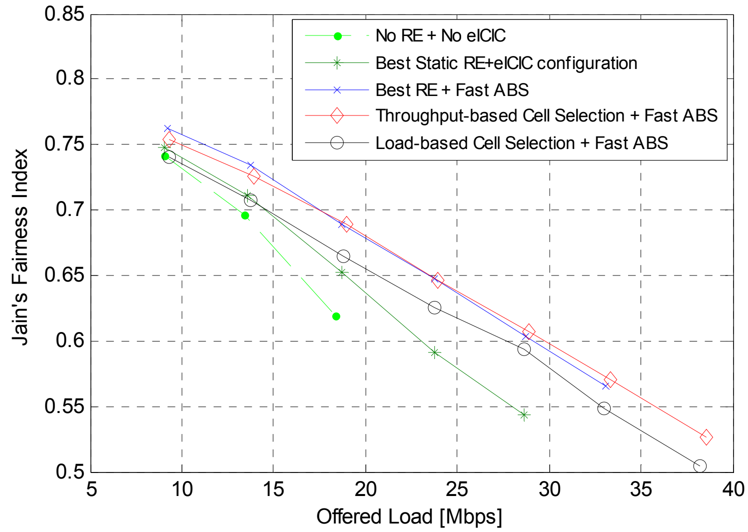


Figure 4.7: Comparison of Jain's Fairness Index for different static and dynamic configurations

4.3.2 Regional Performance

Figure 4.8 shows the throughput of each UE in the network in a high load case. The dark blue zones indicate the regions where most of the 5%-ile UEs are. As it can be observed, these UEs are mostly located in area 2 and 5 according to the division shown in Section 3.3.2. Area 2 is characterized by an uneven distribution of the load; whereas area 5 is a macro-only region, therefore no eICIC techniques are needed in this region.

From Figure 4.8 it can be observed that the user throughput performance is quite different from region to region due to different traffic loads and network layouts. Therefore the global statistics are not sufficient to understand the performance gains by applying different eICIC techniques. In this section we analyze the performance in different regions.

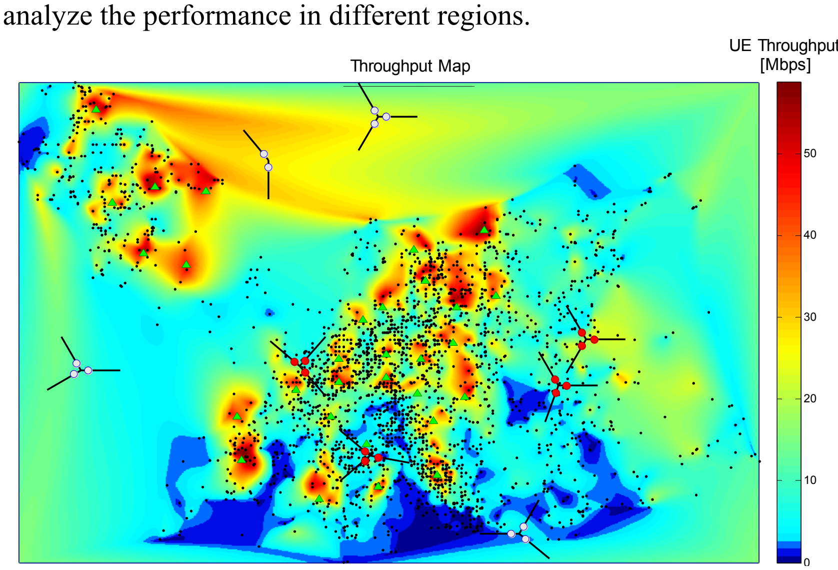


Figure 4.8: Map showing the UEs geographical position and its throughput at high load case using RE + Fast ABS

The followed approach is as explained in Section 3.3.2: the users are geographically separated into 5 areas and their statistics are analyzed separately.

Figure 4.9 shows the 5%-ile and median gain obtained in each region (over no RE + no eICIC) when the best static configuration (fixed RE + static ABS) and dynamic configuration (RE based cell selection or dynamic cell selection + Fast ABS) in each region are applied. Table 4.6 shows the UE throughput gain and system capacity gain that are obtained as compared to the static configuration.

It is worth mentioning that the gains shown in both Figure 4.9 and Table 4.6 are obtained at the highest load that can be handled by a particular area without any RE or eICIC technique, which corresponds to an **average offered load per base station of 6-8 Mbps**. As it has been shown in the global analysis of the network performance, the throughput gains of dynamic configuration over static, become even greater at higher offered loads.

The best static configurations and dynamic configurations that were obtained in each of the areas can be found in Appendix H.

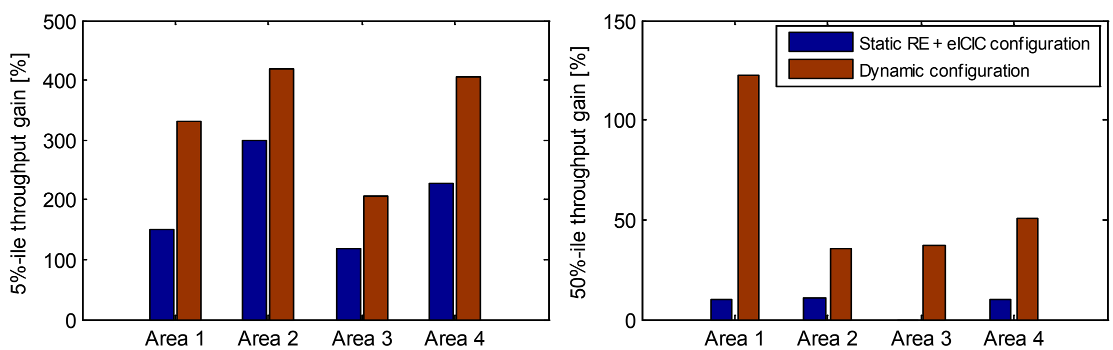


Figure 4.9: 5%-ile and 50%-ile throughput gain in each region for static and dynamic configurations over No RE + No eICIC

Dynamic configuration				
Area	**UE Throughput Gain over Static configuration (%)**[17]		**System Capacity Gain at 2 Mbps (%)**[18]	
	5%-ile gain	**50%-ile gain**	**Over No RE + No eICIC**	**Over Static configuration**
1	70	110	70	35
2	30	25	65	25
3	40	40	35	10
4	50	35	120	15

Table 4.6: Approximated UE throughput and System capacity gains in each region using Dynamic configuration

[17] UE throughput gain obtained in each region when applying the best per-area dynamic configuration
[18] Capacity gain obtained in each region when applying the best per-area dynamic configuration

It is observed that the 5%-ile gains vary from 100% to 300% with a static eICIC configuration and from 200% to 400% with dynamic algorithms, as compared to the case with no RE + no eICIC. Additionally, for a target 5%-ile outage throughput of 2 Mbps, dynamic configuration achieves a system capacity gain over no RE + no eICIC of approximately 70%, 65%, 35% and 120% in areas 1 to 4, respectively. The 5%-ile throughput gain is larger compared to the 50%-ile throughput gain. That is because the 5%-ile UE throughput is the target maximization KPI. Moreover, 5%-ile users are more sensitive to the load conditions and inter-cell interference. With RE and eICIC, the load is more evenly distributed and interference is mitigated, offering opportunities for the 5%-ile users to be served with higher data rates. The performance in area 5 is not shown as it is a macro-only area.

These results show that the gain numbers vary from region to region. As it was discussed before, the gains obtained using the different techniques depend on multiple factors including: the number and location of small cells deployed per macro sector area, user distribution, interference conditions, etc. Due to the lack of space, we do not provide the detailed analysis of each region. The following observations are found from the regional analysis:

- As said before, most 5%-ile users are localized in areas 2 and 5, which means that the best static configuration obtained for the overall network is determined basically by these areas. Using the best static configuration in each area achieves higher gains as in that case the configuration is selected to benefit the 5%-ile users of each area.
- As expected, dynamic configurations achieve higher gains than static configurations. Specifically, fast ABS is responsible for most of the gains obtained with dynamic algorithms. With fast ABS, each macro eNB can individually and dynamically change its muting pattern based on the local traffic and interference conditions.
- Dynamic cell selection techniques achieve considerable gains over a fixed RE in cases of load unbalance, as happens in areas 2 and 5, thanks to their inter- and intra-layer load balancing capabilities. In area 2 those gains are mostly due to inter-layer load balancing, while in area 5 gains are obtained only from user balancing across the macro cells (intra-layer load balancing).
- Areas 1, 3 and 4 do not improve their performance by using dynamic cell selection algorithms as the load is evenly distributed. In these cases, a fixed RE value achieves approximately the same performance.
- Area 3 contains a large percentage of users with very low possibilities of being offloaded to the small cells. Due to this limitation, the gains in this area are smaller than area 1, 2 and 4.

Appendix H shows the 5%-ile and 50%-ile UE throughput at different offered loads for areas 2 and 4, as an example of the fact that dynamic cell selection obtains gains in cases of load unbalance (area 2) but does not improve the performance for evenly distributed load (area 4).

Fairness

Figure 4.10 shows Jain's fairness index using different configurations: no RE + no eICIC, static configuration and dynamic configuration. The configurations selected are the same ones as in the results above, i.e. those which obtain the best 5%-ile UE throughput in each area. The results shown correspond to an average offered load per base station of 6-8 Mbps.

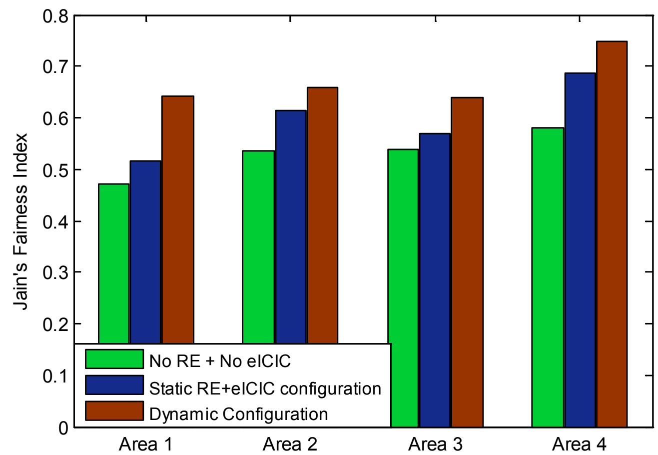


Figure 4.10: Comparison of Jain's Fairness Index in each region for: No RE + No eICIC, static configuration and dynamic configuration

The conclusions obtained from Figure 4.10 are the same showed for the overall network fairness:

- Fairness index is lower than in 3GPP scenarios [10].
- Dynamic configuration provides more fairness than static configuration.

The level of fairness achieved in each region is different, due to the differences between the regions in terms of traffic distribution, small cells layout, pathloss, etc.

4.3.3 Concluding Remarks for Co-Channel Deployment Analysis

From the global network analysis it has been shown that Fast ABS provides good gains in both 5%- and 50%-ile UE throughput compared to a global static eICIC configuration. This is mainly due to the fact that, as a result of the network irregularity in terms of user distribution and interference conditions, very different muting patterns are needed in each macro sector to fully harvest the benefits from eICIC.

Concerning the cell selection, dynamic approaches such as Throughput-based and Load-based algorithm can further improve the performance, especially at high load. While at low load applying a fixed RE offset is enough, at high load the network benefits from these dynamic techniques as they balance the load among the cells, hence allowing both higher UE throughput and larger system capacity.

Throughput fairness decreases with the load in the site-specific scenario. Besides, Fast ABS achieves better fairness than static eICIC. These trends are the same observed in 3GPP scenarios, although fairness level is slightly lower in the operator scenario due to the network irregularity.

Global statistics have to be treated carefully in the site-specific scenario, as they are not able of fully representing the network behavior due to the network irregularity. For that reason, several regions are separated in the network. These regions have very different characteristics.

From the per-area analysis, it is clear that applying a different and customized static RE + eICIC configuration in each area achieves better performance than a global static configuration. It is also observed that gains change from one region to another. Comparing to the case with no RE + no eICIC, good gains are obtained in the 5%-ile throughput with a static RE + eICIC configuration, varying from 100% to 300%. The gains obtained with a dynamic configuration (either fixed RE or dynamic cell selection + Fast ABS) are higher, ranging from 200% to 400%. For the 50%-ile UE throughput, a static configuration provides very low gains, while a dynamic configuration still offers great benefits, showing gains up to 120%.

Additionally, dynamic configurations provide capacity gains up to 35% over a static configuration, for a target 5%-ile throughput of 2 Mbps.

To summarize, the following recommendations are made:

- It is advised not to apply the same configuration in all the base stations. Different configurations in each cell depending on the surrounding conditions give better performance.
- While the performance applying per-area configurations improves, to fully harvest the benefits from eICIC, fast muting adaptation is recommended. Using such a dynamic approach achieves high gains over the traditional slow ABS.
- For the fast ABS, the authors recommend using UE-information based report to the macro cells (i.e. each UE information is reported to its macro aggressor independently of its serving small cell), instead of the traditional cluster-based report. This approach allows the automatic application of fast ABS in any network without previous clusterization.
- Dynamic cell selection techniques prove to be useful in areas with load unbalance, allowing inter- and intra-layer load balancing, hence improving the performance. Thus, these techniques can prove useful in scenarios with a very irregular traffic distribution.

Chapter 5

5 Inter-Site CA and Performance for Dedicated Deployment

As explained in Chapter 2, using different carrier frequencies at the macro and pico layer is a promising solution due to the fact that it enables multi-cell cooperation without the need of interference coordination techniques between the layers. Additionally, the introduction of inter-site carrier aggregation allows better utilization of the fragmented radio resources as the users can connect to both layers, hence benefitting from larger transmission bandwidth. However, as it will be shown in this chapter, load balancing among the cells is still a performance limiting factor and therefore needs to be addressed. This chapter focuses on comparing the performance with and without inter-site CA, as well as investigating different load balancing techniques in the operator-specific scenario.

5.1 Dedicated Deployment Considerations

The packet scheduler and the cell association criteria are the two key elements that determine the allocation of radio resources among the users. For the former, special considerations must be taken into account when inter-site CA is applied to ensure a more fair distribution of the resources between inter-site CA and legacy users. For the latter, we propose a dynamic cell selection algorithm which helps to achieve greater performance at high load compared to the traditional cell selection techniques described in Section 2.2.2.

5.1.1 Packet Scheduler

The fact that UEs can connect to both macro cell and small cell by using inter-site CA offers a fast and efficient way to balance the load among the layers. However, some considerations regarding the radio resource management algorithms must be taken into account in order to fully exploit the benefits of the CA feature. In the packet scheduling functionality it is recommended to use a *joint multi-cell packet scheduling* which basically takes into account the past average throughput over all the configured carriers (for proportional fair scheduler case) when calculating the scheduling metric (see equation (2.1)). As shown in [50], this type of scheduling mechanism provides a more fair resource sharing among the users especially in the cases where some users are served only by one cell, while other users are served by multiple cells using CA functionality.

This is particularly useful in heterogeneous networks scenarios where users might experience very different channel and load conditions on different carriers. By applying this modification, users tend to be scheduled on the cell with better channel conditions hence improving the overall resource utilization efficiency and fairness.

5.1.2 Cell Selection

Inter-site CA offers several benefits to the UEs. However, it is not feasible to configure all UEs with inter-site CA as they might experience poor link quality to one of the layers and also the fact that most of the current LTE terminals in the market do not support CA functionality. Different cell association criterions are used for UEs supporting CA mode or not. Following, these criterions are explained.

Non Inter-site CA Users

The serving cell for a UE is typically determined based on the UE RSRQ measure. A range extension offset can be added to this measure of the small cells in order to offload more users to this layer.

Besides, we propose throughput-based cell selection. This cell selection technique is basically the same as the throughput-based algorithm proposed in 4.1.2. The idea is to individually maximize the throughput of every UE. Every time an UE arrives to the network, the throughput that UE would get by connecting to a base station "i" is estimated according to Equation (4.2) .

The difference with the algorithm in 4.1.2 is that the conditional SINR (Γ_i) in this case only takes into account the intra-layer interference as the pico and macro cells are deployed at different CC. After estimating the throughput of every candidate BSs, the selected cell i^* will be the one that offers the highest throughput to the user, i.e. Equation (4.1).

In this particular case, the set of feasible candidate cells **F** is composed by every cell i which fulfills the following condition: $\Gamma_{i_{dB}} \geq -5\ dB$.

Inter-site CA Users

For UEs supporting inter-site CA, two methods have also been previously described in 2.2.2 that determine whether the UE should operate in CA mode: first, a CA window that dictates the maximum RSRQ difference between the two candidate cells in the two layers; second, a RSRQ threshold which allows to connect to a small cell as long as its RSRQ is above a certain threshold.

Additionally, we also present the throughput-based cell selection algorithm for inter-site CA UEs. The throughput estimation is done according to Equation (4.2); next, the cell selection is according to the following criterion:

$$i^* = \begin{cases} \arg\max \ (\hat{R}_{M^*}, \hat{R}_{P^*}) & if \ |RSRQ_{P^*} - RSRQ_{M^*}| > CA\,window \\ Both & otherwise \end{cases} \tag{5.1}$$

where $\hat{R}_{M^*}$ and $\hat{R}_{P^*}$ are the throughput obtained from the best macro and pico base stations, respectively. As seen in Equation (5.1), two possibilities are considered: first, if the RSRQ difference between the two layers is bigger than the maximum allowed *CA window*, the selected base station will be the one that offers the highest throughput (either macro or pico BS). Otherwise, the UE will connect to both candidate base stations.

It is worth mentioning that the load-based cell selection algorithm could also be adapted to be used in this type of deployment; however, for the sake of simplicity, the performance results of this algorithm are not presented as it shown similar tendency as throughput-based, but with lower performance.

5.2 Performance Analysis

This section analyses the performance applying finite-buffer traffic model. The specific simulation assumptions used for this section appear in Table 5.1.

Bandwidth Allocation	2 x 10 MHz non-overlapping component carriers at 2.6 GHz band	
Cell Association Metric	**No Inter-site CA:** 1) RSRQ + RE 2) Throughput-based	**With Inter-site CA:** 1) RSRQ Threshold: -16, -14, -12 dB 2) CA Window: 2, 6, 10 dB 3) Throughput-based with 10 dB CA Window
Packet Scheduler	Cross-carrier proportional fair	

Table 5.1: Simulation assumptions for dedicated deployment

First, the overall network performance is studied. Afterwards, some results focusing on different regions of the network are presented.

It is worth mentioning that no range extension (i.e. RE = 0 dB) is considered in this study as no significant performance increase was obtained with this technique.

5.2.1 Overall Network Performance

Figure 5.1 shows the 5%-ile and 50%-ile UE throughput performance with and without inter-site CA. Three different carrier aggregation configurations are shown: RSRQ threshold for pico cells of -16 dB, based on a CA window of 10 dB, and throughput-based cell selection with CA window of 10 dB. For the cases with no CA, two configurations are shown: RSRQ-based cell selection, and throughput-based cell selection.

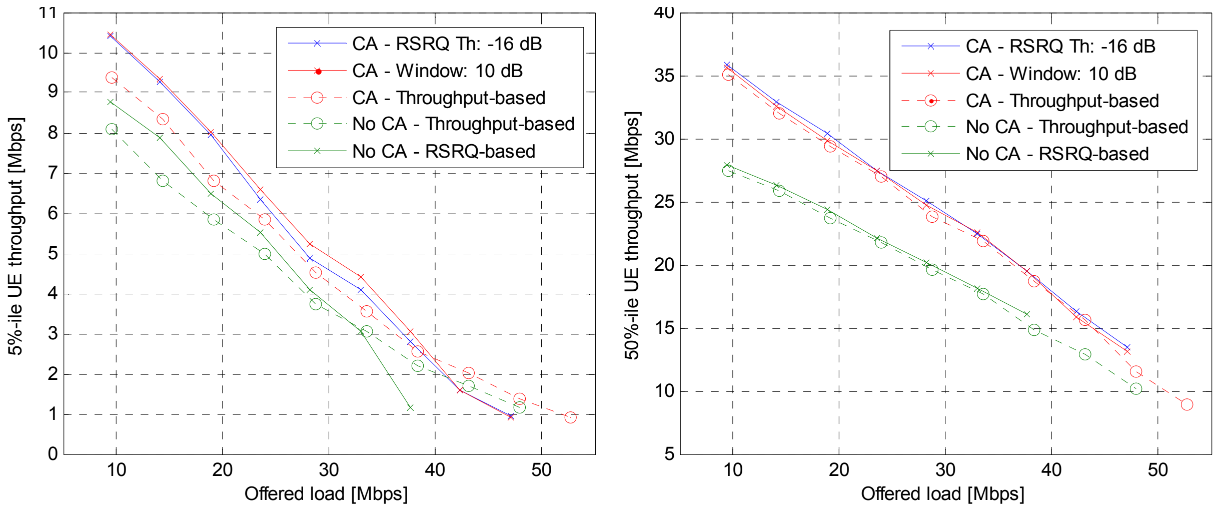


Figure 5.1: Comparison of UE throughput performance for different CA and cell selection configurations

As seen in Figure 5.1, inter-site carrier aggregation functionality does achieve gains from low load to high load. The gains of inter-site CA mainly come from larger transmission bandwidth, increased multi-user diversity and faster inter-site load balancing. At very high load, throughput-based cell selection without dual connectivity surpasses the performance obtained with traditional CA configurations (RSRQ threshold or CA window based) as load balancing acquires big relevance. Throughput-based with dual connectivity also has better performance (at high load) than the rest of carrier aggregation configurations mainly because of two facts: first, even with this configuration, a considerable amount of users are still connected to a single site and -therefore- they get a big benefit from load balancing. Second, some inter-site CA users also benefit from throughput-based cell selection as, in some particular areas, the two main candidate BSs (based on RSRQ measure) can be highly loaded and this algorithm allows the selection of a less loaded cell in some of those cases.

Figure 5.2 shows the per-layer user distribution for different configurations. The dashed lines indicate the potential CA ratio that could be obtained in this operator-specific case if the outer BSs (used for generating interference) were enabled to schedule users. For performance analysis purposes, only the UE distribution in solid colors must be taken into account. This figure also shows some statistics with additional CA configurations (RSRQ threshold of -14 and -12 dB and CA window of 6 and 2 dB). These additional CA configurations will be analyzed in the following subsection.

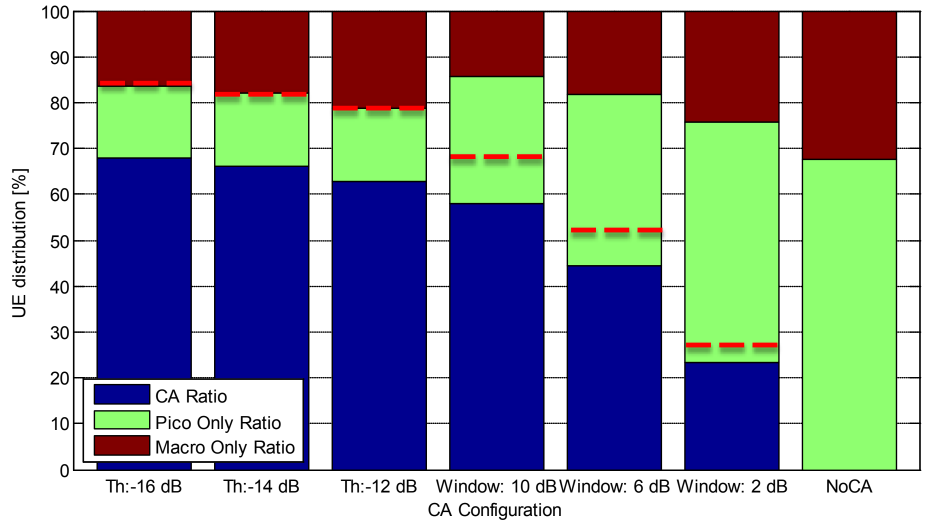


Figure 5.2: UE distribution in the different layers for different CA configurations

From Figure 5.2, the following observations can be stated:

- In the no CA case, a higher pico-only ratio is obtained compared to the co-channel deployment: RSRQ takes into account the interference conditions in each layer (therefore load is implicitly taken into account) which are different in each layer.
- Using an RSRQ threshold of -16 dB, achieves a CA ratio 10% higher than a CA window of 10 dB. CA configuration with a RSRQ threshold has the advantage that allows UEs to connect to both layers even if the $RSRQ_{Pico} >> RSRQ_{Macro}$. However, as it is observed in the 50%-ile performance, this additional CA ratio does not provide a big benefit in the UE throughput as the macro cell channel quality can be very poor in those cases.

Figure 5.3 shows the 5%- and 50%-ile UE throughput gains over no CA - RSRQ-based cell selection from low load to the maximum load that can be handled by this reference case.

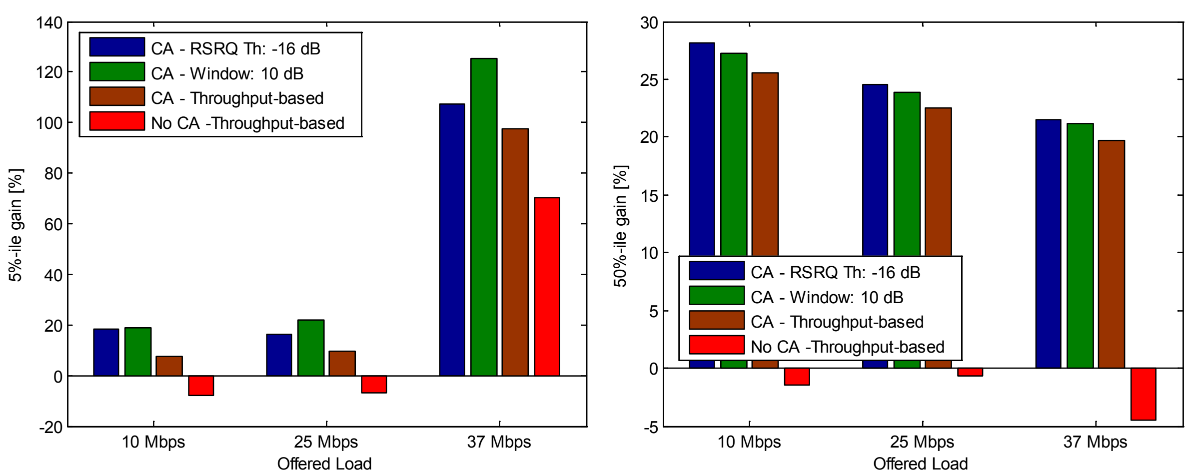


Figure 5.3: Relative gains over No CA - RSRQ-based cell selection for different configurations

In the 5%-ile, it is observed that ~20% gains are obtained at low load. When the load increases, gains of up to 120% are achieved. These gains do not follow the usual trends observed in 3GPP studies (referenced in Chapter 1). However, it is worth mentioning that these global 5%-ile statistics have to be treated carefully as they correspond mostly to users in very specific zones of the network and, therefore, do not fully represent the common behavior in the whole network.

At low load, the CA gains in the 5%-ile are relatively low due to the fact that those UEs are mostly located in cell-edge areas (i.e. with bad signal quality to the serving cell) and without feasible candidate cells for inter-site CA (e.g. users in macro-only areas). When the load increases, gains of up to 120% are achieved: in this case, the benefit comes from the implicit load balancing provided by inter-site CA and/or throughput-based cell selection that avoid the overloading of certain macro sectors in the network (as will be shown in Regional Performance Section). This behavior at high load differs from the typically observed in 3GPP scenarios, where a local overloading is very unlikely to happen.

The common behavior in 3GPP scenarios is obtaining high gains from dual connectivity in the 5th and 50th percentile at low load only, as the probability of having a single user accessing all the available radio resources in both the macro and the small cell is higher; at high load, only a little gain is obtained in such scenario due to the fact that most of the cells are highly loaded and therefore, most of the users having access to double spectrum does not give big benefits over users connecting to only one cell.

Regarding the median UE throughput, the trends are more in line with 3GPP results. Gains up to ~28% are obtained with CA at low load. As the load increases, the gain decreases but still significant gains are achieved over no CA - RSRQ-based at the maximum tolerable offered load. The gains are greater at low load, as happens in 3GPP.

However, even with a CA ratio of around 68%, the gains brought by using inter-site CA are lower than the commonly observed in 3GPP studies. The main reason is the differences in terms of deployment: in 3GPP scenarios, the small cells are commonly placed in traffic hotspots. These traffic hotspots generally have good macro cell coverage (hotspots are uniformly placed in each macro area) and, therefore, good gains are obtained by connecting to both layers. However, in this specific scenario, the small cells are deployed not only in hotspots but also in areas with poor macro coverage. The latter means that some UEs are likely to experience big SINR difference between the layers which limits the gains of inter-site CA.

From the practical point of view, due to signal quality limitations, it is not feasible to apply too permissive conditions for allowing CA. For this reason, performance results for more restrictive CA configurations are also shown:

CA Performance for Different Carrier Aggregation Configurations

Figure 5.4 and Figure 5.5 shows the 5%- and 50%-ile performance for different CA configurations. The case with no CA and cell selection based on RSRQ is used as a reference.

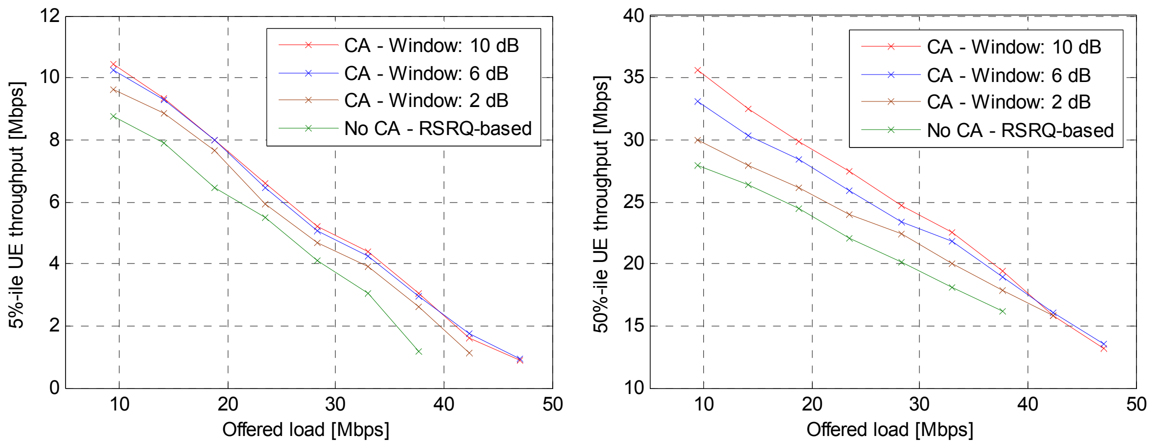


Figure 5.4: UE throughput performance for different CA window configurations

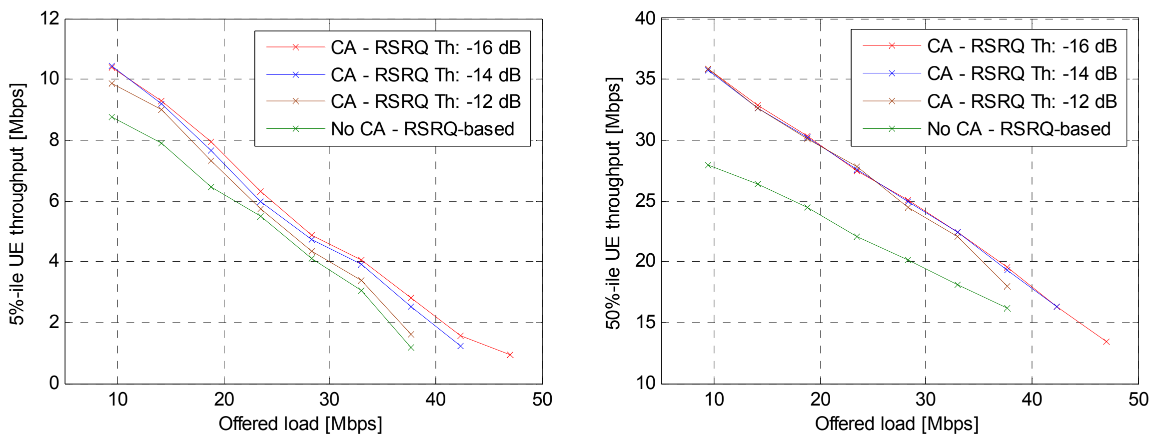


Figure 5.5: UE throughput performance for different RSRQ thresholds for CA configuration

From the 5%-ile, it is observed that the CA configuration does not have a big impact on the performance because, as it was mentioned before, most of the 5%-ile UEs are not in CA mode. However, the median performance is clearly depending on the amount of users with CA: For CA based on a RSRQ threshold, the achieved performance using different thresholds is almost identical as the CA ratio is similar (see Figure 5.2). For CA based on a CA window, the gains obtained vary from 27, 18 and 7% (50%-ile, low load) for a CA window of 10, 6 and 2 dB, respectively.

5.2.2 Regional Performance

In this type of deployment, the global network performance is mainly limited by load unbalance in Area 2 and the macro-only area where only half of the spectrum is available. For this reason, similar to what was done in co-channel section; a per-area analysis of the network is presented in order to facilitate the analysis of this type of deployment.

The followed approach is as explained in Section 3.3.2: the users are geographically separated into 5 areas and their statistics are analyzed separately. The performance is studied at different offered loads, considering the average offered load per BS in each area.

Due to lack of space, only the most representative results will be shown: these are Area 2 and 4 whose performance is illustrated in Figure 5.6 and Figure 5.7.

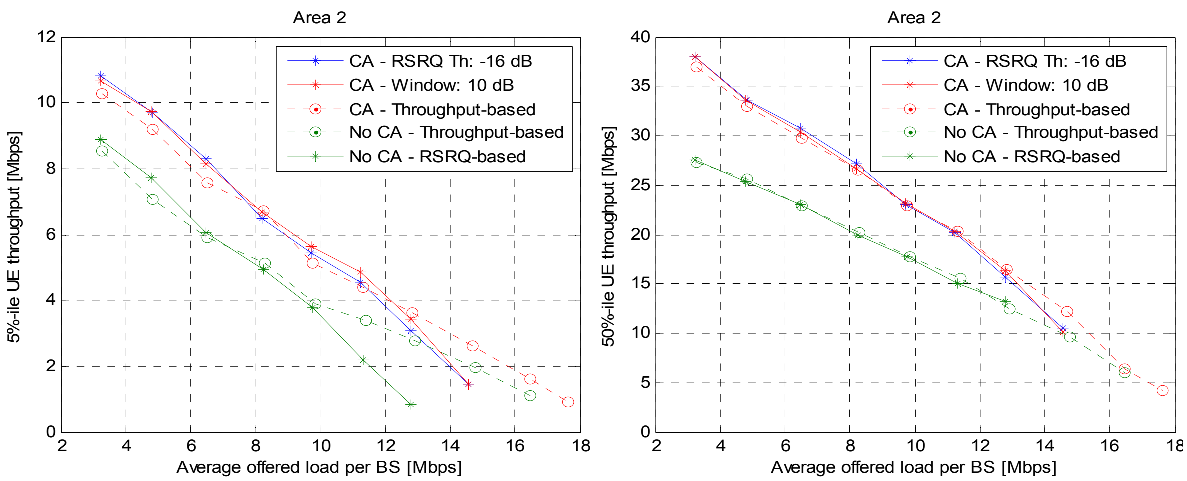


Figure 5.6: Area 2 UE throughput performance for different CA and No CA configurations

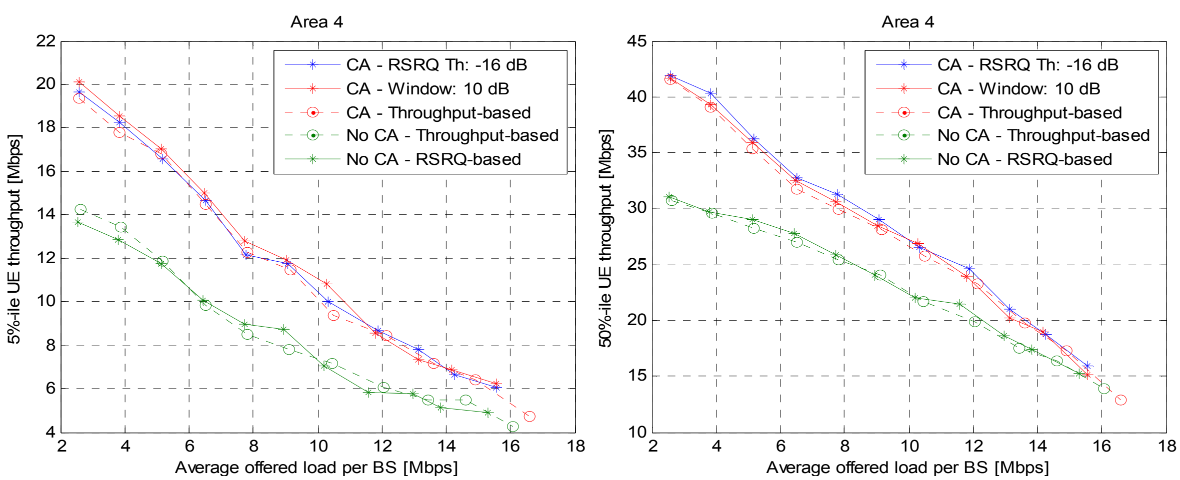


Figure 5.7: Area 4 UE throughput performance for different CA and No CA configurations

For area 2, the observed trends are similar to the observed in the global network performance as the overloading mainly occurs in this area. In the 5%-ile, only ~22% gain is obtained as the 5%-ile users are mostly located in cell-edge areas with low signal quality to the serving cell(s). When the load increases, macro sector no. 55 becomes congested (similar to what happens in co-channel deployment) hence decreasing the performance of the UEs served by that cell. The saturation is overcome by using a load balancing algorithm such as throughput-based or by connecting to two cells with carrier aggregation hence obtaining gains up to 170% in the 5%-ile. Additionally, throughput-based cell selection with carrier-aggregation provides up to 38% capacity gain for a 5%-ile target of 1 Mbps.

A more 3GPP-alike behavior is observed in area 4. The small cells are strategically placed and well distributed in the hotspots which allows achieving up to 45% and 35% gains in the 5%- and 50%-ile respectively (low load). No additional benefit is obtained from the throughput-based cell selection technique as the load is evenly distributed. The obtained gains are generally higher in the 5%-ile because, thanks to the good user distribution, the cross-carrier packet scheduler is able to provide a more fair assignment of the resources. The gains progressively decrease as the load increases as commonly occurs with 3GPP models. At very high load, the benefit of inter-site CA mainly come from increased multi-user diversity, better inter-layer load balancing, and improved mobility robustness.

Finally, Table 5.2 summarizes the performance obtained in different areas of the network for low and high load:

Area	Average Load per BS [Mbps]	5%-ile Gain [%]		50%-ile Gain [%]		CA Ratio [%]	
		RSRQ Threshold: -16 dB	CA Window: 10 dB	RSRQ Threshold: -16 dB	CA Window: 10 dB	RSRQ Threshold: -16 dB	CA Window: 10 dB
1	3	10	14	14	13	38	30
	12	53	61	11	10		
2	3	22	21	37	37	84	75
	12	170	150	28	28		
3	3	34	33	29	24	68	54
	15	12	19	8	3		
4	3	44	47	35	34	77	61
	15	27	31	9	7		

Table 5.2: UE throughput gain and CA ratio in each region for different CA configurations over No CA - RSRQ-based

The results in Table 5.2 show that the gain numbers are good, but vary from region to region. Areas 2 and 4 have been briefly described. From the rest of the areas, the following observations were found from the regional analysis:

- Area 1 presents a similar behavior to area 2: 5%-ile achieves better gains at high load due to load balancing. The gains in this area are limited by the low amount of users in CA mode. This low CA ratio is due to the fact that this area is surrounded by outer macro cells (i.e. for interference generation only). In reality, these base stations would be scheduling UEs and, in that case, up to 90% CA ratio could be obtained, hence allowing the achievement of higher gains.
  It is worth mentioning that the "real" CA ratio would be also higher in areas 2, 3 and 4. However, area 1 is the only one showing such a high difference in the CA ratio due to its placement.

- Area 3 has similar behavior as area 4. In the median, from 28% to 7.5% gains are achieved at low and high loads respectively. The gains in the 5%-ile are generally higher, varying from 45 to 30%.

5.2.3 Concluding Remarks for Dedicated Deployment Analysis

From the global network analysis it has been shown that inter-site CA provides gains in both 5%- and 50%-ile user throughput. The gains mostly come from larger transmission bandwidth, increased multi-user diversity and faster inter-site load balancing provided by inter-site CA. In the 5%-ile, gains below 20% are obtained at low load; however, when the load increases, more than 100% gain is obtained with either throughput-based cell selection and/or inter-site CA as these techniques effectively deal with the load unbalance in some areas of the network. In the median, inter-site CA provides global gains up to 28% and 22% at low load and high load, respectively.

Throughput-based cell selection algorithm was also studied in this type of deployment. The benefits of this algorithm are particularly significant at very high load, where throughput-based cell selection without inter-site CA outperforms the traditional CA configurations (RSRQ threshold or CA window based) as load balancing acquires big relevance.

In general, the gains obtained with inter-site CA are below the typically achieved in 3GPP scenarios. The main reason is that some of the small cells are placed in areas with poor macro coverage hence limiting the applicability of inter-site CA.

A CA ratio of 68% is achieved with a RSRQ threshold of -16 dB. Additional 15% can be obtained if the outer macro BSs were also enabled to serve users. The obtained CA ratio is relatively high for such an irregular deployment, especially having into account that users in the macro-only area cannot connect to multiple cells.

Regarding the per-area analysis, different behaviors are observed in the different areas of the network. For example, a 3GPP-alike behavior is observed in areas 3 and 4, where inter-site CA provided gains of more than 30% in both 5%- and 50%-ile at low load. When the load increases, less than 10% is obtained in the median; however, considerable gains are still achieved in the 5%-ile as these users greatly benefit of the joint packet scheduling functionality.

On the other hand, area 2 performance is very limited by the load unbalance. For this reason, load-balancing techniques proved to be essential to increase the local network capacity. In fact, up to 170% gain is obtained in the 5%-ile when using either inter-site carrier aggregation or the proposed dynamic cell selection technique. In the median, the gains range from 37 to 28% at low and high load, respectively.

At the sight of all these facts, we can conclude that the inter-site CA functionality performs appropriately in our site-specific scenario, therefore, we strongly recommend it as a solution for increasing the data rates in a dedicated deployment. Moreover, in cases with load unbalance and low possibilities of applying CA, dynamic cell selection techniques such as throughput-based can significantly improve the performance.

Chapter 6

6 Conclusions, Contributions and Future Work

6.1 Conclusions and Contributions

In this study we have demonstrated the benefits of using multi-cell cooperation techniques in an operator-specific heterogeneous network scenario. Two types of deployments have been studied: the co-channel deployment, where the advantages of using interference coordination and cell selection techniques were shown. Second, the dedicated deployment, where inter-site carrier aggregation effectively solved the drawbacks of fragmented spectrum between the macro and small cell layers.

Co-Channel Deployment

For co-channel deployment, it has been demonstrated that a static and global RE + eICIC configuration achieves gains in the 5%-ile in an operator-specific scenario. However, due to the irregularity of this particular deployment (e.g., user distribution and network layout), greater gains are obtained when the RE and eICIC configurations are optimized (in terms of 5%-ile UE throughput) in each area. Particularly, 5%-ile gains in the range 100% to 300% were obtained in the different areas of the network. The gains achieved mainly depended on the small cell density and location, UE distribution and interference conditions.

Dynamic algorithms, which can instantaneously adjust the muting pattern and cell selection according to the local conditions, were also proposed and studied. The proposed algorithms demonstrated to be essential to fully exploit the benefits of a heterogeneous deployment: using fast muting adaptation plus additional cell selection techniques brought in the range of 30-70% gains over slow ABS adaptation and up to 35% additional capacity gain for a target 5%-ile throughput of 2 Mbps. Besides, dynamic algorithms provide high gains also in the 50%-ile, contrary to what happens applying slow ABS. At the sight of these conclusions, we strongly recommend using a dynamic configuration to fully harvest the benefits from eICIC.

In areas where the load is unbalanced, dynamic cell selection algorithms confirmed to be effective to increase the network capacity and 5%-ile UE throughput. In other areas, a fixed RE offset proved to be an effective solution for offloading UEs to the small cells, therefore balancing the load among the cells. However, the value of the RE offset needs to be carefully adjusted according to the network conditions.

As an outcome of this study, two dynamic cell selection algorithms are developed for co-channel deployment: Throughput-based and Load-based cell selection (explained in Chapter 4). These algorithms are also used in dedicated deployment in Chapter 5.

Regarding the fast muting adaptation [10], a modification is proposed. This modification consists on changing the report of victim users to the macro cells: instead of cluster-based, we propose an UE-information based report, which means that each UE of a certain small cell will be reported in an independent way to its aggressor macro cell. As a result of this development, an IPR has been filed:

Title: "Inter-eNB load report for interference coordination"

Invention disclosure: PCT/EP2014/056719

Filing date: 3rd April 2014

Dedicated Deployment

For dedicated deployment, the inter-site carrier aggregation feature has been studied. Inter-site CA proved to be a good solution for increasing the peak data rates; especially at low load when the probability of connecting to two low-loaded cells is high. In the studied case, up to 28% of gains in the 50%-ile were obtained at low load when ~70% of the UEs are connected to two cells. At high load, the obtained gains were generally lower; inter-site CA still offers some other advantages such as enhanced mobility robustness, increased multi-user diversity and implicit inter-layer load balancing.

Additionally, dynamic cell selection algorithms were also evaluated in this type of deployment; the outcome is similar to the co-channel deployment: applying dynamic cell selection techniques increased the network capacity, especially when the UEs are connected to a single cell. For example, at high load, the 5%-ile UE throughput in a particular area of the network was increased by more than 150% when applying either throughput-based cell selection and/or inter-site CA techniques, as they managed to solve the load unbalance in that area.

6.2 Future work

Regarding the future work, it is clear that network performance in a co-channel deployment could be improved if optimal RE offsets are independently applied to each small cell. It would be interesting to compare the network performance between the cases when individual offsets are applied and the proposed dynamic cell selection algorithms are used (i.e. throughput-based and load-based cell selection).

It is also clear that additional effort can be made on improving the throughput-based and load-based cell selection algorithms. For these two algorithms, an interesting approach would be to measure network conditions in several TTIs (as it would be done in reality) and perform the cell selection based on the averaged measure. It is expected that -with this enhancement- a more accurate cell selection decision will be achieved; especially at low load when there are big traffic fluctuations in the network. Besides, the implementation of the throughput-based algorithm with information which is already available in current standards could also be studied. Possible approaches could be using the RSRQ measure or the wideband CQI as a starting point to estimate the SINR. Regarding the load-based cell selection, the condition for cell selection when the two final candidates have similar load could also be improved.

For the fast ABS, it is worth noticing that this study has focused on a load-based fast ABS (IL-ABS). It would be interesting to compare with fast ABS based on PF metrics (PF-ABS).

Additionally, it would be interesting to see the performance of the proposed techniques and solutions in other site-specific scenarios.

Finally, some considerations are given regarding the network architecture:

As it was said in the simulation assumptions, an ideal backhaul between the base stations was considered in this study. From the practical point of view, the macro + RRH deployment is a candidate solution as the small cells are connected via a low-latency high-speed fiber (i.e. fronthaul) to a master macro cell. However, this solution still does not fully adapt to our assumptions since a particular small cell might need a fronthaul connection with multiple macro sites.

An appropriate practical solution corresponds to the so-called Centralized/Cloud RAN (C-RAN) deployment where all the base stations are connected via a fronthaul to a single base-band unit (BBU) that allows centralized processing of most of the RRM algorithms. Although this type of deployment offers several opportunities to significantly increase the network performance, it represents a big challenge for operators especially in terms of deployment costs.

However, it is worth mentioning that some studies have demonstrated that comparable performance can be achieved when using Inter-site CA and fast muting adaptation features in distributed architectures. For the former, [51] demonstrates that, with an efficient flow control, ~90% of the gain available with fiber-based fronthaul can be achieved using the standard X2 backhaul. For the latter, nearly identical performance can be obtained for short X2 delays [10]. It would be interesting to study the performance impact of a non-ideal backhaul in the operator-specific scenario.

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Appendices

A Macro and Small Cell Description

Below a brief description of the main characteristics of macro cells and the different types of small cells [2] [4] [28]:

- **Macro** nodes cover a wide area, usually a few kilometers, transmitting typically at 46 dBm power. They are installed by the operators, and serve openly thousands of users, using a dedicated backhaul. They are also known as enhanced NodeBs (eNBs) in LTE.
- **Pico** nodes are regular base stations but with lower transmit power, usually between 23 and 30 dBm. They typically cover areas of 300 meters or less. Their placement is planned by the operators so as to increase capacity in hotspots and enhance coverage in areas with poor macro penetration (like malls or office buildings). They can be placed indoors or outdoors, and usually have omni-directional antennas. The access is open to all users.
- **Micro** nodes are similar to pico nodes, but their coverage area is bigger, usually around 2 kilometers, and they are deployed outdoors.
- **Femto** cells, also known as home eNBs (HeNBs) are user deployed. They have low transmit power, typically less than 23 dBm, and they cover a small area, like a house (less than 50 meters). The backhaul connectivity is facilitated by the user's home digital subscriber line (DSL) or cable modem. They are placed indoors in an unplanned manner, and have omni-directional antennas. Femtos are classified as open or closed depending on whether they allow access to all users or just to a closed subscriber group (CSG).
  It is worth noticing that closed femtos are a source of interference for the users to which they refuse access. Thus, closed femtos cause coverage holes in co-channel deployments.
- **Relay** nodes have transmit power and coverage area similar to picos, and are also deployed by the operators, but they possess a wireless backhaul. They are used to improve the signal strength and the coverage in deadspots (like tunnels or new areas). Relays can be in-band, if they use the same frequency for backhaul operation and communication with the UE, or out-of-band, if they use a different frequency for the back-

haul. In-band relays have been the focus of studies as they do not need additional dedicated spectrum, contrary to out-of-band relays.

- **RRH** (Remote Radio Head) nodes have similar transmit power and coverage area than relays. They are compact and have light weight. RRHs allow more flexibility to operators in deployments with physical limitations or site acquisition problems as they are connected to a conventional macro base station and release it from some radio circuitry, thus decreasing power losses and consumption. Besides, they are very useful in the deployment of centralized architectures, as they connect to the macro through fiber, which allows for nearly ideal transmission (no delays). That allows the possibility of having all the processing at the macro site.

B Examples of Optimal Cell Selection Algorithms and Comparative Table

Algorithm based on Design of Experiments (DOE) for cell-offset optimization [6]

The goal is to achieve an optimal load balancing. The load corresponds to the PRB utilization of each cell. The optimization consists of the maximization of the Jain's fairness index. The algorithm is composed of two algorithms: the first one estimates the cell load while the second one is in charge of the load balancing using DOE, which is a statistical way of estimating the effects of several factors at the same time and identifying the most important ones.

In [6], users are dropped in the network in a single instance with *fixed bit rate traffic model*. That means that, given the required bit rate and the SINR of an UE to a certain cell, the resource utilization of that cell can be estimated.

An iterative algorithm is executed which calculates the optimal range extension of each one of the small cells.

This algorithm has the advantage of focusing on fairness among cells, but the disadvantages are that it is not designed to work with time-dependant traffic, is not dynamic, uses a completely centralized RRM architecture and has high computational complexity.

Distributed algorithm via Lagrangian dual decomposition [5]

The idea is to self-organize the network with a load-aware user association scheme. The goal is to balance the load in a way consistent with the law of supply and demand: if a BS is overloaded, then its "price" increases and fewer users will be associated with it, and the other way around if it is under-loaded. The price is a Lagrange multiplier.

The variables involved are calculated in each time slot. The technique works using two algorithms, one for the users and the other for the base stations:

- **Users' algorithm:** Each user selects a cell based on a function of the instantaneous achievable rate (from SINR measurement) and the value of the Lagrange multiplier received for each BS.
- **BSs' Algorithm:** Each BS broadcast the Lagrange multiplier to the system, and updates the new value of the multiplier and the effective load in the BS in two steps:
  - The effective load is updated based on the number of users in all the network and the previous Lagrange multiplier.

- The Lagrange multiplier is updated based on its previous value, the previous effective load, and the association indicator (matrix showing all UEs that are connected to each BS).

The algorithm works iteratively, and converges to a near-optimal solution with very large gains for most users in the system. The number of iterations depends on the target level which depends on the estimated dual optimal value obtained by dual decomposition.

It is very important to notice that this algorithm was designed only for "equal resource allocation" (resources are allocated to each user in equal portions), and it is not applicable to dynamic settings, such as finite-buffer traffic model for example.

Other disadvantages are that it requires some time to get the best settings for optimizing network performance, and it has a poor scalability (it needs the number of users in all the network and each BS needs to broadcast information to all the rest).

<u>*Comparative Table*</u>

A comparative summary of the cell selection algorithms explained in Section 2.2.1.1 and in this appendix is showed in the following table:

	ALGORITHM					
	Load-based	**Throughput-based (SINR and number of users)**	**Throughput-based (Best SINR)**	**Fuzzy logic**	**Algorithm based on DOE for cell-offset optimization**	**Distributed algorithm via Lagrangian dual decom-position**
Periodicity	Every time an UE arrives	Every time an UE arrives	Every time an UE arrives	Depending on programation	Done once	Done once
RRM architecure	Distributed	Distributed	Distributed	Centralized and distribut-ed	Completely centralized	Distributed
Focus on fair-ness between users	No	No	No	Depending on programation	Yes	Yes
Computational complexity	Low	Low	Low	Low	Very high	Medium
Adapted to finite-buffer traffic	Yes	Yes	Yes	Yes	No	No
Iterative	No	No	No	No	Yes	Yes

Table B.1: Characteristics of cell selection algorithms

C Base Station ID Map

The map below shows the macro and pico cells within the area of interest for the operator-specific scenario used in this study (see Section 3.2). Macro cells appear in red, while pico cells appear in green. For each cell, its base station ID is shown. White circles represent (some) outer macro macro cells (i.e. only for interfering purposes, not scheduling users), which do not have an ID assigned.

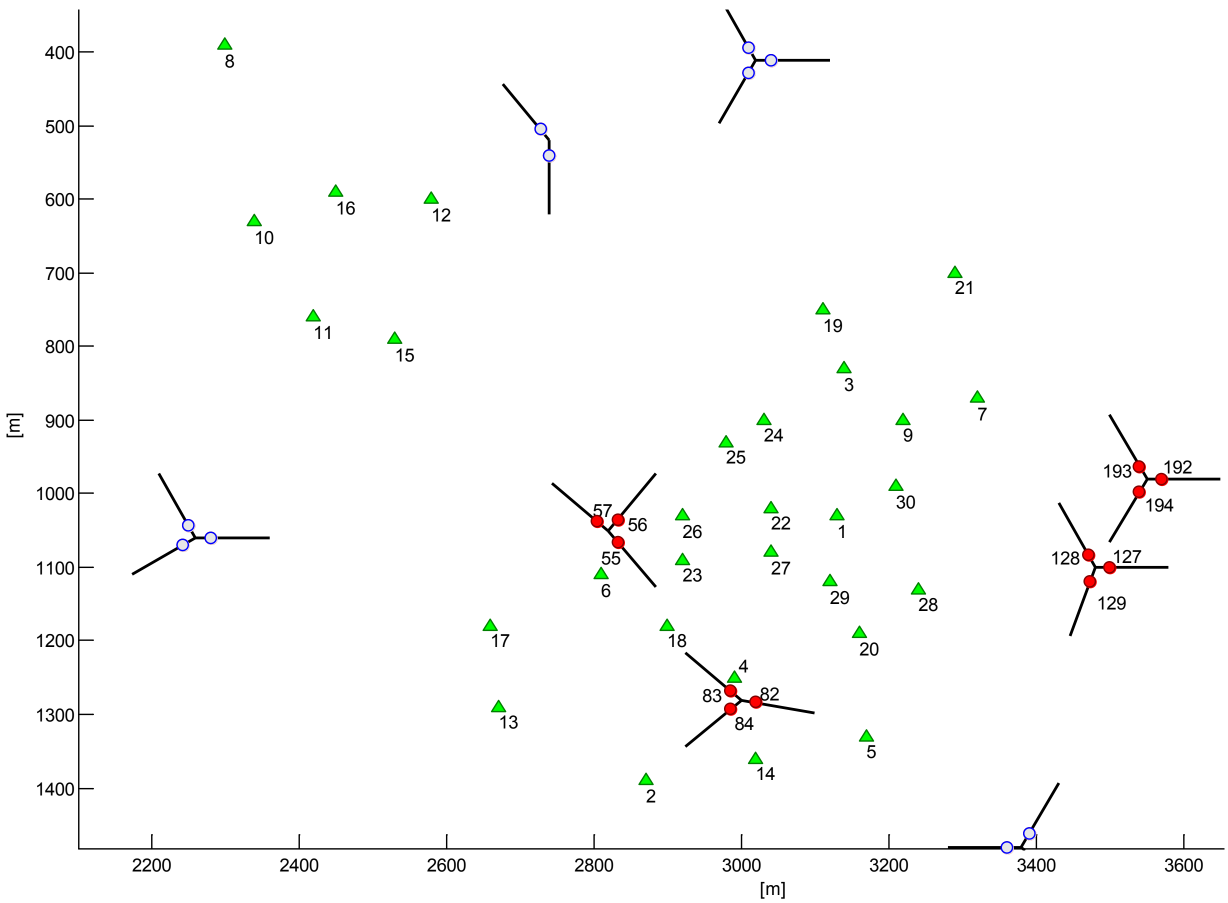

Figure C.1: Map containing the base stations in the site-specific scenario and their IDs

D Normalization for Fast ABS

The criteria for deciding whether to increase or decrease the number of muted subframes in a certain macro cell, is based on the number of victim users. Typically, the number of victim UEs used for the algorithm is just the absolute number of RE pico UEs affected by the macro. This will be called *Normalization 1*. According to this criterion, in the situations depicted in Figure D.1, the number of victim users counted for the Fast ABS algorithm will be 3 for both of them.

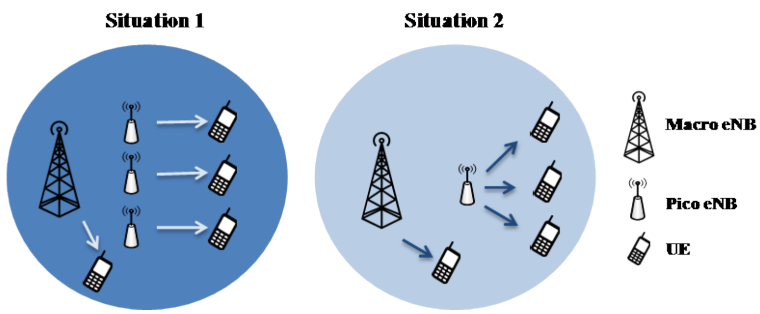

Figure D.1: Example of situations where the Normalization factor for Fast ABS changes depending on the criterion

However, it is logical thinking that Situation 2 can benefit more from a higher muting pattern, as the same pico has more victim users, then needing more ABS resources to allocate all of them. In Situation 1, each pico has only one victim user, and so all of them will be scheduled and benefit in a muted subframe.

In order to have this into account and have a fairer setting of the muting pattern, the number of victim users can be normalized dividing by the number of picos. Thus, in Situation 1 there will be counted 3 victim users for the Fast ABS, but in Situation 2 it will be counted as just one victim user. There are two possibilities for doing this normalization:

- *Fixed Normalization*: this is the traditional approach for the normalization factor, where it equals the number of picos in the cluster. In order to try this approach in the operator scenario, the same manual clusters that were defined before in Section "*Report to macro cells based on UE information"* are used.
  With this approach the normalization factor counts always the pico cells even if they are not scheduling victim users in some subframes, which means that the muting ratio can be underestimated at some moments.
- *Dynamic Normalization*: in this case only the picos that have active victim users in the considered subframe are counted for the normalization factor, which means that factor changes through time.

Figure D.2 shows the results for the different types of normalization. In the figure RE offset is applied for cell selection, and for each load the RE value that gives the best overall network performance was chosen. Finite-buffer traffic model is considered.

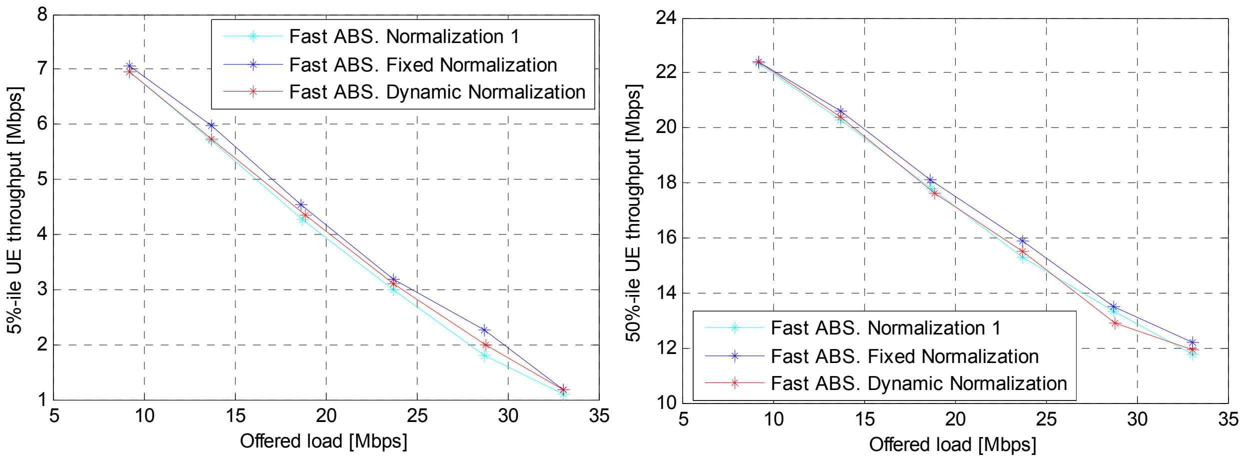

Figure D.2: Different Normalization options for Fast ABS

From the observation of this figure it is plainly obvious that a normalization factor does not improve much the performance. *Fixed Normalization* gets the best performance, which implies that for this network it is better muting less and thus not detriment macro users performance. *Dynamic Normalization* can be applied to any network automatically, while a *Fixed Normalization* would require a predefinition of clusters in each network.

As results show that there are nearly no gains from using a normalization factor, this report focuses on the Fast ABS with *Normalization 1*, for the sake of simplicity.

E Pseudo-code for Throughput-based Cell Selection

Throughput-based cell selection algorithm is explained in Section 4.1.2. The pseudo-code for this algorithm is shown in Figure E.1.

```
New user arrival
for ( each BS_i ) do
     if ( ( RSRP_max / RSRP_i ) < ( 10^(RE_THRESHOLD /10) ) ) then
          if BS_i is pico
               Γ_i = RSRP_i / (Interference – RSRP_STRONGEST_MACRO + Noise)
          else    //BS_i is Macro
               Γ_i = RSRP_i / (Interference + Noise)
          end if;
          R_i = ( 1 / (N_i + 1) ) * BW_i * log_2 (1 + Γ_i )
     end if;
end for;
Select BS with max {R_i }
```

Figure E.1: Pseudo-code for Throughput-based Cell Selection Algorithm

Where:

- BS_i : every BS within reach of the new UE.
- $RSRP_i$: RSRP that UE receives from BS_i.
- $RSRP_{max}$: best RSRP, corresponding to the strongest signal the UE receives.
- $RSRP_{STRONGEST\_MACRO}$: RSRP that UE receives from the macro cell with strongest signal.
- $RE_{THRESHOLD}$ *(dB)*: maximum difference allowed between best RSRP and $RSRP_i$.
- *Interference* : total interference the UE suffers assuming all base stations transmitting at full power.
- *Noise* : thermal Noise.
- Γ_i : Geometry Factor the UE would obtain connecting to BS_i.
- N_i : number of users connected to BS_i.
- BW_i : Component Carrier Bandwidth of BS_i.
- R_i : estimated throughput the UE would obtain connecting to BS_i.

F Pseudo-code and Load Threshold for Load-based Cell Selection

In the improved implementation of this algorithm, two cells are considered in the cell selection. Those two cells are the cells with the lowest load. This is the approach implemented in our study.

Pseudo-code

Figure F.1 shows the pseudo-code for the Load-based Cell Selection Algorithm.

New user arrival

for (*each* BS_i) **do**
    if (($RSRP_{max} / RSRP_i$) < (10^($RE_{THRESHOLD}$ /10))) **then**
        Add BS_i *to list of candidates*
    end if;
end for;

Sort candidates by increasing load
*Select two candidates with lowest load**

// Normalize load in two candidate cells
$n_{TOTAL} = n_{FIRST} + n_{SECOND}$;
$n_{FIRST\_NORM} = n_{FIRST} / n_{TOTAL}$;
$n_{SECOND\_NORM} = n_{SECOND} / n_{TOTAL}$;

// Select serving cell
if (($n_{SECOND\_NORM} - n_{FIRST\_NORM}$) <= ($Load_{THRESHOLD}$)) **then**
    if ($RSRP_{SECOND} > RSRP_{FIRST}$) **then**
        Select BS_{SECOND}
    else
        Select BS_{FIRST}
    end if;
else
    Select BS_{FIRST}
end if;

* In case several candidates have the same load, it is selected the one with best RSRP.

Figure F.1: Pseudo-code for Load-based Cell Selection Algorithm

Where:

- BS_{FIRST} : first candidate BS. It is the one with the lowest number of users from all the candidates.

- BS_{SECOND} : second candidate BS. It is the one with the second lowest number of users from all the candidates.
- $RSRP_{FIRST}$: RSRP that UE receives from first candidate BS.
- $RSRP_{SECOND}$: RSRP that UE receives from second candidate BS.
- n_{FIRST} : number of users in first candidate BS.
- u_{SECOND} : number of users in second candidate BS.
- u_{TOTAL} : total number of users in the two candidate cells.
- u_{FIRST_NORM} : normalized number of users in first candidate.
- u_{SECOND_NORM} : normalized number of users in second.
- $Loa_{dTHRESHOLD}$: load difference allowed between the two candidates.

Load Threshold

It is logical thinking that in situations where the two candidate cells have similar load, it is better for the UE to connect to the candidate which offers better signal. This situation can be taken into account in the algorithm by checking the load difference between the two candidate cells. If the load difference is within a certain threshold, the selected cell will be the one with higher RSRP. The problem is deciding the best setting for the threshold. The threshold will have a value between 0 and 1, as the candidate loads are normalized before applying this threshold.

The idea is that at low load, it is more convenient to connect to the cell with the best signal, thus higher load difference should be allowed between the final candidates. As the load increases, it is more important to balance the load among the cells, thus the value of $Load_{THRESHOLD}$ should become more restrictive.

The first approach used during this study was trying different thresholds for each load. Afterwards, for each offered load, the setting which got the best performance was manually selected. The optimal settings obtained for each load appear in Table F.1. The optimal threshold tends to be smaller when the load increases, which makes sense, because at high loads is important to balance the load in order to avoid saturation.

The second approach was applying a dynamic threshold that changes depending on the load. The manual settings for the threshold have showed that the threshold should decrease with the load. Thus, the selected dynamic threshold is: $\frac{1}{Total\ number\ of\ users\ in\ two\ \ candidate\ cells}$.

Both approaches were tested, comparing the results with the case without any threshold (that is, always selecting the candidate with the lowest load). The performance results for 5%-ile and median UE throughput can be seen in the figure below, while Table F.1 shows the 5%-ile gains obtained by each approach over the case without threshold. These are overall network results, obtained considering finite-buffer traffic model.

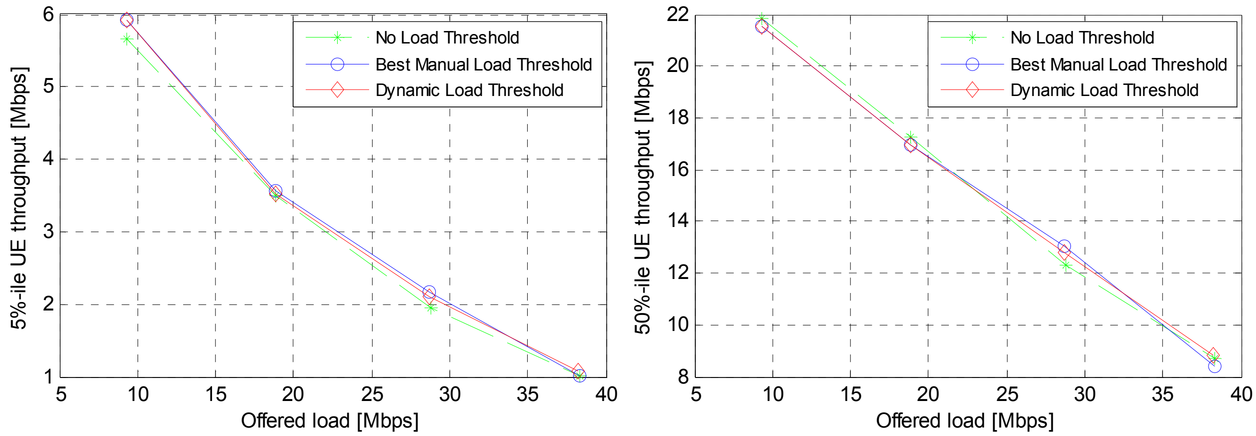

Figure F.2: Performance comparison for different Load Threshold approaches, using Load-based cell selection + Fast ABS

Offered Load (Mbps)	Manual Threshold		Dynamic Threshold
	Best Setting	5%-ile Gain (%)[19]	5%-ile Gain (%)[19]
10	0.4	4.79	4.65
20	0.4	1.95	0.334
30	0.4	11.3	8.48
40	0.1	0.732	6.5

Table F.1: Best settings and 5%-ile UE throughput gains for different Load Threshold approaches, using Load-based cell selection + Fast ABS

From these results it is pretty clear that the load threshold does not help much to improve the performance. In the case of the manual threshold, it is not worth using it because the cost for the network in order to find out the best setting is higher than the little gains obtained. The dynamic threshold also obtains low gains, but the network does not need to do anything. The implementation of the dynamic threshold is very easy and it does not imply any signaling or processing for the network. Therefore, in this study was decided to use the dynamic threshold and get advantage of the gains it provides, even if they are small.

[19] 5%-ile UE throughput gain in the overall network performance respect the case without Load Threshold

G Full-Buffer Results for Co-Channel Deployment

A static (fixed in time) configuration is considered. For the overall network results, the configuration is also global (same for all base stations in the network), while for the regional results a different configuration is considered for each region (the configuration which maximizes the 5%-ile UE throughput in each region).

The cell selection will be done applying a RE offset to the small cells, while static eICIC is used for interference management.

Overall Network Performance

The 5%-ile UE throughput for different configurations of RE + eICIC is shown in Figure G.1. It can be observed that the gain obtained by using this technique is not very large, just around 20% with the best RE + eICIC settings as compared to the reference case without RE and eICIC. This gain is quite low as compared to the results in 3GPP scenarios. Following the user throughput performance will be studied in separated regions to find out the reason for this behavior.

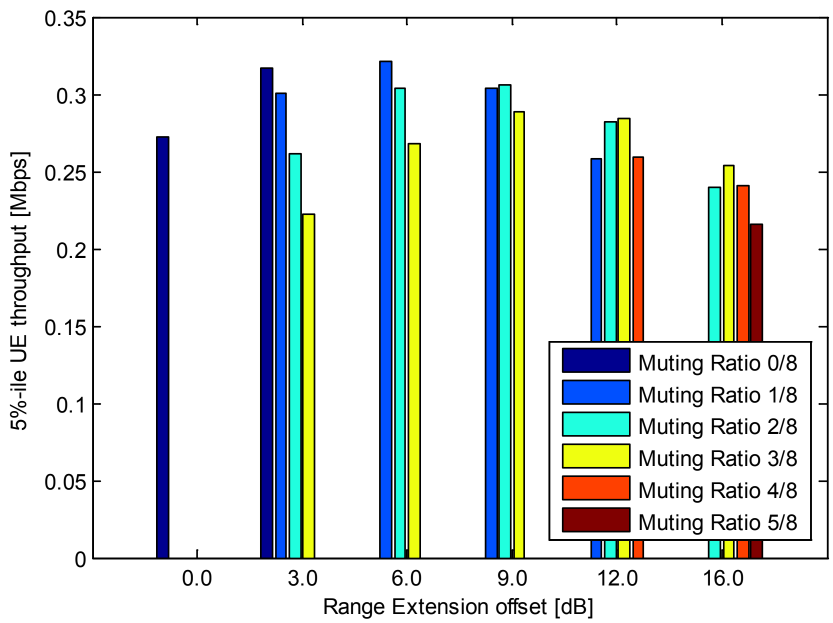

Figure G.1: 5%-ile UE throughput using different static RE + eICIC configurations

Regional Performance

The operator scenario under study is much more irregular (both network layout and user traffic density) than 3GPP scenarios, as explained in Chapter 3. Thus it is useful to separate the network in different regions and study the performance in each one.

Section 3.3.2 explains how are separated the regions. These regions are shown in Figure G.2.

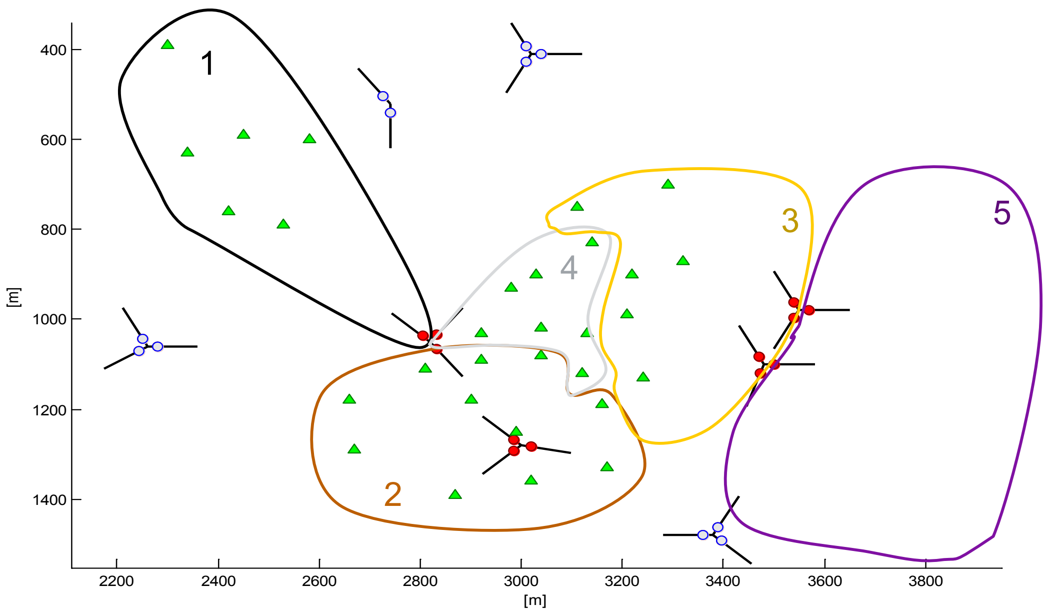

Figure G.2: Regions of study in the network

Previously the performance for different RE + eICIC configurations was studied in the whole network. But those results are not enough to study the network due to its irregularity. Thus below it is shown the 5%-ile UE throughput obtained with different configurations in each one of the regions. For each region, these results are obtained by selecting the users connected to the base stations in that area. Thus, the user statistics are separated by serving cell for the different configurations. It is worth noticing that the finite-buffer results shown in this study are not done in the same way (user statistics are separated geographically).

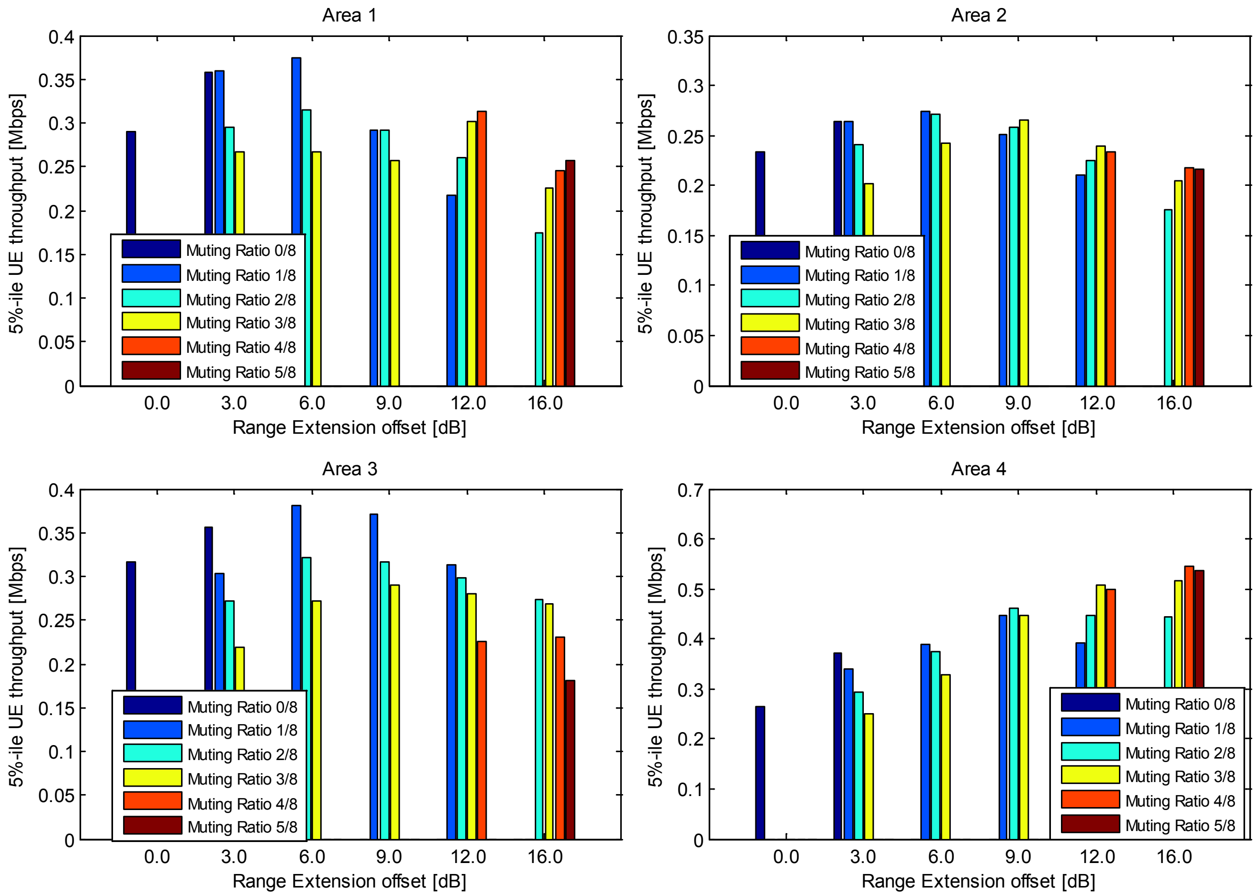

Figure G.3: 5%-ile UE throughput in each region for different RE + eICIC configurations

It is obvious that the performance in each region is very different. The configurations with best user throughput performance are different in each area. This explains why the overall performance of the network by having the same RE + eICIC configuration in different regions does not obtain much gain, as for a certain configuration some regions are gaining but others are having losses.

It is worth noticing that region number five does not have any pico cells, which obviously means that the best configuration for it implies not to mute the macro cells in region number five.

H Finite-Buffer Regional Study for Co-Channel Deployment

Best Configuration in Each Region

Table H.1 shows the best configuration in each region, i.e. the configuration which maximizes the 5%-ile UE throughput in each area, both for static and dynamic configurations, and considering an average load of 6-8 Mbps per BS. It is worth noticing that static configuration consists on applying a fixed RE and muting ratio in the whole network, whereas dynamic configuration can be either RE or dynamic cell selection + Fast ABS.

Area	Static Configuration		Dynamic Configuration
	RE (dB)	Muting Ratio	RE (dB)
1	4	1/8	12
2	4	0/8	Throughput-based Cell Selection
3	3	0/8	14
4	8	1/8	14

Table H.1: Best settings in each region for static and dynamic configurations in a co-channel deployment

UE Throughput in Regions. Example: Areas 2 and 4

Figure H.1 and Figure H.2 show the 5%-ile and 50%-ile UE throughput at different offered loads for areas 2 and 4 respectively. These figures depict the UE throughput for different cases: no RE + no eICIC, static configuration, and two possible dynamic configurations (RE + Fast ABS or Throughput-based + Fast ABS). Results for load-based cell selection are not depicted for the sake of simplicity, as the conclusions that can be drawn from this sub-section are the same for both throughput-based and load-based cell selection.

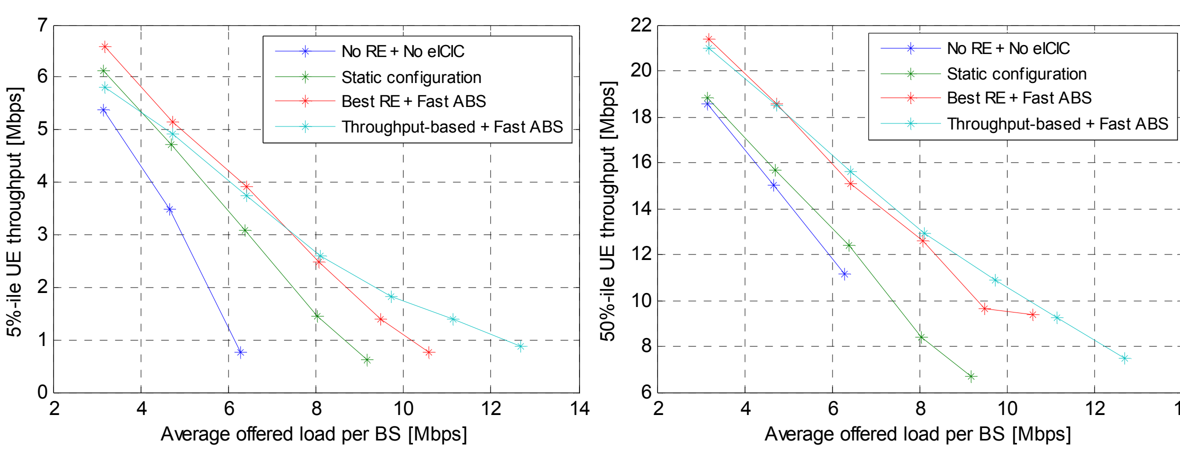

Figure H.1: 5%-ile and 50%-ile UE throughput for different configurations in Area 2

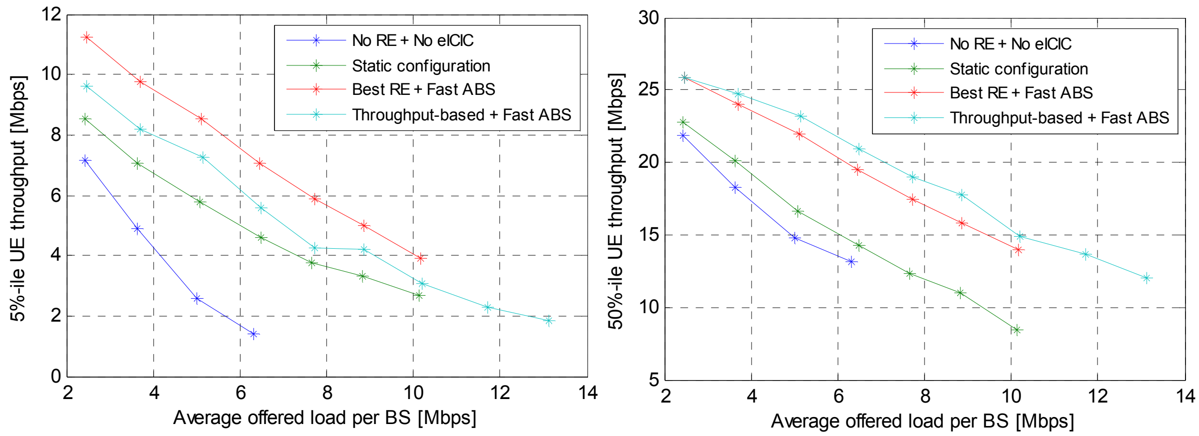

Figure H.2: 5%-ile and 50%-ile UE throughput for different configurations in Area 4

The main purpose of these figures is to highlight the fact that dynamic cell selection (represented by throughput-based) obtains gains in cases of load unbalance (area 2) but does not improve the performance for evenly distributed load (area 4).

Figure H.1 (area 2) shows that throughput-based cell selection achieves better performance than a fixed RE for medium to high offered load. At low load is always better to connect to the best signal, as was explained in Section 4.3.1.

In Figure H.2 (area 4) is observed that throughput-based cell selection performs approximately as RE-based cell selection (slightly lower in 5^{th} percentile while slightly higher in median).