

Analysis of CoMP for the Management of Interference in LTE

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To my family and friends

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Abstract

The deployment of LTE radio networks, namely in urban scenarios, implies that capacity needs to be maximised, thus, being usual that a “single-frequency” is taken, i.e., all base stations share the same overall available spectrum. However, this approach leads to interference, which can achieve quite high levels, with harmful consequences in the QoS and QoE made available to users. Normally, off-centre users are the ones who suffer more interference. In order to manage this interference, off-centre users use the CoMP technique, more precisely the JT one. A detailed analysis of the CoMP effect on throughput is addressed for the 800, 1800 and 2600 MHz bands in urban scenario in a homogeneous network. The model was implemented in a computational tool to provide a generic study of any scenario. Two versions of the simulator were developed, for static and temporal scenarios. The former analyses network performance at a given time instant, aiming to assess the correct functioning of CoMP. The latter has the capability to do a temporal analysis, with the objective of understanding how CoMP affects network performance. In the second version two separate studies were performed: the low and mid load scenarios. With CoMP in low load scenarios, the off-centre users’ throughput presents a gain above 74% in the 2600 MHz band and above 58% in 1800 MHz; in the mid load scenario one achieves a gain around 40% in 2600 MHz.

Keywords

Coordinated Multipoint, Joint Transmission, LTE, Management of Interference, Quality of Service, Urban Scenarios.

Resumo

A implementação de redes LTE, nomeadamente em cenários urbanos, implica que a capacidade necessita de ser maximizada, portanto, usualmente apenas uma “única frequência” é utilizada, ou seja, todas as estações base compartilham o mesmo espectro. Contudo, esta abordagem conduz a interferências que podem atingir níveis bastante elevados, com consequências prejudiciais na QoS e QoE disponibilizada aos utilizadores. Normalmente, os utilizadores fora do centro são aqueles que sofrem mais interferência. Para gerir essa interferência, os utilizadores fora do centro usam a técnica de CoMP, mais precisamente a técnica de JT. Uma análise detalhada do efeito do CoMP no ritmo binário foi efetuada nas bandas de 800, 1800 e 2600 MHz num cenário urbano com uma rede homogénea. O modelo foi implementado numa ferramenta computacional para fornecer um estudo genérico de qualquer cenário. Foram feitas duas versões do simulador, um cenário estático e um temporal. O primeiro analisa o desempenho da rede num determinado instante, com o objetivo de avaliar o funcionamento do CoMP. O segundo tem a capacidade de fazer uma análise temporal, com o objetivo de compreender como o CoMP afeta a rede. Na segunda versão foram realizados dois estudos distintos: cenários de cargas baixa e média. Em cenários de carga baixa, o ritmo binário dos utilizadores fora do centro apresenta um ganho acima de 74% na banda de 2600 MHz e acima de 58% na banda de 1800 MHz. No cenário de carga média é alcançado um ganho em torno de 40% na banda de 2600 MHz.

Palavras-chave

Coordenação Multiponto, Transmissão Conjunta, LTE, Gestão de Interferência, Qualidade de Serviço, Cenário Urbano.

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List of Acronyms

3D	3-Dimensional
3G	3 rd Generation of Mobile Communications Systems
3GPP	Third Generation Partnership Project
4G	4 th Generation
ABS	Almost Blank Sub-frames
ACK	Acknowledgement
aGW	Access Gateway
AMBR	Aggregated MBR
ASA	Authorised Shared Access
BS	Base Station
CoMP	Coordinated Multipoint
CP	Cyclic Prefix
CQI	Control Quality Indicator
CS	Cell Selection
CS/CB	Coordinated Scheduling and Beamforming
CSI	Channel State Information
D2D	Device-to-Device
DCS	Dynamic Cell Selection
DL	Downlink
DM	Demodulation
DMFR	Dynamic Frequency Reuse
DPB	Dynamic Point Blanking
DPS	Dynamic Point Selection
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
eCoMP	Enhanced CoMP
EDGE	Enhanced Data Rates for Global Evolution
eICIC	Enhanced Inter-Cell Interference Coordination
eNodeB	E-UTRAN Node B
EPC	Evolved Packet Core Network
EPS	Evolved Packet System
FDD	Frequency Division Duplex
feICIC	Further Enhanced ICIC
FFR	Fractional Frequency Reuse
FTP	File Transfer Protocol

GBR	Guaranteed Bit Rate
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat Request
HetNet	Heterogeneous Network
HFR	Hard Frequency Reuse
HSPA	High Speed Packet Access
HSPA+	HSPA Evolution
HSS	Home Subscription Server
HTTP	Hypertext Transfer Protocol
IC	Interference Cancellation
ICIC	Inter-Cell Interference Coordination
IM	Instant Messaging
IMS	IP Multimedia Sub-System
IP	Internet Protocol
IRC	Interference Rejection Combining
ITS	Intelligent Transport Systems
JP	Joint Processing
JT	Joint Transmission
LoS	Line-of-Sight
LTE	Long Term Evolution
LTE	LTE for Unlicensed Bands
M2M	Machine-to-Machine
MBR	Maximum Bit Rate
MIMO	Multiple Input Multiple Output
MM	Mobility Management
MME	Mobility Management Entity
MRC	Maximal Ratio Combining
MU-MIMO	Multi-User MIMO
NACK	Negative Acknowledgement
NLoS	Non-Line-of-Sight
Non-GBR	Non-Guaranteed Bit Rate
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
P-GW	Packet Data Network Gateway
PAPR	Peak-to-Average Power Ratio
PBCH	Physical Broadcast Channel
PCC	Policy and Charging Control
PCFICH	Physical Control Format Indicator Channel
PCRF	Policy and Charging Resource Function
PDCCH	Physical Downlink Control Channel

PDSCH	Physical Data Shared Channel
PHICH	Physical HARQ
PoS	Point of Sale
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PSS	Primary Synchronisation Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QCI	QoS Class Identifier
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RBG	Resource Block Group
RF	Radio Frequency
RRM	Radio Resource Management
RS	Reference Signals
S-GW	Serving Gateway
SAE-GW	System Architecture Evolution Gateway
SC-FDMA	Single Carrier Frequency Division Multiple Access
SFR	Soft Frequency Reuse
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SRI	Scheduling Request Indicator
SRS	Sounding Reference Signals
SSS	Secondary Synchronisation Signal
SU-MIMO	Single-User MIMO
TDD	Time Division Duplex
TE	Terminal Equipment
TTI	Transmission Time Interval
UE	User Equipment
UHF	Ultra High Frequency
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UP	User Plane
USIM	Universal Subscriber Identity Module
UTRAN	UMTS Terrestrial Radio Access Network
V2X	Vehicle-to-Everything
VoIP	Voice over IP
VoLTE	Voice-over Long-Term Evolution

VRB

Virtual Resource Block

WCDMA

Wideband Code Division Multiple Access

List of Symbols

α_{pd}	Average power decay
Δ	Convergence
θ	Angle between the pointing direction of the antenna in the vertical plane
θ_1	Angle for LoS conditions
θ_2	Angle for NLoS conditions
θ_{3dB}	Vertical half-power beamwidth
θ_{etilt}	Electrical antenna downtilt
μ	Mean value
$\rho_{IN[dB]}$	SINR
ρ_N	SNR
σ	Standard deviation
σ_e	Standard deviation of propagation model chosen
τ_{TTI}	Subframe period
φ	Angle between the pointing direction of the antenna in the horizontal plane
φ_{3dB}	Horizontal half-power beamwidth
ϕ	Angle of incidence of the signal in the buildings, on the horizontal plane
A_m	Front-to-back attenuation
$A_{SL[dB]}$	Sidelobe attenuation
B_{ch}	Channel bandwidth
B_{RB}	Bandwidth of one RB
d	Distance between the BS and the UE
F	Noise figure
f	Signal carrier frequency
f_f	The total output parameter cumulative mean
f_n	The partial output parameter cumulative mean at interval
G	Total gain of the antenna
G_{CoMP}	Gain of CoMP
G_H	Horizontal radiation pattern
G_{max}	Maximum gain of the antenna
G_r	Gain of receiving antenna
G_t	Gain of transmitting antenna
G_V	Vertical radiation pattern

h_b	Height of the BS antenna
H_B	Height of the buildings
h_m	Height of the UE
I	Interference power
k_a	Increase of path loss for the BS antennas below the rooftops of the adjacent buildings
k_d	Controls the dependence of the multi-screen diffraction loss versus distance
k_f	Controls the dependence of the multi-screen diffraction loss versus frequency
L_0	Free space propagation path loss
L_{bsh}	Loss due to the height difference between rooftop and the antennas
L_c	Losses in cable between transmitter and antenna
L_{ori}	Loss due to the street orientation
L_p	Path loss from the COST 231 Walfisch-Ikegami model
$L_{p,total}$	Path loss
L_{rm}	Attenuation due to diffraction from the last rooftop to the UE
L_{rt}	Attenuation due to propagation from the BS to the last rooftops
L_u	Losses due to user
m	Modulation
M_F^p	Fading margin
M_{FF}	Fast fading margin
M_{SF}	Slow fading margin
N	Average noise power at the receiver
N_I	Number of interfering signals reaching the receiver
N_{RB}	Number of RBs
N_{RB}^u	Number of user resource blocks
$N_{RB,user}$	Number of RBs allocated to UE
$N_{streams}$	Number of streams
N_{subc}	Number of sub-carriers
N_{sym}^{sf}	Number of symbols per sub-frame
$N_{u,sec}$	Number of users served by the sector
P_{Bch}	Percentage of used channel bandwidth
P_{EIRP}	Effective isotropic radiated power
P_t	Power fed to the antenna
P_{Tx}	Transmitter output power
P_r	Power available at receiving antenna
$P_{r,min}$	Power sensitivity at the receiver antenna
P_{Rx}	Power at the input of the receiver
R	Maximum cell radius

R_b	Throughput
$R_{b,best}$	Best throughput
$R_{b,CoMP[Mbps]}$	CoMP throughput
$R_{b,RB}$	RB throughput
$R_{b,user}$	User throughput
R_{codrat}	Channel coding rate
u	Value obtained from the respective percentage value for the normal distribution
w_B	Distance between buildings' centres
w_S	Width of the streets

List of Software

MapBasic V15.0	Programming software and language for the creation of additional tools and functionalities for MapInfo
MapInfo Professional V15.0	Geographical information system software
Microsoft Office 2016	Text editor software
Microsoft Excel 2016	Calculation and graphical software
C++ Builder 6	C++ app development environment
Notepad++	Source code editor
Atom	Source code editor
WinPython 3.6.0	Python app development environment
Photoshop CS6	Image editor software
Google Maps	Geographic plotting tool
Draw.io	Flowcharts marker and diagram online software

Chapter 1

Introduction

This chapter introduces the subject of this dissertation and a brief overview of the mobile communications systems evolution, with a particular focus on LTE technology. Furthermore, it establishes the thesis motivation and content of this document.

1.1 Overview

Over the years, mobile communication systems became crucial for peoples' lives. Currently, mobile phones are very important, being possible to do several tasks with them, such as: making phone calls, sending messages and e-mails, watching videos and taking notes. Although recently the number of consumers has not been having an exponential growth, mobile traffic suffered changes and data traffic has grown a lot.

According to [Eric16], the growth in data traffic is being driven both by increased smartphone subscriptions and a continued increase in average data volume per subscription, fuelled primarily by more viewing of video content. As it can be seen in Figure 1.1, data traffic grew 10% quarter-on-quarter and 60% between Q1 2015 and Q1 2016.

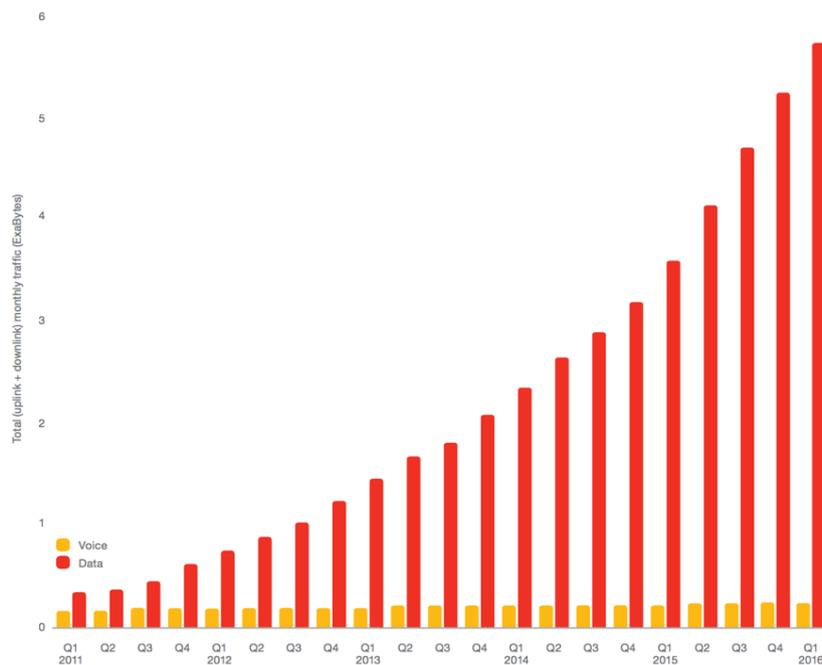


Figure 1.1. Global total traffic in mobile networks, 2011-2016 (extracted from [Eric16]).

GSM ensured voice traffic, however the users' needs changed and a new technology appeared. The Third Generation Partnership Project (3GPP) introduced a new technology, the Universal Mobile Telecommunications System (UMTS), also known as 3rd Generation (3G). According to [HoTo11], for UMTS, Wideband Code Division Multiple Access (WCDMA) Release 99 specification work was completed at the end of 1999 (Release 99) and was followed by the first commercial deployments during 2002. After this technology appeared, further developments have occurred, such as High Speed Packet Access (HSPA) and HSPA+. Afterwards, 3GPP approved Long Term Evolution (LTE), also known as 4th Generation (4G), which was introduced in Release 8. The specifications were completed and backwards compatibility started in March 2009. In Figure 1.2, it is possible to observe 3GPP Release availability dates.

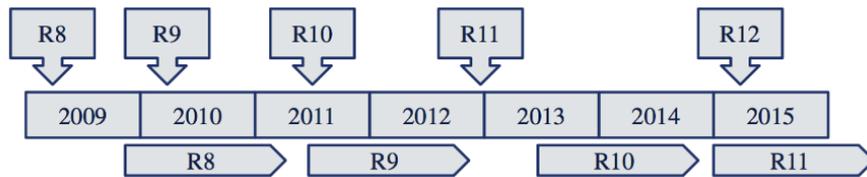


Figure 1.2. 3GPP Release availability dates (extracted from [HoTR16]).

According to [HoTR16], Release 8 enabled a peak rate of 150 Mbps with 2x2 MIMO. Although, in theory, it enables a peak rate of 300 Mbps with 4x4 MIMO, practical devices so far have two antennas limiting the data rate to 150 Mbps. Release 9 was completed one year after Release 8, bringing features as a complete standardisation of Voice over Long-Term Evolution (VoLTE) and femto base station handovers. Release 10 provided a major step to the development of LTE, also known as LTE-Advanced. Release 10 was completed in June 2011, and the first commercial carrier aggregation network started in June 2013. This release provided 8x8 MIMO in downlink (DL), 4x4 MIMO in uplink (UL), and support for Heterogeneous Network (HetNet) with feature enhanced Inter-Cell Interference Coordination (eICIC). The first Release 11 commercial implementation was available during 2015. Release 11 brought some techniques to mitigate interference, such as Coordinated Multipoint (CoMP) and further enhanced ICIC (feICIC). Also brought advance User Equipment (UE) interference cancellation and carrier aggregation improvements. Release 12 was completed in 3GPP in March 2015 and the deployments are expected by 2017. Release 12 includes dual connectivity between macro and small cells, enhanced CoMP (eCoMP), machine-to-machine (M2M) optimisation and device-to-device (D2D) communication. Release 13 was completed during 2016 and brought LTE for Unlicensed bands (LTE-U), Authorised Shared Access (ASA), 3-dimensional (3D) beamforming and D2D enhancements. According to [3GPP16a], the Release 14 and 15 are still in development. These releases have improved data rate, and as it can be observed in Figure 1.3, there was an evolution of data rate.

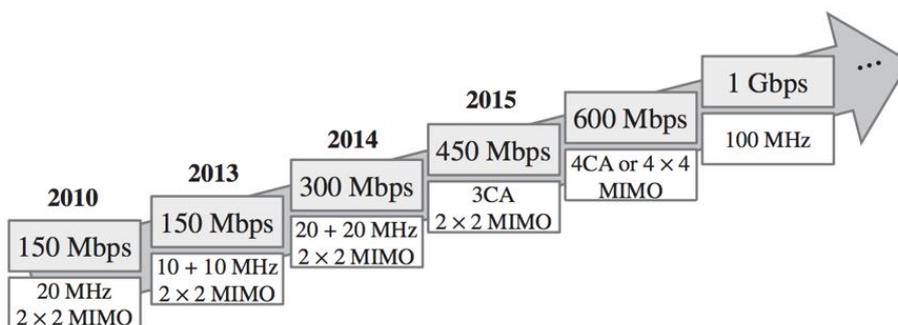


Figure 1.3. Peak data rate evolution in commercial devices (extracted from [HoTR16]).

The theme of this thesis is the study of CoMP as a technique for the management of interference. As previously mentioned, CoMP was launched in Release 11, and uses multi-cell transmission and reception for improving radio communications. With this technique, the most harmed users, i.e., off-centre ones, with particular emphasis on cell-edge users, may have a better throughput, improving their communications.

Global System for Mobile Communications (GSM) or Enhanced Data Rates for Global Evolution (EDGE)

subscriptions presently represent the largest share of mobile subscriptions, however in 2019, LTE will be the dominant mobile access technology. Since LTE became a reality, the number of LTE subscriptions has grown rapidly. The first billion of LTE subscriptions was reached during 2015, and will reach a total of 4.3 billion subscriptions by the end of 2021, as it can be observed in Figure 1.4.

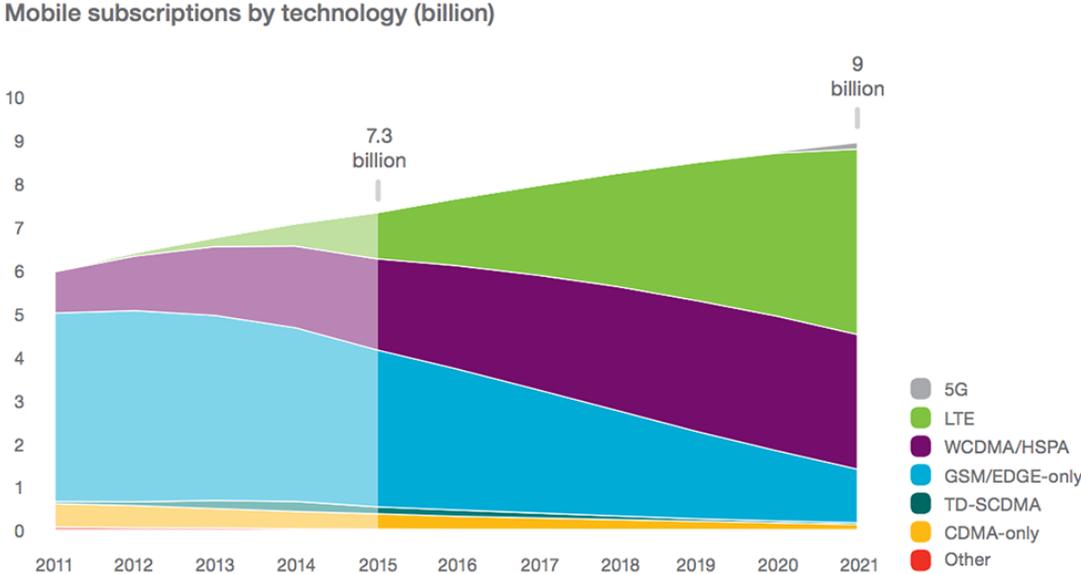


Figure 1.4. Number of global mobile subscriptions for different technologies, 2011-2021 (extracted from [Eric16]).

Nowadays, mobile traffic is consumed by smartphones, PCs and tablets. According to [Eric16], between 2015 and 2021, there will be a twelve times growth in smartphone traffic. Around 90% of mobile data traffic will be from smartphones by the end of 2021. North America is the region in the world with the highest monthly data usage per active smartphone subscription. This trend will continue in the coming years. In 2021, monthly smartphone data usage per subscription in North America will be 22 GB and in Western Europe, region where Portugal is included, will be 18 GB.

1.2 Motivation and Contents

Nowadays, LTE is the best technology implemented and used in mobile communication systems. Although it has several advantages, it has also some disadvantages. One of them is the interference caused by the capacity that LTE offers, particularly in urban scenarios. Urban scenarios have a lot of buildings, which increase interference. Also, there are a lot of people in these scenarios, for this reason being crucial that the network has an acceptable capacity. This capacity is obtained by usage of HetNets, which are usually composed by macro-, micro-, pico- and femto-cells. HetNets also increase interference, because sometimes the macro-cell coverage interferes with the pico-cell one, cell-edge users being the most affected.

The main scope of this thesis is to study techniques to manage interference. To solve this problem, one uses the CoMP technology. When an urban user is connected to a base Station (BS) and it is situated in cell-edge, it is probable for he/she is covered by more than one BS. These neighbour BSs, can be harmful and cause interference. Cell-edge users, for obvious reasons, has a worse throughput than cell-centre ones, however, interference deepens this difference. CoMP allows the user to be connected to more than one BS, increasing cell-edge users' throughput.

This thesis was done in collaboration with Vodafone Portugal. Vodafone Portugal agreed to give the required information about their network in Lisbon in order for this work to be realistic.

The thesis is composed of 5 chapters and 4 annexes. Chapter 1, the present one, provides an overview of the problem being solved and the motivation behind its study.

Chapter 2 provides a brief introduction to LTE fundamental concepts, being a crucial element for understanding subsequent chapters. It provides a brief description of LTE's network architecture, presenting the main elements that are part of it. A radio interface description follows, where LTE DL and UL are described, as well as the differences between LTE and previous 3GPP systems. The Services and Applications section provides information about the services, such as main services, traffic classes and resources types. Coverage and Capacity considerations are provided, including cell types and impact of frequency band and bandwidth on the system. The Interference section presents information about techniques to mitigate and to manage interference, where the CoMP technique is included. In the end of the chapter, it is possible to find the State of the Art with studies already done about the area.

A description of the models and the algorithms developed in this thesis is provided in Chapter 3. The mathematical formulation for further analysis is detailed, with a particular focus on Signal to Noise Ratio (SNR), Signal to Interference plus Noise Ratio (SINR), coverage, antennas, throughput, capacity and fading. Thereafter, the algorithms used in the model are described, model functioning being explained. To conclude the chapter, a brief assessment of the model is provided, in order to ensure the correct functioning of the simulator.

The analysis of the results extracted from simulation is provided in Chapter 4. It starts by defining the reference scenario and justifying the assumptions taken. Then, a study of the parameters in the reference scenario is done, followed by different analysis where some parameters are changed to measure their impact on the network. Results are presented along the chapter together with the corresponding discussion.

Chapter 5 contains the main conclusions of this thesis, an analysis of the overall obtained results, and suggestions on future work. A summary of all the work performed is also provided, in order to allow the reader having an idea of the main aspects addressed in this thesis.

Finally, a group of annexes contains additional information within the scope of this thesis. In Annex A, one provides all the mathematical equations for the calculation of the link budget, between the user and the BS. Annex B presents the COST 231 Walfisch-Ikegami model, which is connected with the previous

annex. Annex C provides the formulas that relate the SNR with throughput in each Resource Block (RB). The user's manual intended to aid the understanding of the simulator's user interface is provided in Annex D.

Chapter 2

Fundamental Concepts

This chapter provides an overview of the basic concepts of an LTE network, such as its network architecture, radio interface, services, applications, coverage, capacity and interference issues. A brief state of the art is also presented.

2.1 LTE Aspects

The purpose of this section is to provide an overview on LTE, including its network architecture, radio interface, coverage and capacity, being based on [HoTo11], [SeTB11], [Pent15] and [Corr16].

2.1.1 Network Architecture

With the introduction of LTE, the architecture of cellular networks suffered significant changes. LTE's network architecture is presented in Figure 2.1, being divided into four main high levels domains: UE, Evolved UMTS Terrestrial Radio Access Network (E-UTRAN), Evolved Packet Core Network (EPC) and the Services domain. One of the biggest significant architecture changes in the core network area is that the EPC does not contain a circuit switched domain. The EPC function is equivalent to the packet switched domain of the existing 3GPP networks.

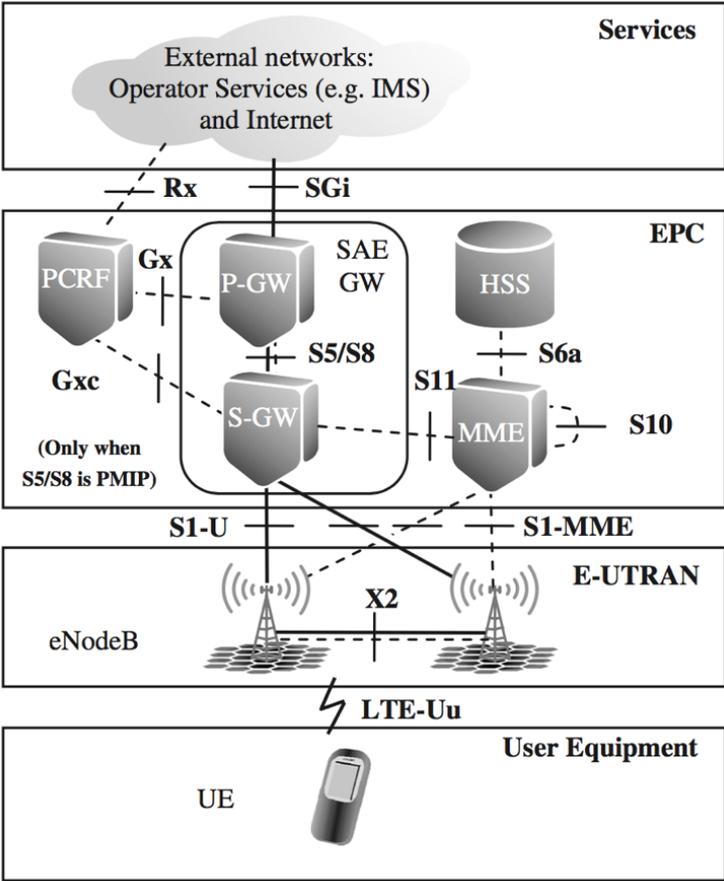


Figure 2.1. LTE architecture for E-UTRAN only network (adapted from [HoTo11]).

The Internet Protocol (IP) Connectivity Layer is represented by UE, E-UTRAN and EPC and that part of the system is called the Evolved Packet System (EPS).

The UE is also called the Terminal Equipment (TE), being the device that users use for communication that contains a Universal Subscriber Identity Module (USIM). The USIM is used to identify and authenticate the user and protects the radio interface transmission with security keys. The UE is a platform for communication applications. It sets up, maintains and removes the communication links needed by the user, and it contains mobility management functions, such as handover and reporting terminals location.

E-UTRAN has just one node, the E-UTRAN Node B (eNodeB), which is a BS that controls all radio functions in the fixed part of the network. The eNodeBs are responsible for establishing a connection between UE and the EPC, and are connected to each other through the X2 interface. The eNodeB performs IP header compression/decompression and ciphering/deciphering of User Plane (UP) data. The eNodeB is also responsible for many control plane functions, such as Radio Resource Management (RRM) and Mobility Management (MM). RRM allocates resources based on requests, prioritises and schedules traffic according to required Quality of Service (QoS), and performs a constant monitoring of the resource usage situation. The MM decides when the UE executes a handover between cells, based on signal level measurements performed both at the eNodeB and the UE.

As stated before, the EPC does not contain a circuit switched domain, its main elements being the following:

- The Mobility Management Entity (MME), which is the main control element in the EPC. The MME operates only in control plane, so usually it would be a server in a secure location in the operator's premises. It provides some functions in the basic System Architecture Configuration, such as authentication and security, mobility management, managing subscription profile and service connectivity.
- The System Architecture Evolution Gateway (SAE-GW), which incorporate Serving Gateway (S-GW) and Packet Data Network Gateway (P-GW). The S-GW is responsible for UP tunnel management and switching and the P-GW is the edge router between the EPS and external packet data networks, it is considered the highest level mobility anchor.
- The Policy and Charging Resource Function (PCRF), which is responsible for Policy and Charging Control (PCC).
- The Home Subscription Server (HSS), which is a database that contains permanent user data, such as their profiles, their authentication and authorisation and their physical location.

Lastly, to conclude the network architecture description, the Services domain may include various sub-systems with several logical nodes. The Services domain includes other services not provided by the mobile network operator, such as services provided through the internet and IP Multimedia Sub-system (IMS). The IMS is defined as a part of the 3GPP standards and it is an architecture based on internet standards. The IMS can provide a common IP interface for signalling, traffic and applications. For example, the VoLTE scheme providing voice over an LTE system utilises IMS enabling.

2.1.2 Radio Interface

LTE uses two duplexing types: Frequency Division Duplex (FDD) and Time Division Duplex (TDD). According to [3GPP16a], LTE has 32 bands allocated to FDD and 15 bands to TDD. In Europe, operators have over 600 MHz of spectrum available for LTE, in the 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz FDD and TDD bands. According to [ANAC16], in Portugal, the operators can choose bands in 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz. Nonetheless, Portuguese operators have available frequencies for LTE in the bands of 800 MHz, 1800 MHz and 2600 MHz. Table 2.1 presents the frequency bands and the respective bandwidth.

Table 2.1. Frequency band used by the three operators in Portugal (based on [ANAC14]).

Operator	Frequency Band [MHz]	Bandwidth [MHz]
MEO	800	2 x 10
	1800	2 x 20
	2600	2 x 20
NOS	800	2 x 10
	1800	2 x 20
	2600	2 x 20
Vodafone	800	2 x 10
	1800	2 x 20
	2600	2 x 20

The DL multiple access is based on the Orthogonal Frequency Division Multiple Access (OFDMA), while the UL one is based on the Single Carrier Frequency Division Multiple Access (SC-FDMA), Figure 2.2.

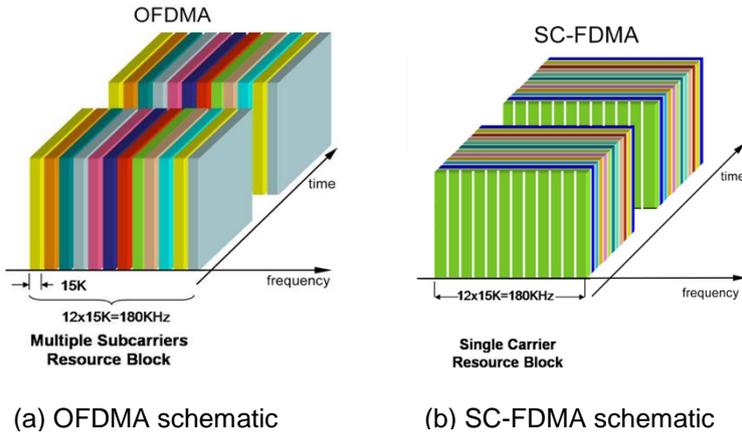


Figure 2.2. OFDMA and SC-FDMA schematics in frequency and time domain (adapted from [ExGa12]).

OFDMA is based on Orthogonal Frequency Division Multiplexing (OFDM), however in OFDM systems, only a single user can transmit on all of the subcarriers at a given time. On the other hand, the OFDMA allows multiple users to transmit simultaneously on different sub-carriers per OFDM symbol. In LTE, the

sub-carrier spacing is 15 kHz regardless of the total transmission bandwidth. Nonetheless, the allocation is not done at an individual sub-carrier basis, but on Resource Blocks (RBs) that have 12 sub-carriers, resulting in the minimum bandwidth allocation of 180 kHz.

In UL, it is not efficient to use OFDMA, because the transmitter needs to have a high Peak-to-Average Power Ratio (PAPR) and the UE does not have that capability. Therefore, the technology used in UL is the SC-FDMA due to a lower PAPR, since all sub-carriers are modulated with the same data symbol, while in OFDMA each sub-carrier is modulated by a different data symbol. Such as OFDMA, SC-FDMA has 15 kHz sub-carrier spacing, so the minimum resource allocated uses 12 sub-carriers, thus being equal to 180 kHz.

Figure 2.3 shows the structure of one radio frame, which has 10 ms, being subdivided into ten 1 ms sub-frames. Furthermore, a sub-frame is divided into two RBs, each one with a duration of 0.5 ms. Each RB is composed for seven OFDM symbols, in the case of the normal Cyclic Prefix (CP) length, or six when the extended CP length is taken. Also, it is possible to observe that each RB has 12 sub-carriers, where the sub-carrier spacing is 15 kHz, thus, resulting in a 180 kHz minimum bandwidth allocation.

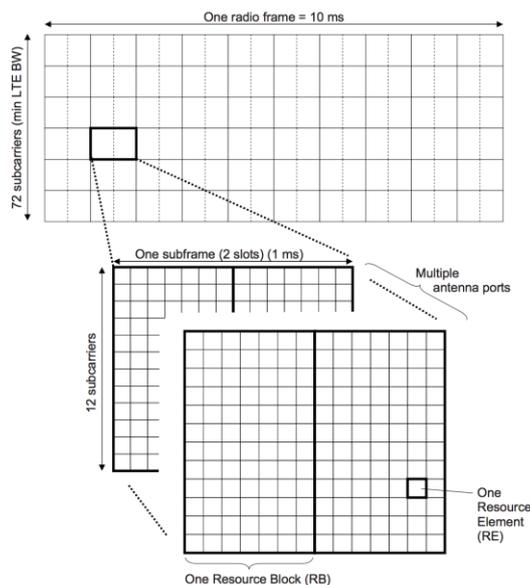


Figure 2.3. Basic time-frequency resource structure of LTE for the normal CP case (extracted from [SeTB11]).

LTE can use three types of QAM modulation schemes: Quadrature Phase Shift Keying (QPSK) and Quadrature Amplitude Modulation (QAM) in 16-QAM and 64-QAM. The QPSK modulation provides the largest coverage areas, but with the lowest capacity per bandwidth. On the other hand, 64-QAM offers more capacity but less coverage.

Multiple Input Multiple Output (MIMO) exists since the first LTE Release, allowing to increase peak data rates by a factor 2 (MIMO 2x2) or 4 (MIMO 4x4), depending on antenna configuration. MIMO uses Reference Symbols, which provide an estimate of the channel at given locations within a sub-frame.

According to [Pent15], there are three types of resource allocation in DL. Resource allocation type 0

corresponds to the allocation granularity of the Resource Block Group (RBG), a set of consecutive Physical Resource Block (PRBs), the size of which depends on transmission bandwidth. The resource allocation type 1, which enables distributed allocations, but where the minimum distance between two allocated PRBs is the RBG size. The resource allocation type 2, where the allocation simply consists of a set of consecutive Virtual Resource Block (VRB), where VRB to PRB mapping changes in a pseudo random fashion on a time slot basis.

There are three channel types: Physical Channels, Transport Channels and Logical Channels. Physical Channels are transmission channels that carry user data and control messages. They are divided into: DL Physical Channels and UL Physical Channels. DL Physical Channels are divided into:

- Physical Data Shared Channel (PDSCH), which carries downlink data;
- Physical Control Format Indicator Channel (PCFICH), which informs the UE about the format of the being signal received and indicates the number of OFDMA symbols for control information;
- Physical Downlink Control Channel (PDCCH), which carries mainly scheduling information such as: DL resource scheduling, UL power control instruction, UL resource grant and indication for paging or system information;
- Physical HARQ (Hybrid Automatic Repeat Request) Indicator Channel (PHICH), which provides uplink HARQ feedback Acknowledgement (ACK) or Negative Acknowledgement (NACK);
- Physical Broadcast Channel (PBCH), which carries part of the system information needed by UE in order to access the network;
- Synchronisation Signals, which consist of Primary Synchronisation Signal (PSS) and Secondary Synchronisation Signal (SSS), which enable cell synchronisation and identification.

UL Physical Channels are divided into:

- Physical Random Access Channel (PRACH), which is used for random access;
- Physical Uplink Shared Channel (PUSCH), which is the UL counterpart of the PDSCH;
- Physical Uplink Control Channel (PUCCH), which carries the downlink HARQ feedback (ACK/NACK), downlink Control Quality Indicator (CQI) if there is no UL data transmission or Scheduling Request Indicator (SRI);
- Uplink Reference Signals (RS), which send by the UE in order to enable demodulation (DM) of PUCCH or PUSCH and send by the UE as sounding reference signals (SRS) in order to enable channel quality estimation in the eNodeB.

2.2 Services and Applications

At the beginning of telecommunications systems, the main goals were voice communication and text messaging. With the advent of UMTS, data transfer became a reality, which allowed the introduction of new services and applications. The emergence of smartphones increased data usage at high rate. This increase was solved with the creation of LTE, which enabled the improvement of services and applications and the introduction of new ones.

Mobile data traffic is essentially consumed by smartphones, tablets and mobile PCs. One of the main causes to increase data usage is the possibility to watch videos in the devices mentioned above. According to [Eric16], video accounts for the biggest percentage of mobile traffic data, and tends to increase. As shown in Figure 2.4, mobile traffic is going to continue increasing, and in 2021 it will account for around 70% of mobile data traffic.

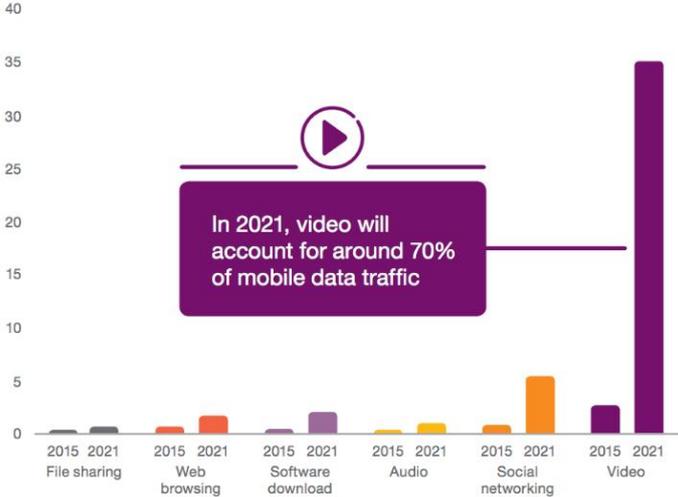


Figure 2.4. Mobile traffic by application category per month in Exabytes (extracted from [Eric16]).

UMTS characterises services into four different QoS classes: conversational, streaming, interactive and background [BaLu16]. Although these classes were established for UMTS, they offer a general view of traffic classes, which is applicable to LTE. The traffic classes are shown in Table 2.2.

Table 2.2. UMTS traffic classes (based on [BaLu16]).

Traffic class	Fundamental Characteristics	Example of the application
Conversational	Preserve time relation between information entities of the stream. Conversational pattern (stringent and low delay).	Voice over IP (VoIP)
Streaming	Preserve time relation (variation) between information entities of the stream.	Streaming Video
Interactive	Request response pattern. Preserve payload content.	Web browsing
Background	Destination is not expecting the data within a certain time. Preserve payload content.	Background non-real-time downloads

In LTE case, the lowest level for QoS control is represented by the bearer. The support of QoS requirements involves different bearers that are set up within EPS. According to [Pent15], bearers can be classified as Guaranteed Bit Rate (GBR) or Non-Guaranteed Bit Rate(Non-GBR). Each EPS bearer (GBR and non-GBR) is associated with the following bearer-level QoS parameters signalled from the Access Gateway (aGW) (where they are generated) to the eNodeB (where they are used): QoS Class Identifier (QCI) and Allocation Retention Priority (ARP).

GBR bearers require reserving transmission resources when the user is admitted by an admission

control function. Beside the parameters referenced previously, GBR bearers have more two parameters, the maximum bit rate (MBR), which defines the maximum bit rate for the bearer, and GBR, which guarantees the bit rate to the bearer. These can be used for applications such as VoIP.

Non-GBR bearers do not guarantee any particular bit rate and may experience congestion-related packet loss, which occurs in case of resource limitations. Besides QCI and ARP parameters, the non-GBR bearers use aggregated MBR (AMBR), which indicates a limit on the maximum bit rate that can be consumed by a group of non-GBR bearers belonging to the same user. These can be used for applications such as web browsing or File Transfer Protocol (FTP) transfer.

QCI is characterised by priority, delay and loss ratio. The set of standardised QCIs and their corresponding characteristics is shown in Table 2.3.

Table 2.3. Standardised QCIs for LTE (adapted from [3GPP16b]).

QCI	Resource Type	Priority Level	Packet Delay Budget	Packet Error Loss Ratio	Example services	
1	GBR	2	100 ms	10^{-2}	Conversational Voice	
2		4	150 ms	10^{-3}	Conversational Video (Live Streaming)	
3		3	50 ms		Real Time Gaming	
4		5	300 ms	10^{-6}	Non-Conversational Video (Buffered Streaming)	
65		0.7	75 ms	10^{-2}	Mission Critical user plane Push To Talk voice	
66		2	100 ms		Non-Mission Critical user plane Push To Talk voice	
75		2.5	50 ms		Vehicle-to-everything (V2X) messages	
5	Non-GBR	1	100 ms	10^{-6}	IMS Signalling	
6		6	300 ms		Video (Buffered Streaming), TCP based services	
7		7	100 ms	10^{-3}	Voice, Video (Live Streaming), TCP based services	
8		8	9	300 ms	10^{-6}	Video (Buffered Streaming), TCP based services
9						
69		0.5	60 ms	10^{-6}	Mission Critical delay sensitive signalling	
70		5.5	200 ms		Mission Critical Data	
79	6.5	50 ms	10^{-2}		V2X messages	

ARP indicates the bearer priority compared to other bearers and decides if a bearer establishment or modification request can be accepted or needs to be rejected in case of resource limitations.

Examples of services are represented in Table 2.4, as well as their classes. Also, it is possible to observe the data rate of the various services. For the QoS requirements to be fulfilled, Table 2.4 values should be taken into consideration.

Table 2.4. Services characteristics (adapted from [Sina16]).

Services		Service Class	Data Rate [kbps]			Duration [s]	Size [kB]
			Minimum	Average	Maximum		
Voice		Conversational	5.3	12.2	64	60	-
Music		Streaming	16	196	320	90	-
File Sharing		Interactive	384	1024	-	-	2042
Web Browsing		Interactive	30.5	500	-	-	2600
Social Networking		Interactive	24	384	-	-	45
Email		Background	10	100	-	-	300
M2M	Small Meters	Background	-	200	-	-	2.5
	eHealth	Interactive	-	200	-	-	5611.5
	ITS	Conversational	-	200	-	-	0.06
	Surveillance	Streaming	64	200	384	-	5.5
Video	Calling	Conversational	64	384	2048	60	-
	Streaming	Streaming	500	5120	13000	1080	-

LTE include several services, such as:

- Voice, which is converted to packet switched, i.e., VoIP. In LTE, the voice service provided by operators is called VoLTE. Voice can have two states, silence or inactive state and talking or active state.
- Video, where each frame arrives at a regular interval determined by the number of frames per second. Each video frame is decomposed into a fixed number of slices, each of them transmitted as a single packet. The size of these packets is modelled as a truncated Pareto distribution. The video encoder introduces encoding delay intervals between the packets of a frame, which are also modelled by a truncated Pareto distribution [Khan09].
- Music, a streaming service like video, transferred constantly between the sender and receiver.
- File Sharing. One example of this is FTP that is considered as the best effort traffic, where a FTP session is a sequence of file transfers separated by reading times [Khan09].
- Interactive gaming, which in UL and DL, has three parameters: initial packet arrival, packet inter-arrival and packet size. In UL, the initial packet arrival time is uniformly distributed and it is very small with a sub-frame duration of 1 ms. The packet inter-arrival time is deterministic. The packet size is assumed to follow the largest extreme value distribution, which is also known as the Fisher-Tippett distribution or the log-Weibull distribution. In DL, the initial packet arrival and packet size are the same kind of distributions as the ones used in UL. The packet inter-arrival time is modelled using the largest extreme value distribution [Khan09].
- Web browsing. One example of is Hypertext Transfer Protocol (HTTP), used in web browsing sessions, and being divided into active and inactive periods, which are a result of human interaction. When the user downloads a webpage, it is considered as an active period, whereas the intervals between webpages downloading are considered as an inactive period [Khan09].
- Social networking, which uses commonly and repeatedly instant messaging (IM). IM is a

communication method over packet data networks that offers fast delivery text messages between users and provides possibility for real-time online chat [Pent15].

- Email, which is modelled by two-state ON-OFF Markov model, with periods modelled by exponentially distributed. The packet call inter-arrival time is Pareto distributed [Corr06].
- Machine-to-Machine (M2M), which includes a broad array of services such as eHealth, Surveillance and Security, V2X, Intelligent Transport Systems (ITS), Point of Sale (PoS), among others.

2.3 Coverage and Capacity

In mobile communication systems, it is possible to classify the environment in three categories, which influences coverage: rural, suburban and urban. In addition, one should take into account several parameters, such as: terrain undulation, vegetation density, building density and height, open areas and water areas density. Depending on environment, cells are classified according to their radius, to the relative position of BS antennas (to the neighbouring buildings) and its transmitted power. There are four cell types, macro-, micro-, pico-, and femto-cells, as presented in Table 2.5.

Table 2.5. Cell Types (based on [Pent15]).

Cell Type	Radius [km]	Volume	Typical output power [dBm]
Macro	> 1	Large	>40
Micro	0.1-1	Medium	36-40
Pico	< 0.1	Small	30-36
Femto	< 0.01	Compact	<30

These four cell types correspond to a need to solve the various coverage problems. A large share of mobile traffic is originated inside buildings, leading to coverage problems; in public buildings, such as supermarkets and underground parkings, there may be a severe problem to signal penetration. Operators solve these problems by deploying repeaters, whereas in residential buildings this is not a solution.

According to [Pent15], macro-cells usually are on the top of buildings, especially in suburban and urban scenarios. As shown in Figure 2.5, that can cause reflections and diffractions in other buildings, which originate multipath problems and high link losses between the UE and BS, causing interference in nearby sites, degrading the quality of service. In indoor mobile traffic, in Ultra High Frequency (UHF), the path loss increases because walls cause an attenuation between 1 and 20 dB, according to [Corr16]. From Figure 2.5, immediately below the cell, there may be zones with bad coverage (weak zone). Therefore, there are other solutions, such as micro-cells that utilise antennas which height remains lower than the average height of the buildings in the area [Pent15].

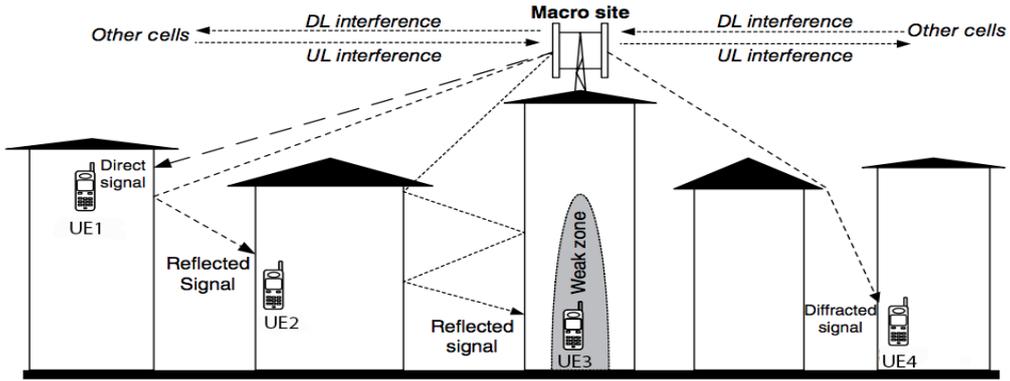


Figure 2.5. Macro-cell BS covering distinct indoor users (adapted from [Tols15]).

Figure 2.6 shows the Line-of-Sight (LoS) between UE and BS exists, improving coverage. Pico- and femto-cells are used to cover a limited area (under 100 m) with poor coverage.

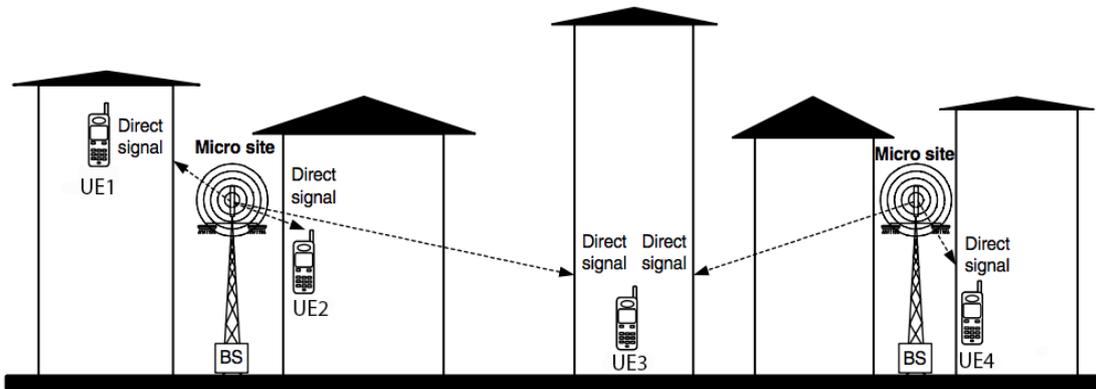


Figure 2.6. Micro cell BS covering distinct indoor users (adapted from [Tols15]).

Concerning the calculation of coverage, one can be use the link budget expression combined with an appropriate propagation model for the path loss to determine the maximum cell radius, [Corr16]:

$$R_{[\text{km}]} = 10^{\frac{P_t[\text{dBm}] + G_t[\text{dBi}] - P_{r,\text{min}}[\text{dBm}] + G_r[\text{dBi}] - L_p[\text{dB}]}{10 \alpha_{pd}}} \quad (2.1)$$

where:

- P_t : power fed to the antenna;
- G_t : gain of transmitting antenna;
- $P_{r,\text{min}}$: power sensitivity at the receiver antenna;
- G_r : gain of the receiving antenna;
- L_p : path loss;
- α_{pd} : average power decay.

Capacity is associated with channel bandwidth. A higher bandwidth provides more RBs, and more RBs maximises the number of users. The correspondence between some bandwidths and the respective number of RBs is represented in Table 2.6, which can be calculated by using, [Pire15]:

$$N_{RB} = \frac{B_{ch} [\text{kHz}]}{B_{RB} [\text{kHz}]} \cdot \frac{P_{Bch} [\%]}{100} \quad (2.2)$$

where:

- N_{RB} : number of RBs;
- B_{ch} : channel bandwidth;
- B_{RB} : bandwidth of one RB, which is 180 kHz;
- P_{Bch} : percentage of the used channel bandwidth, which is around 77% for 1.4 MHz channel; bandwidth and 90% for remaining ones.

Table 2.6. Number of RBs and sub-carriers associated with channel bandwidth (based on [Pent15]).

Channel bandwidth [MHz]	1.4	3.0	5.0	10	15	20
Number of RBs	6	15	25	50	75	100
Number of sub-carriers	72	180	300	600	900	1200

DL and UL peak data rates are influenced by several factors, such as: modulation schemes, the number of antennas used, and the number of RBs. In Layer 1, overlooking the control and reference signal overheads, the theoretical DL peak data rates and UL peak data rates can be calculated by, [Carr11]:

$$R_{b[\text{Mbps}]} = R_{codrat} N_{RB}^u N_{streams} \log_2(m) N_{subc} \frac{N_{sym}^{sf}}{10^3 \tau_{TTI[\text{ms}]}} \quad (2.3)$$

where:

- R_{codrat} : channel coding rate;
- N_{RB}^u : number of user resource blocks;
- $N_{streams}$: number of streams (e.g. 1 for single stream, 2 for 2x2 MIMO);
- m : modulation order (e.g. 4 for QPSK);
- N_{subc} : number of sub-carriers;
- N_{sym}^{sf} : number of symbols per sub-frame (14 for normal CP, 12 for extended CP);
- $\tau_{TTI[\text{ms}]}$: subframe period (1 ms).

2.4 Interference

Since the beginning of mobile communications that interference poses problems to a good QoS, so it is necessary to reduce them. Interference can be classified into two types, inter- and intra-cell interferences. Inter-cell interference happens when the UE receives signals from neighbouring cells, as seen in Figure 2.7, while intra-cell interference happens when UEs, under the coverage of the same eNodeB, interfere with each other, shown in Figure 2.8.

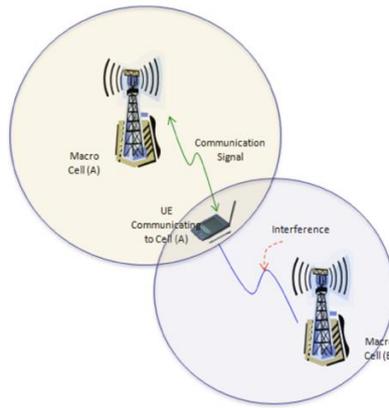


Figure 2.7. Inter-cell interference (extracted from [ShTe13]).

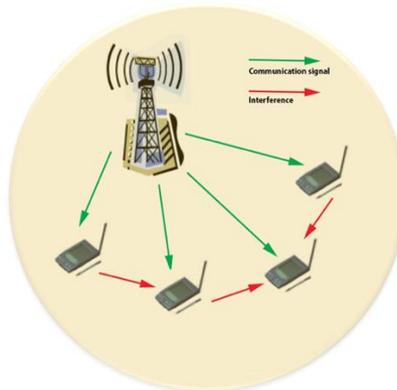


Figure 2.8. Intra-cell interference (adapted from [ShTe13]).

However, in HetNets, interference can be higher, when small cells are deployed within the coverage of a macro-cell network to improve coverage and spectrum efficiency. Small cells are installed to increase capacity and to improve coverage, but, as shown in Figure 2.9, they also degrade the SINR for users near those small cells.

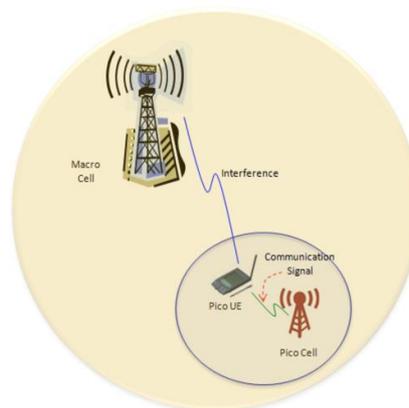


Figure 2.9. Inter-cell interference between macro-cells and small-cells (extracted from [ShTe13]).

There are mechanisms available to operators for managing and mitigating interference. According to [Paol12], operators can work with three mechanisms:

- within the E-UTRAN;

- coordinating between E-UTRAN and UE;
- within the UE.

In the first mechanism, all techniques use entirely E-UTRAN elements to manage interference. According to [HoTR16], there are some mechanisms that help to mitigate interference, such as: Inter-Cell Interference Coordination (ICIC), eICIC, CoMP and eCoMP. In addition to the techniques mentioned in [HoTR16], [Pent15] includes the adjustment of antenna tilt on base stations and [SeTB11] the fractional power control and frequency reuse.

ICIC, defined in 3GPP Release 8 [HoTR16], uses the power and frequency domains to mitigate cell-edge interference from neighbour cells. Using the X2 interface to share the information between eNodeBs, ICIC performs reutilisation of frequency from the following techniques: Hard Frequency Reuse (HFR), Fractional Frequency Reuse (FFR) and Soft Frequency Reuse (SFR) [Pent15].

eICIC was defined in 3GPP Release 10 [HoTR16] and coordinates interference in the time domain. To mitigate interference, in pico- and femto-cells, the macro-cell stops its transmission in some sub-frames, which are called Almost Blank Sub-frames (ABS). During ABS, interference is reduced and the pico- and femto-cells are able to serve UEs that are further away from them.

CoMP was completed in 3GPP Release 11 and uses multi-cell transmission and reception in order to improve radio communications. CoMP modes can be identified in Coordinated Scheduling and Beamforming (CS/CB), and Joint Processing (JP). CS/CB requires the least amount of information exchange between eNodeBs, since UEs receive a data transmission from their respective serving cell only, but adjacent cells perform coordinated scheduling and/or transmitter precoding to avoid or reduce inter-cell interference. JP CoMP aims to provide the UE data for multiple transmission points (eNodeBs) so more than just the serving cell can take part of the transmission for a UE. This requires a large bandwidth, very low latency backhaul, in practise, fibre connectivity, between eNodeBs sites. JP is divided into Dynamic Cell Selection (DCS) and Joint Transmission (JT).

In DCS, data is sent always from one eNodeB only, based on the UE feedback. In JT, multiple cells jointly and coherently transmit to one or multiple terminals on the same time and frequency resources. The most advanced version of CoMP, which uses JT and JP, requires centralised baseband solution, high data rate and low latency fibre connection between the baseband and the Radio Frequency (RF). On the other hand, a less demanding version, using DCS, can operate without centralised baseband. UL CoMP allows the reception of the transmission signal from one UE by several cells. The combination of these cells is called a CoMP set, which can be within one eNodeB or between eNodeBs, called respectively intra- and inter-cells CoMP. The benefit of UL CoMP is experienced in a macro-cellular network and in HetNet with co-channel macro- and pico-cells. CoMP gains in UL with JP are higher for cell-edge users than for cell-average ones, because the UE transmission from the cell-edge is more likely to be received by more than one cell. Cell-edge users are those that suffer most with low data rates, thus it is beneficial to get high gains at cell-edge. Cell-edge gains are, on average, two times higher than cell-average ones. In a HetNet scenario with Cell Selection (CS) and JP in UL, the results are almost the same. DL CoMP gains are expected to be lower than UL ones. UL CoMP uses multi-cell reception, which can provide clear gains, while DL CoMP gains rely on selection diversity or JT, which

also adds interference. One challenge in DL is the availability of channel estimates at the eNodeB transmitter. The UE first needs to estimate the multipath channel from all cells in a CoMP set, and then the UE can provide the Channel State Information (CSI) to the network in the UL feedback channel. The feedback adds delay and quantisation errors. DL CoMP can use JT or Dynamic Point Selection (DPS), which is also known as DCS. DPS is a simple but effective DL CoMP scheme that switches the serving transmission point to the UE based on the UE's channel estimate feedback and cell loading conditions. The switching can be done very fast even on a subframe-to-subframe basis without any handover signalling. It provides both macro diversity and fast load balancing gains: the former benefit is obtained by choosing the best serving transmission point according to the UE's current channel conditions, while the latter are realised by transmitting to the UE from the less-loaded transmission point. The UE estimates the CSI from up to three cells. A DPS solution can be implemented with reasonably low backhaul requirements [HoTR16].

eCoMP was defined in 3GPP Release 12 [HoTR16] and coordinates the multi-cell transmission between the BS instead of relying on UE feedback. The coordination can use two types of architecture. In one of them, decisions are carried by eNodeBs and the information is exchanged over X2 interface, while the other uses a new network element for centralised scheduler. Centralised element coordinates the scheduling of the individual eNodeBs from load and interference information received by eNodeBs.

The adjustment of antenna tilt is a method utilised for lowering the uncontrolled same channel interferences. The antenna tilt is defined as the angle of the main beam of the antenna below or above the horizontal (azimuth) plane. When the angle is positive is called of downtilt. Tilting can also be done in reversed way, that is, antennas are tilted to face slightly upwards. The tilts can be mechanical and electrical. The electrical tilt allows to control the tilt angle via network management system, on the other hand, the electrical tilt range is limited compared to the mechanical one. According to [Pent15], combining the negative mechanical downtilt with the electrical one leads to a "cleaner" result than in pure mechanical downtilt as in the latter case the back lobes are inclined upwards, which in turn increases interferences in the back side of the antenna.

In UL, fractional power control is used to improve throughput near the eNodeB and mitigate inter-cell interference at the cell edge. Power control can be performed jointly with frequency-domain resource allocation, whereby cell-centre UEs are allocated more RBs to enhance data rate, while cell-edge UEs are allocated fewer RBs for coverage extension. PUCCH and PUSCH are mapped onto different RBs in the frequency domain, meaning that independent interference management techniques, such as power control, can be applied for control and data channels [SeTB11].

Frequency Reuse is the process of using the same RF on BSs within a geographic area that are separated by sufficient distance to cause minimal interference with each other. LTE uses a frequency reuse of factor 1 because it maximises spectral efficiency. Frequency reuse of factor 1 provides the best service for cell-centre users, because they experience the best throughput and the higher SINR, the cell-edge users the SINR is significantly lower.

In the second mechanism, the management of interference is performed by E-UTRAN and UE. The techniques are Multi-User MIMO (MU-MIMO) and Single-User MIMO (SU-MIMO). As stated in [Paol12],

in MU-MIMO (Release 10), a cell can transmit to up to 8 UEs concurrently using the same spectrum, by directing an adaptive beam to the UE (beamforming). In SU-MIMO (Release 10), the BS concurrently transmits and receives from a single UE over up to 4 layers.

In the third mechanism, all techniques use entirely UEs to manage interference. In [Paol12], it is referred that the techniques used are: Maximal Ratio Combining (MRC), Interference Rejection Combining (IRC) and Interference Cancellation (IC). MRC improves low SINR environments and consists of a diversity combining technique, where the signal is received by two separate receivers and, after channel compensation, it is linearly re-combined in a composite signal [Paol12]. IRC is a more advanced receiver-diversity technique than MRC that incorporates the analysis of the spatial component of the received signal. It is designed to improve the SINR by computing the temporal and spatial correlation of received signals to eliminate the interfering ones [Paol12]. IC done by UE operates as an interference management tool complementary to involving E-UTRAN. IC can use beamforming techniques to direct its receiving beam towards the better signal, and ignores the other interfering signal [Paol12].

2.5 State of the art

The problems under study in this thesis are the analysis of techniques for the management of interference in LTE, and there are many studies already done that address these techniques. The main technique with relevance for this thesis is CoMP. As stated before, CoMP modes can be identified in CS/CB and Joint Processing JP.

The authors in [Mond12] studied the performance of DL CoMP in LTE under practical constraints. LTE Release 10 (also called LTE-Advanced) further improves spectral efficiency primarily by providing support for MU-MIMO transmissions. Beyond LTE Release 10 the capability to support CoMP transmissions has been prioritised by many cellular operators worldwide as a principal focus area for improving spectral efficiency with LTE Release 11. In order to study CoMP performance under realistic LTE deployment constraints, two techniques were considered, DCS and CoMP JT.

The simulation results focus on two deployment scenarios, a macro-only urban scenario with each cell transmitting 46 dBm power and a HetNet where four pico-cells transmitting at 30 dBm power each are additionally placed (randomly) within each macro-cell area. It was concluded that CoMP transmission primarily benefits cell-edge UEs and can provide a 5%-tile UE throughput gain of up to 30%.

In [XZHB15], the Inter-cell Interference is mitigated by Dynamic Point Blanking (DPB), which is a CoMP technology, allowing dynamic point muting in the time and frequency domains. The performance of SU-MIMO without CoMP is used as the baseline for comparison with CoMP DPB scheme. The evaluated CoMP DPB scheme has coordination within one macro-cell and the small cells within its geographical area. SU-MIMO is supported for UE scheduling at each coordinated cell. The maximum number of SU-MIMO data streams per UE is 2, and dynamic rank adaptation is supported.

The performance of CoMP DPB with ideal backhaul and coordination within one macro-cell and its

covered small cells can give 48% cell-edge throughput gain with the cost of 1% cell-average throughput loss compared to SU-MIMO. For macro-cell UEs, there are 1% cell-average throughput gain and 20% cell-edge throughput gain. For small-cell UEs, there is 46% cell-edge throughput gain, at the cost of 1% cell-average throughput loss. It was also done the evaluation results for inter-eNodeB CoMP, with non-ideal backhaul. The evaluated inter-eNodeB CoMP DPB is between one macro-cell and small cells within its geographical area. Each coordinated cell uses SU-MIMO for UE scheduling. The non-ideal backhaul configuration transmission delay was done for 4, 8, 12, 16, 20, 40, 60 ms of two-way backhaul delay. CoMP DPB with 4 ms two-way backhaul delay is used as the baseline for performance analysis. There is almost no performance loss with the backhaul delay from 4 ms to 16 ms and only marginal performance degradation for the backhaul delay from 20 ms to 60 ms. These gains are shown to be robust against two-way backhaul delays of up to around 16 ms.

The algorithm described in [Agra14] is applied in [HoTR16], showing the gains with DPS both in three-sector macro-cell environment and in HetNet scenario, with ideal backhaul assumed between the baseband units. A DPS solution can be implemented with reasonably low backhaul requirements. The cell-edge gain in macro-cell is 75% and in HetNet case about 50%, which illustrates the power of DPS solution. These results assume a realistic handover margin of 2 dB, and DPS is able to fully overcome the negative effects of handover margin.

In [JaWe15], the study used a Dynamic Frequency Reuse (DMFR) and CoMP technique, which are applicable to LTE heterogeneous network (macro-/femto-cells) and they are able to enhance both cell edge and adjacent sector transmission performance through adaptive spectrum allocation, interference management and CoMP techniques. DMFR allocates dynamically and reuses spectrum based on the numbers of UEs in adjacent cell sectors and cell edge, and the cell outside surplus spectrum for cell center. The study also implemented the concept of CoMP to assist data transmission for cell edge UEs. CoMP has two operating modes: JP and CS/CB, respectively.

In JP operating mode, data is transmitted from several BSs to the same UE coherently (tight synchronisation is needed) or non-coherently (gain obtained from power boost). In CS/CB operating mode, scheduling and beamforming are coordinated among cluster BSs. The simulations assumed an urban area and the UEs are randomly distributed (cell-centre, cell-outside or cell-edge). The total bandwidth was 20 MHz with each subcarrier 12 kHz. Each RB was made of 18 sub-carriers within one time slot. Each transmission time interval (TTI) consisted of two time slots and makes 1 ms. The cell layout was composed by 3-sectored hexagonal and 7-cell cluster. Femto-cells were uniformly distributed among 7-cell clusters.

For the first simulation, the cells were divided into 3 sectors (C, D and E), and it was considered that cell 1, cell 6 and cell 7 were neighbours. The cell 1 of the sector E, the cell 7 of the sector C and the cell 6 sector D became neighbours. If the number of UEs of cell 1 sector E is greater than sum of the numbers of UEs of cell 6 sector D and cell 7 sector C then cell 1 uses CoMP CS/CB method, otherwise uses CoMP JP method. This simulation compared the throughput of both DMFR and FFR, and the results shown that DMFR outperforms FFR by 33.51% in terms of throughput for 7-cell scenario and 78.12% for (1 cell/CS/CB) scenario.

In the second simulation, it was compared the 7-cell spectrum utilisation of both DMFR and FFR and the results showed that DMFR outperforms FFR by 99.87% for 7-cell scenario and 140.12% for (1 cell, CS/CB) scenario.

Chapter 3

Models and Simulator Description

This chapter provides an overview of the development and implemented model, wherein all the mathematical formulation, algorithms and implementation are detailed. At the end of the chapter, a brief assessment is done to check tha the simulator provides realistic results.

3.1 Model Overview

The model described in this section, Figure 3.1, has the objective to improve QoS and QoE in urban scenarios with CoMP. As stated in Chapter 2, interference is present in mobile communication systems, and off-centre users are the most affected because usually are covered by more than one BS. The off-centre users' throughput decreases due to this interference, and thus the centre users have usually better QoS than off-centre ones. In this model, to classify whether users are centre or off-centre, one calculates the received power. If the received power is above a threshold, the user is classified as a centre user, otherwise he/she is classified as an off-centre one. The strategy adopted to combat off-centre users' problems was to implement CoMP, more precisely the JT technique, which allows off-centre users to receive signals from different BSs simultaneously.

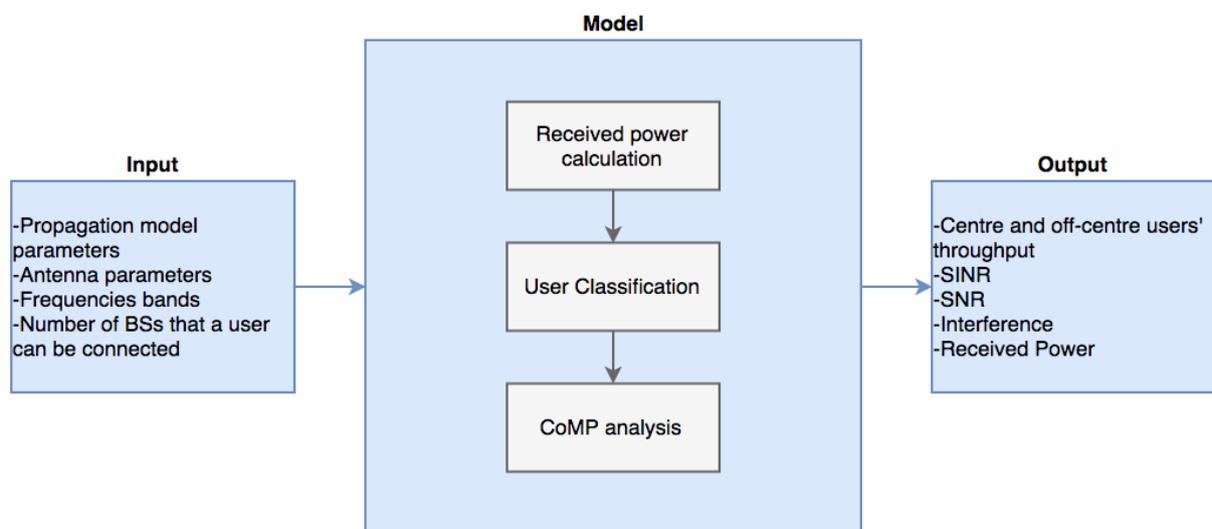


Figure 3.1. Model overview.

The model reads input parameters such as: propagation model parameters, antenna parameters, frequency bands and the number of BSs that an off-centre user can be connected simultaneously. Some of the input parameters are fixed, others being changeable. JT is an interference management technique, thus, it is expected that interference decreases and off-centre users' throughput increases.

One has developed two versions for this thesis. The first one is used to assess the performance of CoMP in a static scenario, i.e., it is taken a "snapshot" of the network to simulate the network in certain a period of time. The second version has two more features, a temporal option and the slow fading value oscillates over time making the tests more realistic and making it possible to better evaluate CoMP's behaviour.

3.2 Model

This section provides information about the important parameters and algorithms developed for the modules of the model.

3.2.1 SNR and SINR

Firstly, the calculation of SNR is done for each user, which is used to determine the radio channel conditions for a given UE. The interfering power is not considered, because there are no active communications between BSs and UEs. The SNR can be calculated by (A.7) and the power at the input of the receiver is given by (A.4), taking into account the link budget presented in Annex A and the COST 231 Walfisch-Ikegami propagation model presented in Annex B. Furthermore, the noise power is calculated using (A.8).

Since there is communication between BSs and UEs, there is information about RBs distribution. The interference power at the receiver is calculated as the sum of the received power of the signals that are supported in sub-carriers placed in the same frequency as the desired signal, according to:

$$I_{[\text{mW}]} = \sum_{n=1}^{N_I} I_{i[\text{mW}]} \quad (3.1)$$

where:

- I_i : interference power coming from transmitter i ;
- N_I : number of interfering signals reaching the receiver.

Afterwards, the SINR available at each UE's receiver is calculated in order to study the impact of interference on system performance, based on (A.9).

3.2.2 Coverage and Antennas

The maximum sector antenna's range is calculated taking the service minimum throughput into account. Therefore, a user is covered by a sector if the distance between UE and BS is below the maximum sector antenna's range. The antennas' gain affects coverage, and in the case of a gain increase, the sector's coverage increases too, which may cause interference in other sectors, causing an impact on SINR. According to [Guit16], the total gain of the antenna is obtained by, for the horizontal radiation pattern,

$$G_{H[\text{dB}]}(\varphi) = -\min \left[12 \left(\frac{\varphi_{[\text{°}]}}{\varphi_{3\text{dB}[\text{°}]}} \right), A_{m[\text{dB}]} \right] \quad (3.2)$$

where:

- φ : angle between the pointing direction of the antenna in the horizontal plane;

- φ_{3dB} : horizontal half-power beamwidth;
- A_m : front-to-back attenuation.

and for the vertical radiation pattern,

$$G_{V[dB]}(\theta) = -\min \left[12 \left(\frac{\theta_{[^\circ]} - \theta_{etilt}}{\theta_{3dB[^\circ]}} \right)^2, A_{SL[dB]} \right] \quad (3.3)$$

where:

- θ : angle between the pointing direction of the antenna in the vertical plane;
- θ_{etilt} : electrical antenna downtilt;
- θ_{3dB} : vertical half-power beamwidth;
- $A_{SL[dB]}$: sidelobe attenuation.

The θ angle can be calculated for an UE that is either in LoS or in Non-LoS (NLoS) with the BS, in the latter case assuming that the UE is at the centre of the street. In LoS, the θ_1 angle is obtained by:

$$\theta_{1[rad]} = \arctan \left(\frac{h_{b[m]} - h_{m[m]}}{d_{[m]}} \right) \quad (3.4)$$

where:

- h_b : height of the BS antenna;
- h_m : height of the UE;
- d : distance between the BS and the UE.

while in NLoS, the θ_2 angle is obtained by:

$$\theta_{2[rad]} = \arctan \left(\frac{h_{b[m]} - H_B[m]}{d_{[m]} - \frac{w_s[m]}{2}} \right) \quad (3.5)$$

where:

- H_B : height of the buildings;
- w_s : width of the streets.

leading to:

$$\theta_{[rad]} = \frac{\theta_{1[rad]} + \theta_{2[rad]}}{2} \quad (3.6)$$

The total contribution of the two radiation patterns, hence, the total gain of the antenna is given by:

$$G_{[dB]}(\varphi, \theta) = G_{\max[dBi]} - \min \{ -[G_{H[dB]}(\varphi) + G_{V[dB]}(\theta)], A_{m[dB]} \} \quad (3.7)$$

where:

- G_{\max} : maximum gain of the antenna.

3.2.3 Throughput and Capacity

The equations presented in Annex C are a good approximation to calculate the throughput of an RB, giving the throughput of one RB as a function of its SNR or SINR. The user throughput is given by (3.8), being the sum of the throughputs from all RBs allocated to the UE [Guit16]. The modulation chosen is the one that enables to achieve the best throughput for one RB.

$$R_{b,user}[\text{Mbps}] = \sum_{i=1}^{N_{RB,user}} R_{b,RB\ i}[\text{Mbps}] \quad (3.8)$$

where:

- $N_{RB,user}$: number of RBs allocated to UE;
- $R_{b,RB\ i}$: RB i throughput.

The total throughput of a given sector can be obtained from [Guit16]:

$$R_{b,sector}[\text{Mbps}] = \sum_{i=1}^{N_{u,sec}} R_{b,user\ i}[\text{Mbps}] \quad (3.9)$$

where:

- $N_{u,sec}$: number of users served by the sector.

A user is allocated when the RBs reserved to the UE guarantees the service minimum throughput. If there are more RBs free, the throughput will be increased up to a predefined maximum.

To observe the impact of CoMP, some assumptions were made. The best throughput among the two or three connections available is given by:

$$R_{b,best}[\text{Mbps}] = \begin{cases} R_{b,1}[\text{Mbps}], & R_{b,1} \geq R_{b,2} \wedge R_{b,1} \geq R_{b,3} \\ R_{b,2}[\text{Mbps}], & R_{b,2} > R_{b,1} \wedge R_{b,2} \geq R_{b,3} \\ R_{b,3}[\text{Mbps}], & R_{b,3} > R_{b,1} \wedge R_{b,3} > R_{b,2} \end{cases} \quad (3.10)$$

where:

- $R_{b,n}$: the served throughput by BS n .

In order to calculate CoMP's throughput, there was the need to assume the scenario as ideal, summing all of throughputs in all available connections, whereas losses may exist in a real scenario.

$$R_{b,CoMP}[\text{Mbps}] = \sum_{n=1}^3 R_{b,n}[\text{Mbps}] \quad (3.11)$$

To calculate the throughput's gain between a system with CoMP and a system without CoMP is used equation (3.13).

$$G_{CoMP} = \frac{R_{b,CoMP}[\text{Mbps}] - R_{b,best}[\text{Mbps}]}{R_{b,best}[\text{Mbps}]} \quad (3.12)$$

3.2.4 Time and Fading

The received power changes over time due to fading, which can be of two kinds: fast and slow. In the former, the channel impulse response changes rapidly within a symbol duration, whereas for the latter, the impulse response changes much slower than the transmitted signal, thus one only takes slow fading, which is described by the Log-normal distribution.

The fading margin can be calculated by [Corr16]:

$$M_{F[\text{dB}]}^{p\%} = u(p\%)\sigma_{e[\text{dB}]} \quad (3.13)$$

where:

- $u(p\%)$: value obtained from the respective percentage value for the normal distribution;
- σ_e : standard deviation of propagation model chosen.

The total path loss is calculated by (A.6), and the slow fading margin by (3.13). To calculate $u(p\%)$ the inverse of the Normal Distribution is used. The third module of the model has a function that generates a probability between the values predefined and another that receives this probability value, and uses the inverse of the Normal Distribution to return the respective $u(p\%)$. The chosen propagation model was the COST 231 Walfisch-Ikegami, with the standard deviation in [4, 7] dB.

3.2.5 User Allocation and CoMP DL

It is important to divide the cell in several regions. As it can be seen in Figure 3.2, the cell is divided into cell-centre and off-centre regions. Normally, cell-centre users have a good QoS and, for that reason, for this thesis only cell off-centre users need to be concerned, with particular attention to cell-edge ones. Off-centre users are the most affected by interference, thus CoMP is used for these users, allowing users to be connected to more than one BS. In a theoretical scenario, one user can be covered by three sectors (middle of three sectors), thus a maximum of three connections was defined.

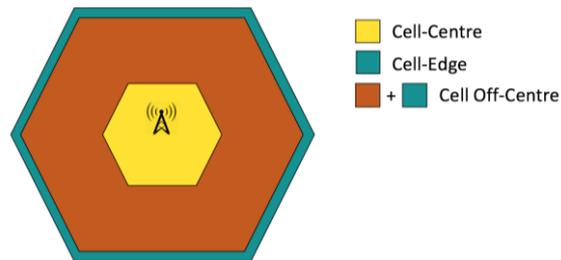


Figure 3.2. Cell regions.

The algorithms to allocate users are presented in Figure 3.3 and Figure 3.4. The algorithm starts searching for users in each sector, after which calculates the received power for each user, and then it starts to search for users in other BSs. This analysis stops when all BSs have been analysed. If the received power for a user is equal or higher than the threshold, this user is considered as a cell-centre one and it is served uniquely by one BS, otherwise the user is considered as an off-centre one, being served by either one, two or three BSs.

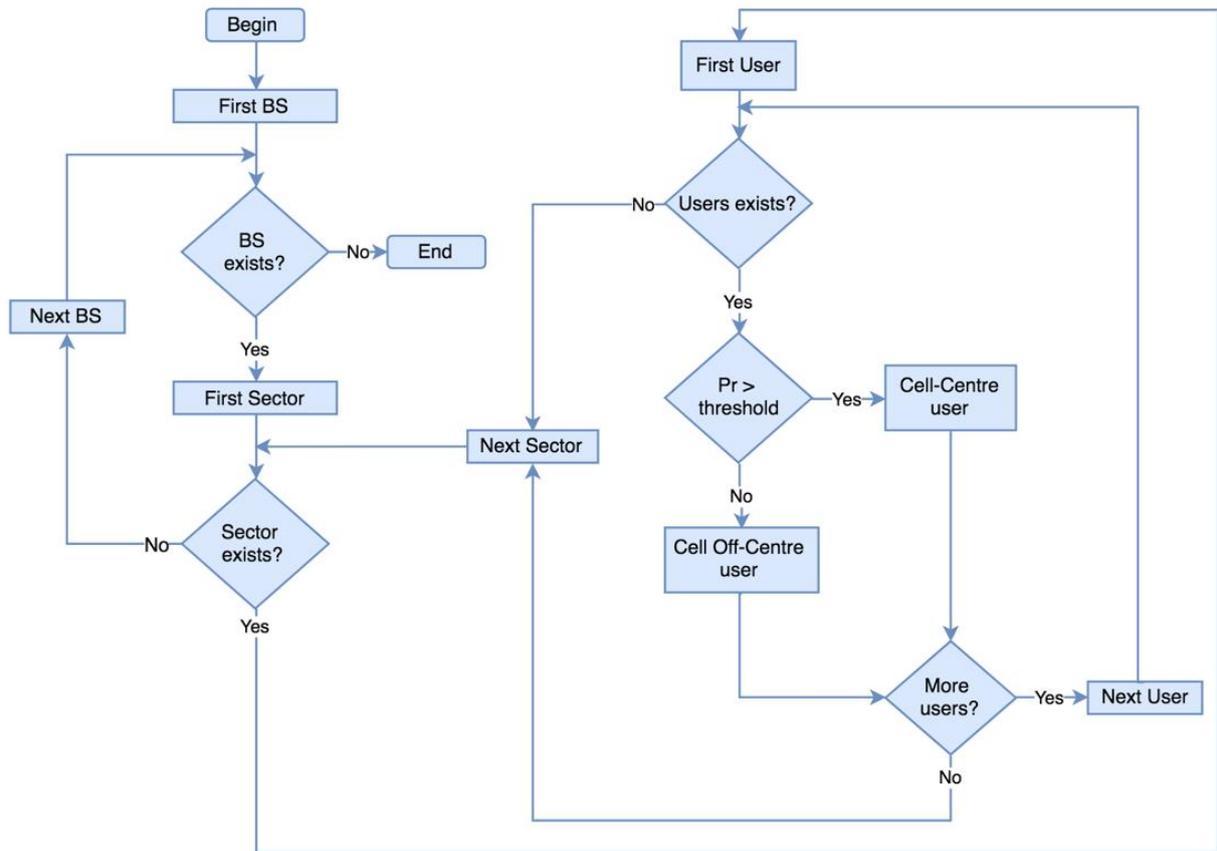


Figure 3.3. Algorithm to classify users.

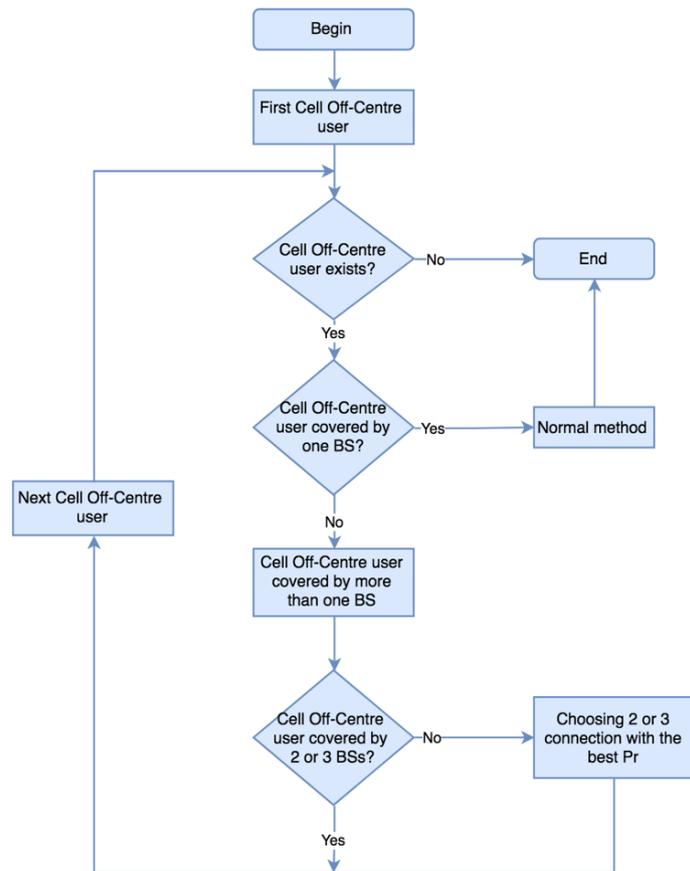


Figure 3.4. Algorithm to allocate the users.

In this thesis, one only considers DL communication. As mentioned above, the concern is the cell off-centre users, thus only these users use CoMP for the management of interference, more precisely the JT technique.

3.2.6 Time Algorithm

The first module, described in Section 3.3, generates a file with users, which have different geographic coordinates, performing different services. This module is based on modules built in previous theses, for cases where there is no temporal domain, the approach being to use this module to generate geographic coordinates, which perform different services. The file generated in the first module is read by the second module, and thereafter it is done a verification whether it is a service with a duration (video calling, video streaming and music) or a service with a size (e-mail, web browsing and file sharing). The duration of services and pauses is generated with the Exponential Distribution and the size of the services is generated with the Log-normal Distribution [Serr12]. Hence, the total number of users is no longer the number of geographic positions, but the number of users that start a service, i.e., the sum of all started services is the total number of users. When the service is terminated, the user is considered as a served user.

In Figure 3.5, one represents the algorithm for temporal simulation. Before starting the simulation, the duration is chosen. Afterwards, all geographic coordinates are analysed, and if there is an active user in this coordinate, his/her throughput is calculated for each millisecond. When the user finishes the service, that geographic coordinated is paused during a random generated interval. As soon as the pause has finished, it generates a new user in that geographic position. This process is repeated until the end of the simulation.

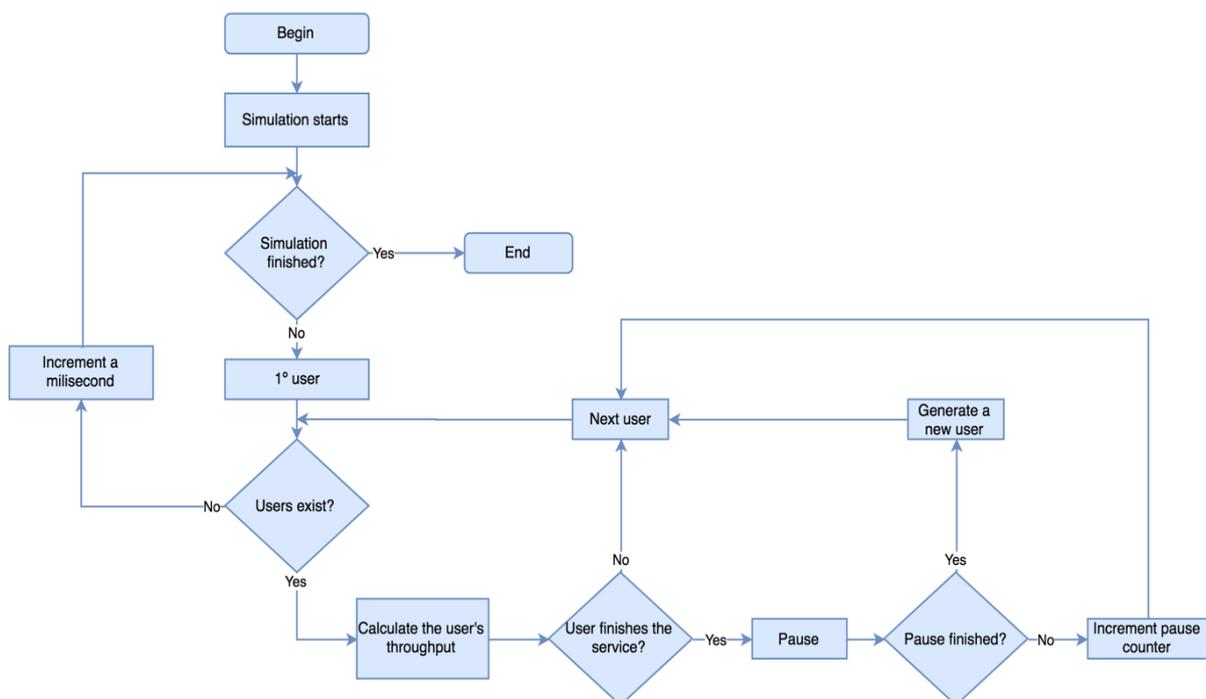


Figure 3.5. Algorithm for time simulation.

3.3 Model Implementation

The simulator was developed to implement the models described in preceding sections, based on previous work, [Alme13] e [Guit16]. This simulator was implemented using four different programs: C++ Builder, C++ Builder XE, Python 3+ and MapBasic. As stated before, two versions of the model were developed, with some differences between them. The first version analyses network performance at a given time instant, taking a “snapshot” of traffic, with the objective to assess the correct functioning of CoMP. The second version has the capability to do a temporal analysis, with a variation of the received power over time, allowing to understand how CoMP affects the network.

In Figure 3.6 and Figure 3.7, one presents the simulator workflows of the two versions. The simulator workflows are represented by three modules: Users, UMTS_Simul and ACMIL_Stats. The workflows have four main colours: blue, red, green and grey. The blue blocks are code portions that were not modified, being based on previous theses. The red blocks are portions modified with changed parameters or additional ones. The green blocks are new portions completely developed for this thesis; however, in ACMIL_Stats, all blocks were rewritten for Python, whether the other simulators used C++. Finally, the grey blocks are input files containing information about the city (Lisbon) and BSs location:

- *DADOS_Lisboa.tab* contains information about each district of the city (Lisbon);
- *ZONAS_Lisboa.tab* holds information about the area characterisation (e.g., habitational dense, green zones, etc.);
- *BSs Location (BS.tab)* has information on BSs' location.

There are intermediate outputs that serve as inputs for other modules:

- *Users.txt* provides information about users' location and respective type of service;
- *Data.dat* provides information about BSs' location, the sectors each one of them has, and also information about users who are potentially covered by them, including their location, requested service and distance to the BS;
- *Definitions.dat* contains information about propagation model parameters, frequency band, bandwidth, antennas' parameters, services' minimum and maximum throughputs, duration of the simulation and the maximum number of BSs that users can be connected.

The main differences between the simulator workflows are in the first and third modules. In the first, the first version uses a program developed in other theses; this program generates users taking the real population density in the city of Lisbon into account. Since the third module was rewritten to Python, the first version of the simulator seizes some output files used in [Alme13]. Afterwards, in the second version these output files are changed, because it was more helpful to organise the output.

The third module of the first version returns the following output files:

- *active_bss_file.csv* contains information about active BSs, such as served throughput, number of served users, number of served RBs and the distance of the farthest user being served;
- *active_ss_file.csv* provides the same information as *active_bss_file.csv*, but this information is detailed for each sector;

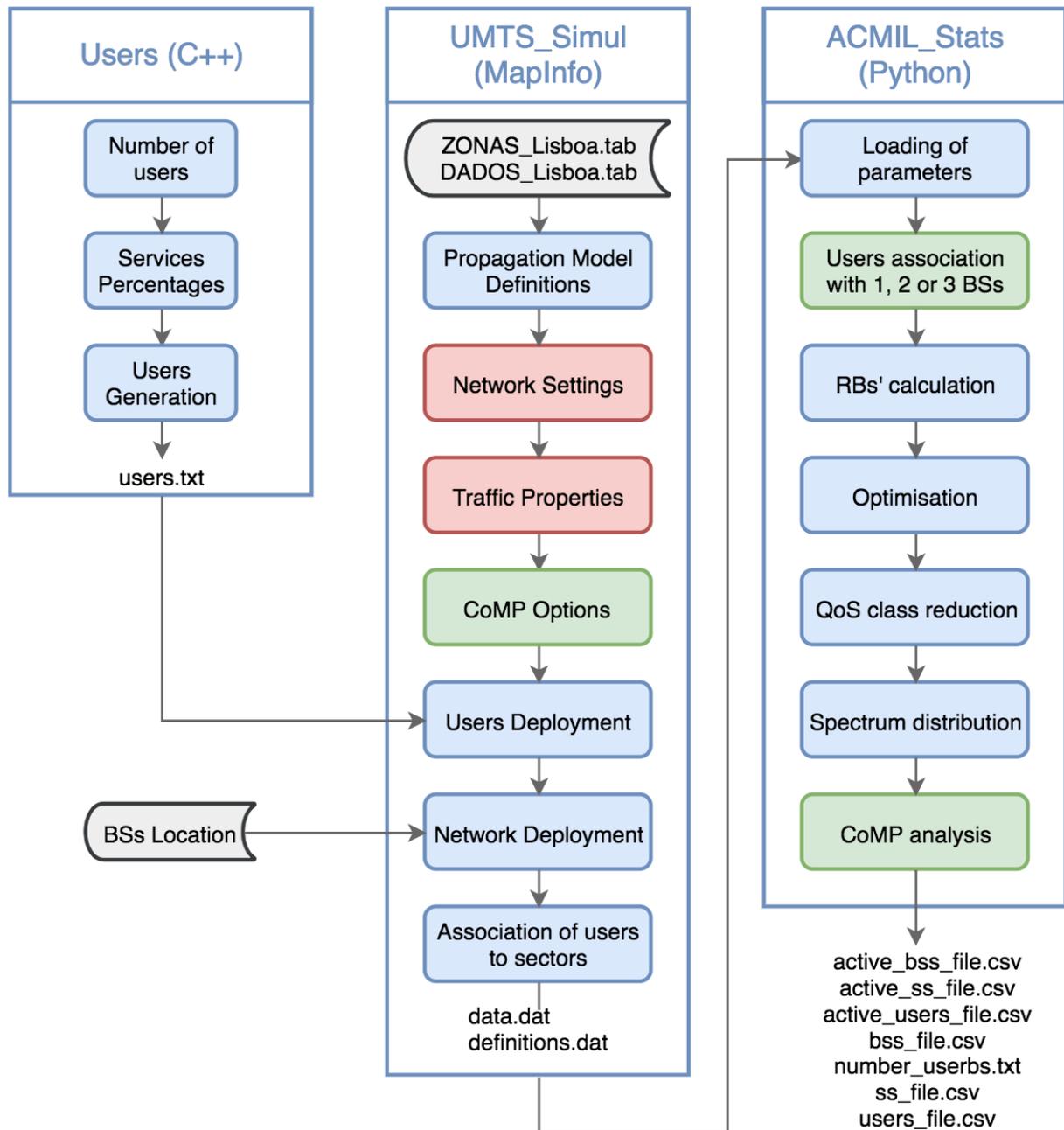


Figure 3.6. Simulator Workflow (version 1).

- *active_users_file.csv* contains information about a served UE's throughput, number of RBs, distance from the serving BS, average SNR, average SINR, average received power and average interfering power;
- *bss_file.csv* provides the same information as *active_bss_file.csv*, except that it extends data collection to BSs that became non-active after the algorithm took place;
- *number_userbs.txt* contains the number of users that are connected to one, two or three BSs;
- *ss_file.csv* provides the same information as *active_ss_file.csv*, except that it extends data collection to sectors that became non-active after that the algorithm took place;
- *user_file.csv* contains the same information as *active_users_file.csv*, except that it extends data collection to non-served UEs.

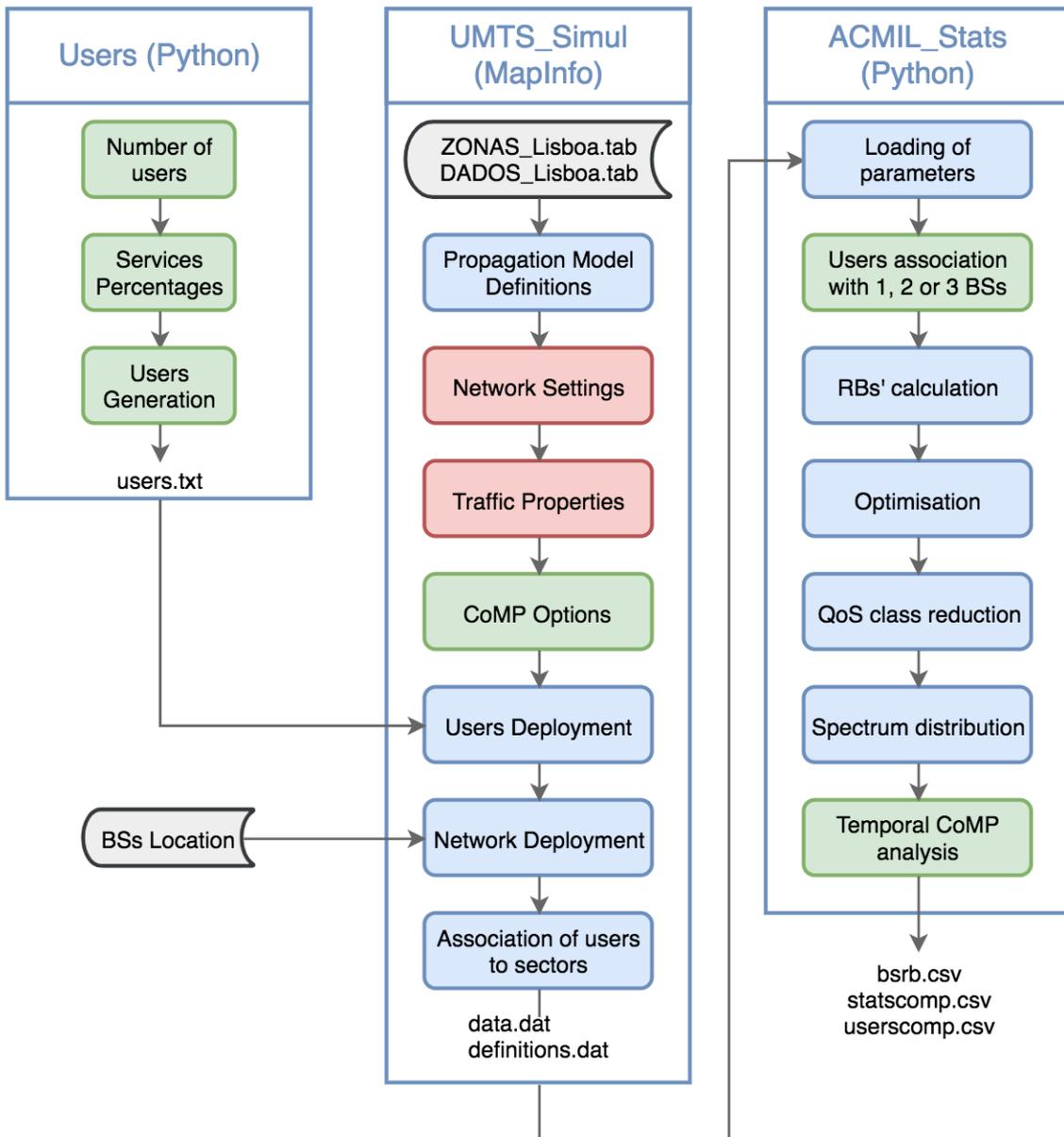


Figure 3.7. Simulator Workflow (version 2).

The third module of the second version returns the following output files:

- *bsrb.csv* provides information about the number of RBs used for each BS;
- *userscomp.csv* contains information about the number of users connected to one, two or three BSs;
- *statscomp.csv* provides information about the system, such as centre users' and off-centre users' throughput with CoMP and without CoMP, received power, SNR, interference and SNR.

In the next paragraphs, one explains each module, and only when necessary, the distinction between versions one and two is done.

In version one, the first module creates a .txt file with users' positioning along the entire city, which also contains information about the users' service request, according to the percentage introduced as input. It takes the real population density in the city into account. On the other hand, in version two, the first

module of the simulator was completely built for this thesis and it deals with user generation, creating a .txt file that includes the users' ID, their position (latitude and longitude), as well as information about the service that each one is requesting. This module has the capability to generate users in the entire city of Lisbon, but was especially developed to generate users in Parque das Nações, which is the area that was analysed during simulations. The simulator generates users in a square or rectangular area, and since maps have irregular areas some users are generated outside the boundaries of the city, and consequently they are not covered.

After that, one should have all input files needed in order to execute the UMTS_Simul.mbx in the second module, which is the same for both versions. This program has the UMTS word in its name because it is based on previous works that dealt with 3G systems. The user's manual with the procedures for the execution of this module is presented in Annex D. After the introduction of parameters detailed in Annex D, a preliminary coverage study is done. SNR is calculated using the expression of QPSK given in Annex C, because it is the most reliable modulation scheme for low SNR conditions. The calculated SNR is used to calculate the minimum received power, considering the COST 231 Walfisch-Ikegami model presented in Annex B, and calculating the maximum distance between a BS and a UE. With both the BSs' coverage and the users generated in the first module, a network is created, where users are associated with all the sectors that cover them. Lastly, the *data.dat* and *definitions.dat* files are created.

As stated earlier, the third module of the first version has differences in relation with the second one, which are presented in the second and seventh blocks in Figure 3.6 and Figure 3.7. In version two, the second block has a slow fading value oscillating over time, in contrast to the first version that has a fixed one. The second version also has differences in the seventh block, since it has the capability to perform temporal simulation. The block does the management of the users that can be activated or paused. Consequently, the seventh block of the second version returns different outputs, as seen above. The following paragraphs provide a detailed explanation about all blocks of the third module.

The first block of the third module is to load the files created in the second module (*data.dat* and *definitions.dat*). The second block of this module reads the information expressed in that files and associates users with BSs. This block is crucial for CoMP, because it associates users with one, two or three BSs. At first, it reads how many BSs one user can be connected to (this information is expressed in *definitions.dat*); if the value is one, CoMP cannot be applied, because the user cannot be connected to more than one BS, and even though the module works with only one BS, the effect of CoMP in the system will not be observed; if the value is higher than one, the first step of the algorithm is to classify users as cell-centre or cell off-centre ones, and if the received power is above of the predefined threshold, the user is considered at cell-centre, and this type of users are connected to only one BS, since these users usually have a good QoS, thus being unnecessary to overload other BSs. CoMP is used in the cell off-centre, because users in this region are the most affected by interference and their throughputs suffer a negative impact. After that, off-centre users are analysed and the best two or three connections is chosen (depending on the value detailed in *definitions.dat*), i.e., connections with higher received power. As for an off-centre user covered by one BS, CoMP is not used.

After all users are associated with one, two or three BSs, it is time to calculate how many RBs are

needed. The next four blocks are based on [Alme13], which were programmed in C++ and rewritten in Python. Each sector has a number of RBs dictated by the bandwidth being considered, according to Table 2.6. At this step, network capacity is not taken into account, hence, all RBs being given to users so that each service is performed with the maximum throughput. Subsequently, it is checked if all allocations are coherent with network capacity; if not, a reduction has to occur, so that users are not requesting more resources than the ones the network is able to provide them. If users are requesting more resources than the network can provide, their requested throughput is decreased until the minimum throughput is reached or network capacity becomes coherent. Users' services are classified with different QoS priorities, as defined in Table 4.4, therefore, services with the highest priority are the last ones to have their resources reduced, while the services with the lowest priority are the first ones to do so. However, the reduction is proportional and fair: lowest priority service users are assigned a half of the RBs they previously had, and so on and so forth, until network capacity is not exceeded. From the second round of reductions onwards, if the minimum throughput is not guaranteed, users' services are delayed. If there is the need to perform reductions, before all reductions take place, optimisation is performed. When the number of RBs used by UEs is congruent with network capacity, all RBs are assigned a position on the available spectrum, and this allocation is done according Resource Allocation Type 2, described in Chapter 2.

Finally, the last block is responsible for all data analysed in Chapter 4. This block creates files with information about CoMP effects in throughput, SNR, interference, SINR and capacity of BSs.

During the temporal simulation, the last five blocks are repeated for each millisecond, thus, for example, in a simulation with thirty minutes (1.8 millions of milliseconds) the process is repeated 1.8 million times.

3.4 Model Assessment

In order to validate model implementation, a set of empirical tests was applied to the simulator to ensure the correct behaviour of the program. Basically, this assessment was a set of tests in which the outcome of the simulator must generate an equivalent output compared with the theoretical viewpoint.

The structural tests that were applied to the program are described in Table 3.1 and Table 3.2. The results of the simulation were saved in Microsoft Excel files, which enabled a more efficient validation of some tests. These tests ensure that the data being read by the simulator are treated properly.

The tests applied to the first version ("snapshot" version) are described in Table 3.1. This first version was used to prove the good results of CoMP and it was also used as a pre-test for the second version. As the first version is based on previous theses, which is programmed in C++, the first tests were compared the C++ results with Python results.

Being included two more features (mentioned during this Chapter) in the second version of the simulator, it was necessary to test these features. The tests applied to this version are described in Table 3.2.

Table 3.1. Validation of the simulator (version 1).

Test	Description
1	Check if the C++ results are equal with the Python results.
2	Check if an error message is shown after an input parameter is inserted beyond the confidence interval.
3	Verify if the radius of each sector in the three frequencies band varies according to different input parameters.
4	Check if all input files are inserted and read correctly.
5	Check if all the output files exist and are located in the output directory.
6	Verify if the users are connected to the best BSs (the best received power).
7	Verify if the users are connected to two or three BSs in maximum.
8	Check if the CoMP improves the total throughput of users in the Active_Users file.

Table 3.2. Validation of the simulator (version 2).

Test	Description
1	Check if the services duration (time and size), pauses duration and slow fading value are generated correctly.
2	Check if the users are active during the time previously simulated.
3	Verify if the users enter in pause.
4	Check if the users paused are not occupy resources in system.
5	Check if all the output files exist and are located in the output directory.
6	Check if the CoMP improves the off-centre users' throughput

First of all, when one simulates 60 minutes of the network behaviour, that time is not the real simulation duration. The real time that one simulation takes, depends on several factors. With the increase of load, simulations take more time to execute. Another factor that influences is the time chosen to study the network behaviour. If the user wants to study the network for 40 minutes, the algorithm takes more time to execute the outcome than for 10 minutes of study. For example, in a low load scenario a simulation with 10 minutes takes two days for systems with CoMP with three BSs and in mid load scenario takes five days. Thus, the times described in Figure 3.8 and Figure 3.9, are the duration of a study and not the real-time duration.

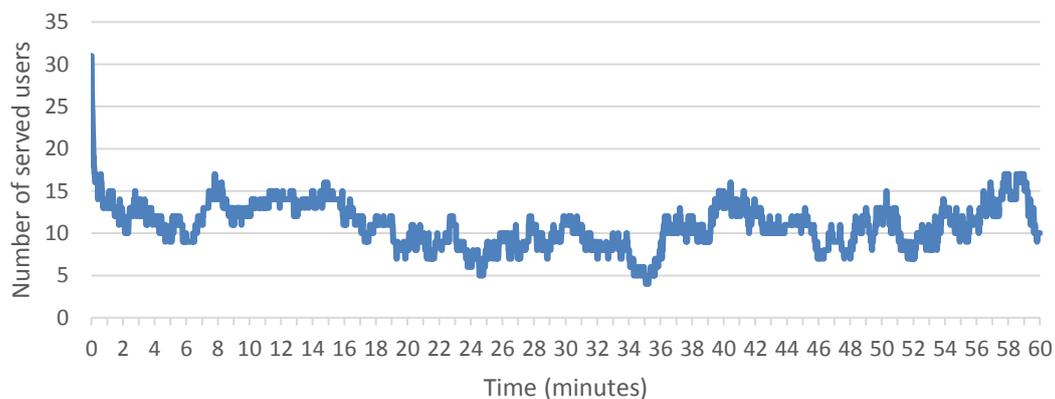


Figure 3.8. Number of served users in each minute.

Also, in order to ensure how much time the system needs to stabilise, some tests were performed. As reference, was chosen the 2600 MHz frequency band with a bandwidth of 20 MHz and the users can be connected simultaneously with three BSs. According to Figure 3.8, the system takes approximately one minute to stabilise, therefore for statistical reasons the first minute is ignored.

For each analysis, in order to ensure statistical relevance of results, the total average is calculated, together with standard deviation and convergence, using (3.14), (3.15) and (3.16), respectively.

$$\mu = \frac{1}{N} \sum_{n=1}^{N_s} \mu_n \quad (3.14)$$

where:

- N_s : number of simulations;
- μ_n : average obtained in simulation n .

$$\sigma = \sqrt{\frac{1}{N} \sum_{n=1}^N \sigma_n^2} \quad (3.15)$$

where:

- σ_n : standard deviation obtained in simulation n .

$$\Delta[\%] = \frac{|f_n - f_f|}{f_f} 100 \quad (3.16)$$

where:

- f_n : the partial output parameter cumulative mean at interval;
- f_f : the total output parameter cumulative mean.

The simulation presented in Figure 3.9, serves to demonstrate that the throughput value is analogous during 10 minutes of simulation and during 60 minutes of simulation.

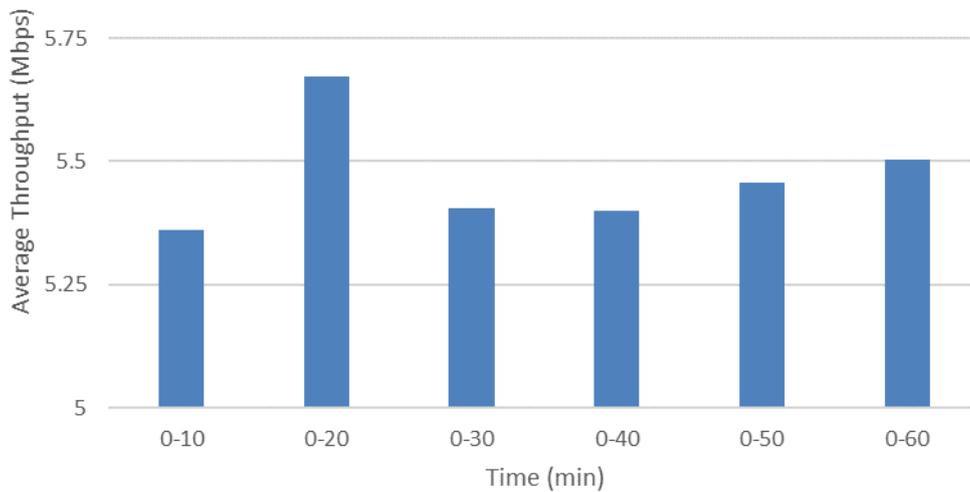


Figure 3.9. System average throughput in different time intervals.

It is not necessary to do simulations with a long duration, since the results obtained for 10 minutes are similar to those obtained for 20, 30, 40, 50 and 60 minutes of simulation. To enhance this conclusion, Figure 3.10 shows that using the first interval with 10 minutes, the convergence is below of 3% in relation with the interval with 60 minutes.

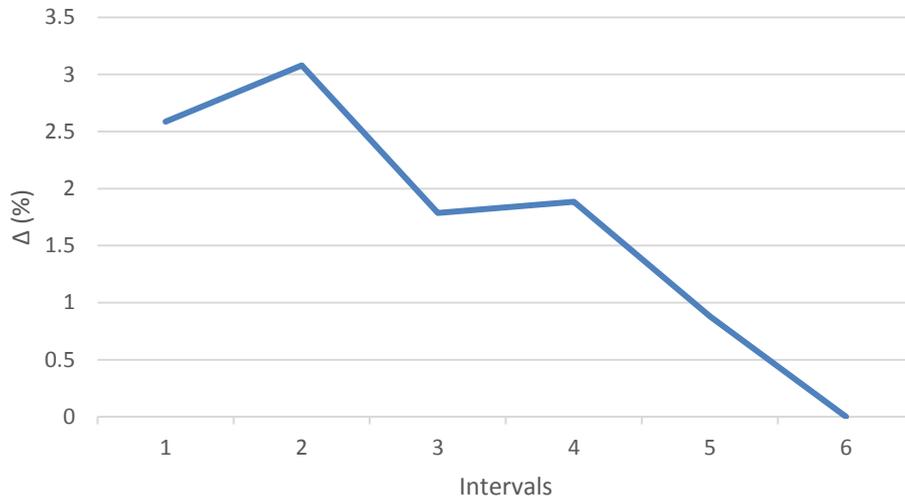


Figure 3.10. Convergence of average throughput.

In Chapter 4, with objective to reduce the real simulation time, simulations have 11 minutes in duration, since the system needs one minute to stabilise, as shown in Figure 3.8.

In Figure 3.11, it is possible to examine the ratio of the standard deviation over the average value for each one of the analysed parameters. With the used number of simulations, it is already possible to notice that the standard deviation over average of UE's throughput tends to a constant value. The tests were repeated for scenarios without and with CoMP where a user can be connected simultaneously to two BSs with similar conclusions.

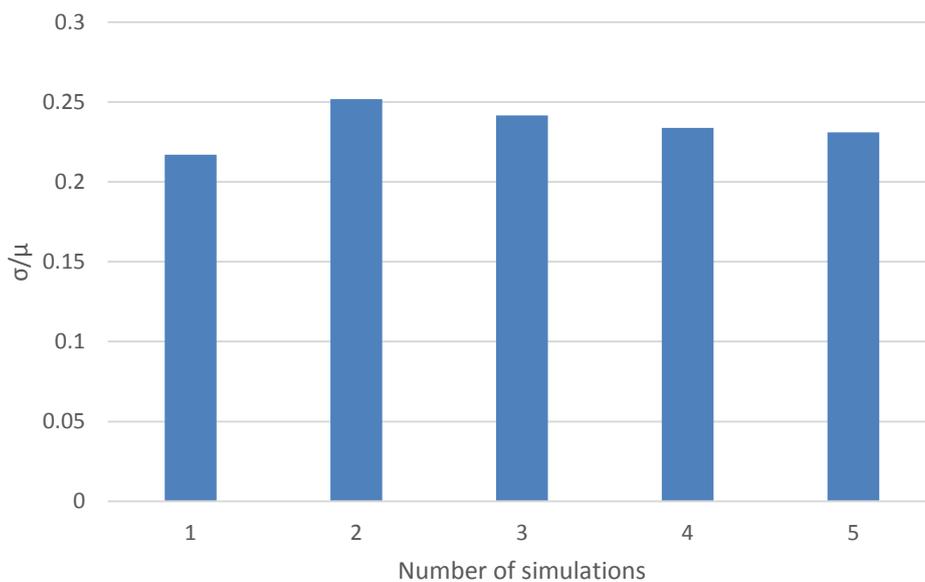


Figure 3.11. Standard deviation over average of UE's throughput along the number of simulations.

Chapter 4

Results Analysis

This chapter presents the reference scenario along with the associated results and their analysis.

4.1 Scenarios Description

The geographical scenario studied for this thesis is different for the two versions of the simulator. In the first version, all tests are executed in city of Lisbon, while the second version considers Parque das Nações (marked with a red rectangle), which is an urban environment in the city of Lisbon. Figure 4.1 represents the studied areas.



Figure 4.1. City of Lisbon.

Path loss is calculated using the COST-231 Walfisch-Ikegami propagation model provided in Annex B and the parameters are shown in Table 4.1.

Table 4.1. Parameters for COST-231 Walfisch-Ikegami model (based on [Guit16]).

Parameter Description	Value
Height of the BS antennas (h_b) [m]	25.0
Height of the buildings (H_B) [m]	21.0
Street width (w_s) [m]	30.0
Distance between buildings' centre (w_B) [m]	50.0
Incidence angle (ϕ) [°]	90.0
UE height (h_m) [m]	1.2

Three different frequency bands associated with their maximum available bandwidths are considered:

- 800 MHz band (with an associated bandwidth of 10 MHz), which provides high coverage,

however it may suffer more inter-cell interference;

- 1800 MHz band and 2600 MHz (with an associated bandwidth of 20 MHz), designed to offer better capacity.

The study of each frequency band is done separately, therefore, each sector during a simulation has the bandwidth and the frequency band previously selected.

The antenna parameters chosen for each frequency band are different, Table 4.2.

Table 4.2. Antenna parameters (adapted from [Guit16]).

Parameter Description	Value		
	800	1800	2600
Frequency band [MHz]	800	1800	2600
Maximum bandwidth [MHz]	10.0	20.0	20.0
DL transmission power [dBm]	43.0	42.0	43.0
BS maximum antenna gain [dBi]	16.4	17.8	17.5
Vertical half-power beamwidth [°]	7.4	5.5	4.2
Horizontal half-power beamwidth [°]	65.0	62.0	63.0
Electrical downtilt [°]	12.0	8.0	6.0
Sidlobe attenuation (vertical) [dB]	20.0		
Front-to-back attenuation (horizontal) [dB]	50.0		

The reference scenario parameters can be seen in Table 4.3. The slow fading value is only considered in the first version of the simulator, whereas the second version uses a randomly generated value mentioned in Chapter 3.

Table 4.3. Parameters for the reference scenario (adapted from [Guit16]).

Parameter Description	Value
UE antenna gain [dB]	1.0
UE losses for data [dB]	1.5
Cable losses [dB]	2.0
Noise Figure [dB]	7.0
MIMO order	2.0
Slow fading margin [dB]	8.8*

*only used in first version of the simulator

Simulations were performed regarding six types of the services: video calling, video streaming, music, web browsing, file sharing and e-mail. The voice service was excluded for several reasons: for the chosen services, each BS sends packets each millisecond, but for VoLTE, packets are sent every 20 ms; voice users do not benefit from CoMP; the simulator is based on previous theses and VoLTE is not presented there. In future, it can be interesting to include voice to observe the network behaviour.

In Table 4.4, each service has a QoS priority, minimum and maximum throughputs in each BS, a duration or size, and a percentage of service mix. QoS priorities are used to choose which service receives resources first, in other words, services with lower indexes are served first than those with higher indexes (e.g., video calling is the highest priority service). The service mix is the number of users,

in percentage, that are using each different service.

Table 4.4. Services characteristics (based on [Sina16], [Guit16], [Eric16] and [HTTP17]).

Service	QoS Priority	Minimum throughput [Mbit/s]	Maximum throughput [Mbit/s]	Duration [s]	Size [MB]	Service Mix [%]
Video Calling	1	0.064	2.000	60	-	8
Video Streaming	2	0.500	13.000	300	-	30
Music	3	0.016	0.320	180	-	20
Web Browsing	4	0.400	6.000	-	2.600	20
File Sharing	5	0.400	6.000	-	2.042	12
E-Mail	6	0.400	1.000	-	0.300	10

The number of BSs used in each version was different. The first version of the simulator used 270 BSs distributed in Lisbon, Figure 4.2.

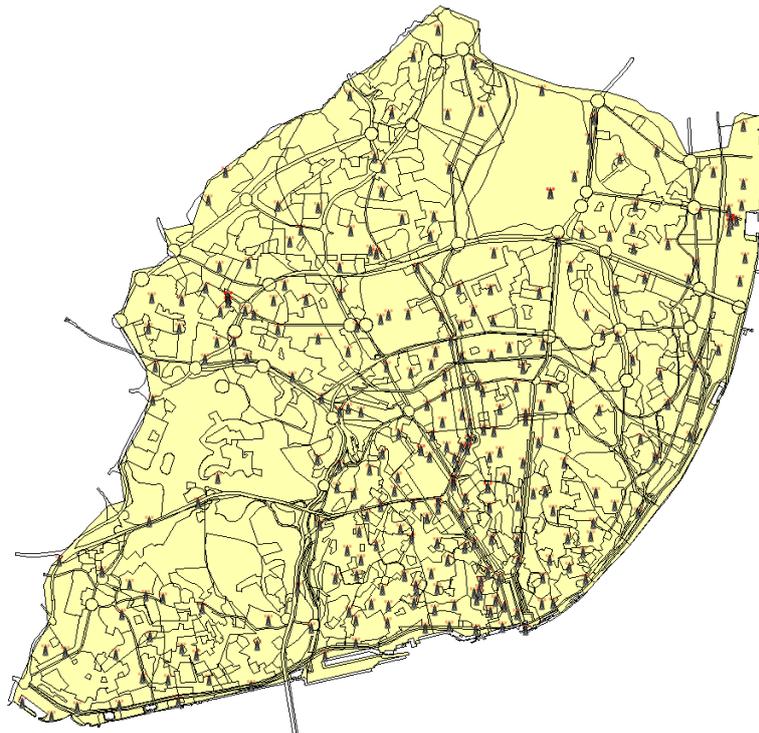


Figure 4.2. Map of Lisbon with all BSs.

In the second version of the simulator, simulations are slow, since the algorithm is executed several times. For example, if the duration of the simulation is 10 minutes, the algorithm is repeated 600 000 times, one time every millisecond. Therefore, a small scenario in Parque das Nações with 6 BSs was chosen, Figure 4.3.

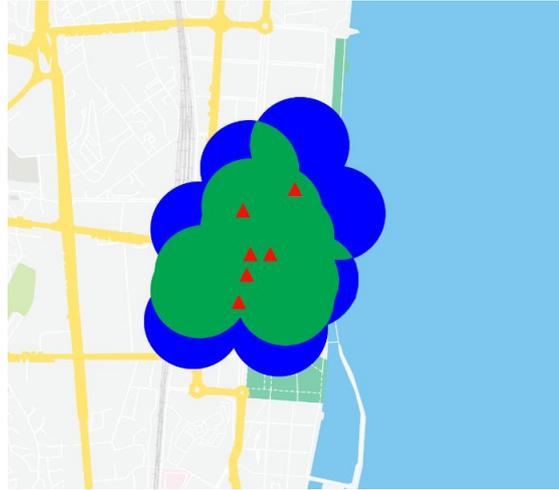


Figure 4.3. Map of Parque das Nações with 6 BSs.

The covered area in Figure 4.3 was performed for the 2600 MHz frequency band. The blue zones are covered by one BS and the green zones by two or more BSs. In Table 4.5, one represents the area covered by one BS and the one by two or more BSs for each frequency band.

Table 4.5. Covered area by each frequency band.

Frequency Band [MHz]	Covered area [km ²]		
	1BS	≥ 2 BSs	Total
800	0.370	3.224	3.594
1800	0.295	0.654	0.949
2600	0.221	0.276	0.497

4.2 CoMP Analysis in a Static Scenario

This section presents the CoMP analysis in the static scenario, i.e., it presents a “snapshot” of the network and how CoMP can affect it. Results were obtained from the first version of the simulator, for the city of Lisbon, inside which there are 399 users. Ten simulations were performed for each frequency band, results being observed in Figure 4.4 and Figure 4.5.

In Figure 4.4, it is possible to observe the coverage for each frequency band and how many users are served. As expected, the 800 MHz band corresponds to the band with more covered users, even covering all users. However, not all users are served, because the minimum services’ requirements are not ensured. One disadvantage of CoMP is that the technique affects capacity, since, if a user is connected to more than one BS, it consumes resources in all of these BSs. As the 800 MHz band has 10 MHz bandwidth, it overloads quicker. In these simulations, when a user is connected to a maximum of two BSs, the number of served users increases, because when a user is connected to one BS, that BS may have its resources consumed, and without CoMP this user is not served. On the other hand, when a user is connected to a maximum of three BSs, the number of users served is affected, due to the priority users connected to two or three BSs.

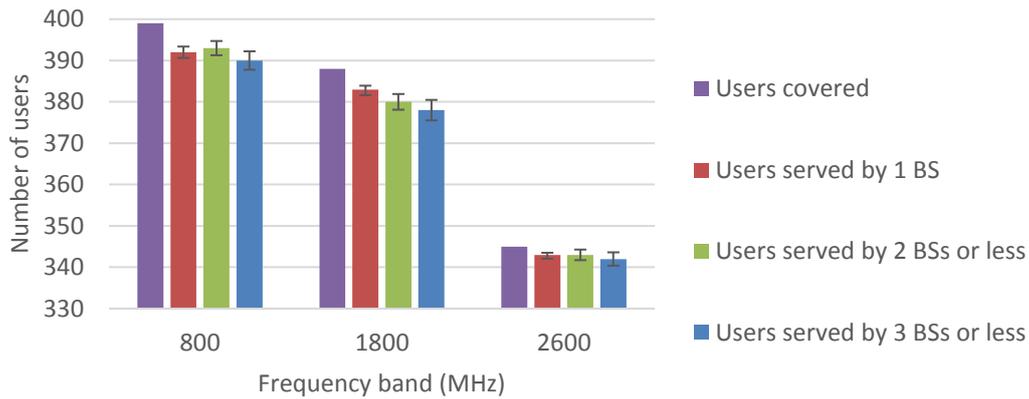


Figure 4.4. Number of users covered vs. number of users served.

The 1800 MHz band is an intermediate band, since it has good coverage and better capacity than the 800 MHz one. This frequency band covers 388 users out of the possible 399. With CoMP, capacity is a bit affected, nonetheless results without it are similar.

Finally, the 2600 MHz band is the best in terms of capacity, but it has the worst coverage. In this case, the system with CoMP serves a similar number of users than without it, the explanation lying on the fact that covered users decrease from 399 to 345, hence the network has more capacity for the users that are connected to more than one BS. In the second version of the simulator, networks with more load are tested, being possible to take more conclusions about this band.

The results illustrated in Figure 4.5 were obtained using (3.10), (3.11) and (3.12). When a user is connected to a maximum of two BSs, gains are above 30%. If a user is connected to a maximum of three BSs, the gains go beyond 60% in the 800 and 1800 MHz bands and above 45% in 2600 MHz.

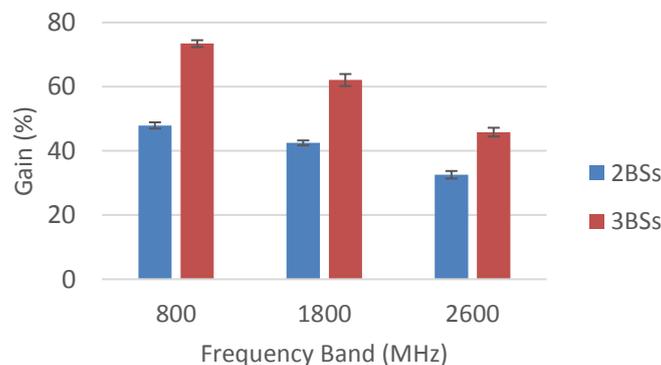


Figure 4.5. Throughput gain.

4.3 CoMP Low Load Analysis in a Temporal Scenario

In this section, a detailed study of CoMP is performed, followed by the results obtained for the 800, 1800 and 2600 MHz bands. Results were obtained from the second version of the simulator. To simplify the results' description, CoMP with two BSs means that an off-centre user can be connected to a maximum

of two BSs, and CoMP with three BSs that an off-centre user can be connected to three BSs maximum.

A total of 50 geographic coordinates were generated, however 9 of them were outside the serviced area boundaries, thus the analysis of the low load scenario was performed for 41 locations. The services generated in these locations may be covered up to six BSs, given the network in Parque das Nações.

4.3.1 Frequency Band Analysis

This subsection deals with the behaviour of CoMP with the variation of the frequency band, which results in a change in capacity and coverage. Table 4.6 presents the maximum number of users' positions covered by each frequency band.

Table 4.6. Coordinates covered by each frequency band.

Frequency Band [MHz]	Bandwidth [MHz]	Users' Positions Covered
800	10	41
1800	20	40
2600	20	35

As expected, the 800 MHz frequency band offers the best coverage and the 2600 MHz frequency band, the worst one. The difference between these two is not substantial, because the area of the scenario is small. Results are organised in the following order of bands: 2600 MHz, 1800 MHz and 800 MHz.

As previously mentioned, the interference is harmful to throughput, and off-centre users are the most affected. In Figure 4.6, five of the six services (Video Calling, Music, Web Browsing, File Sharing and E-Mail) have worse throughputs in cell off-centre conditions than in cell-centre ones. For three of them (Web Browsing, File Sharing and Music), centre users have approximately twice the throughput in relation to off-centre users.

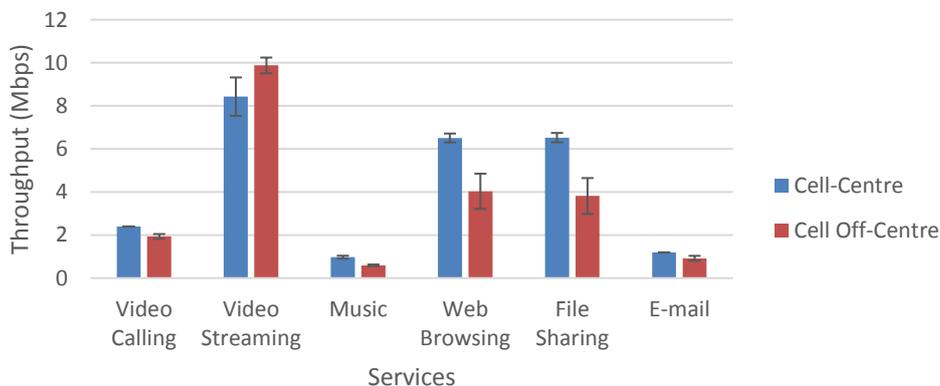


Figure 4.6. Centre users vs. off-centre users without CoMP for the 2.6 GHz band.

However, for this case, Video Streaming off-centre users have better throughputs comparing with centre ones, because the BS that serves cell-centre users also serves other services, or off-centre users can have a received power near -80 dBm, or the sector of the BS covers only Video Streaming services.

The objective of CoMP is to offer better conditions to off-centre users, managing interference and increasing throughput for off-centre users. In Figure 4.7 and Figure 4.8, it is possible to observe CoMP's impact. Figure 4.7 presents the throughputs for users situated in cell-centre, in cell off-centre, which are covered by one BS, and in cell off-centre with CoMP, covered by two BSs. Once again, centre users, in general, are in better conditions than off-centre ones without CoMP, as in Figure 4.6. However, the throughput of off-centre users with CoMP increases substantially and, on average, off-centre users with CoMP have a better throughput than centre ones. This result proves that, with CoMP, interference is manageable and the throughput of off-centre users is improved.

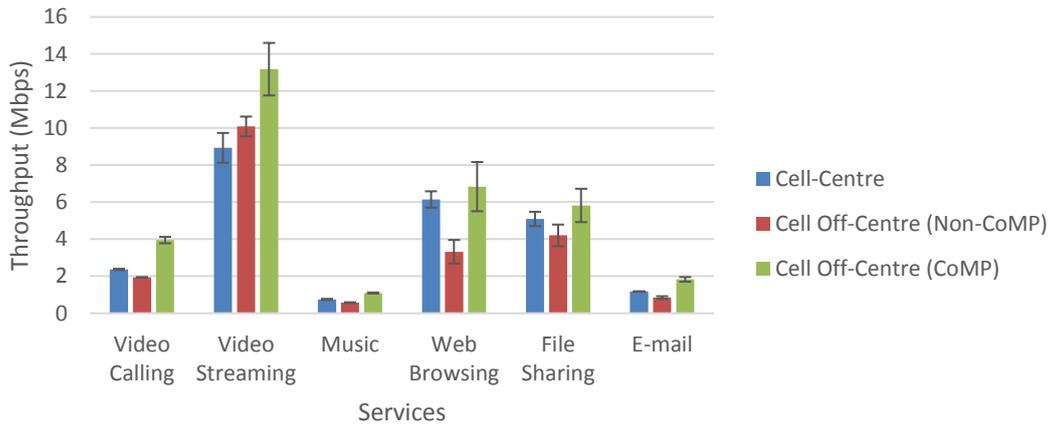


Figure 4.7. Centre users vs. off-centre ones without and with CoMP (connected to 2 BSs simultaneous) for the 2.6 GHz band.

In Figure 4.8, one presents a simulation where off-centre users can be connected to up to three BSs. Results are similar to the ones obtained in Figure 4.7, where off-centre users without CoMP have in general worse throughput than centre ones, and off-centre users who perform CoMP have better throughput than centre one. Another difference between Figure 4.7 and Figure 4.8 is the throughput values for off-centre users who perform CoMP, since systems with CoMP with three BSs have a greater throughput than those with two.

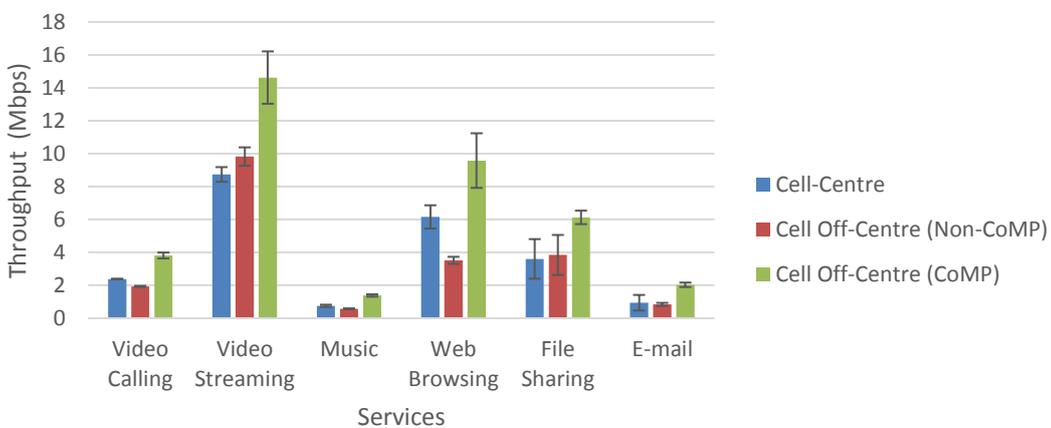


Figure 4.8. Centre users vs. off-centre ones without and with CoMP (connected to 2 or 3 BSs simultaneous) for the 2.6 GHz band.

Off-centre users with CoMP present significant gains in comparison with the ones without CoMP. However, with CoMP, centre and off-centre users that are connected to just one BS usually suffer a negative impact. In Figure 4.9, it is possible to observe the advantages of CoMP. All services gain throughput, and in the majority of cases, CoMP with 3BSs present better results than CoMP with 2 BSs. On the other hand, CoMP introduces a negative impact in centre and off-centre users connected to one BS. In Figure 4.10 and Figure 4.11, one presents CoMP's influence in centre and off-centre users connected to one BS, respectively.

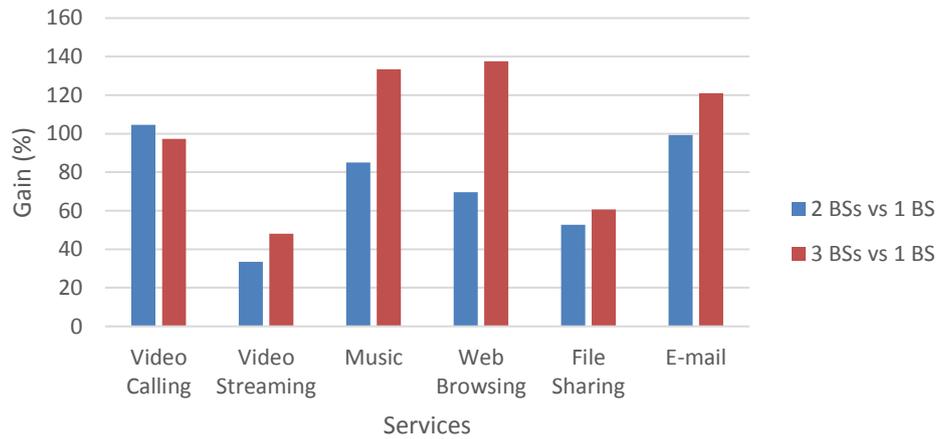


Figure 4.9. Throughput gain between off-centre users with and without CoMP for the 2.6 GHz band.

First of all, the losses on the music service in Figure 4.10 and Figure 4.11 should be ignored, since the throughput is above 320 kbps, as seen in Figure 4.7 and Figure 4.8. The analysis of CoMP with two BSs and with three BSs should be done separately. Another important point is that in Figure 4.10 and Figure 4.11, the blue bars are a comparison between a system with CoMP where an off-centre user can be connected to two BSs and a system without CoMP, and the red bars are a comparison between a system with CoMP where an off-centre user can be connected to three BSs and a system without CoMP.

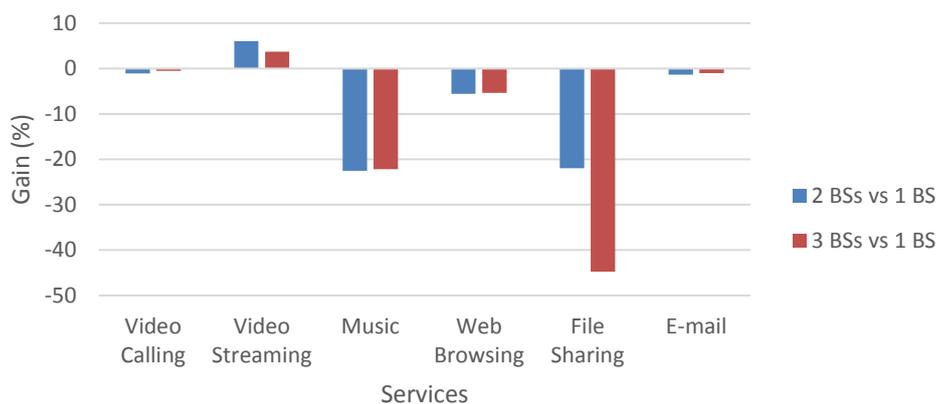


Figure 4.10. Throughput gain and loss between users with CoMP and centre users without CoMP for the 2.6 GHz band.

As depicted by the blue bars in Figure 4.10, centre users suffer negligible losses, except for File Sharing, since throughput decreases approximately 20%; surprisingly, Video Streaming users present a gain. One explanation is that off-centre users who perform CoMP and services with size (Web Browsing, File

Sharing and E-Mail) are active in the system for a short duration, because the throughput is higher and service finishes sooner. In the blue bars in Figure 4.11, off-centre users that do not perform CoMP in a system with CoMP are compared with off-centre users in a system without CoMP, and again losses are negligible, the worst case being Web Browsing, and loss below 18%.

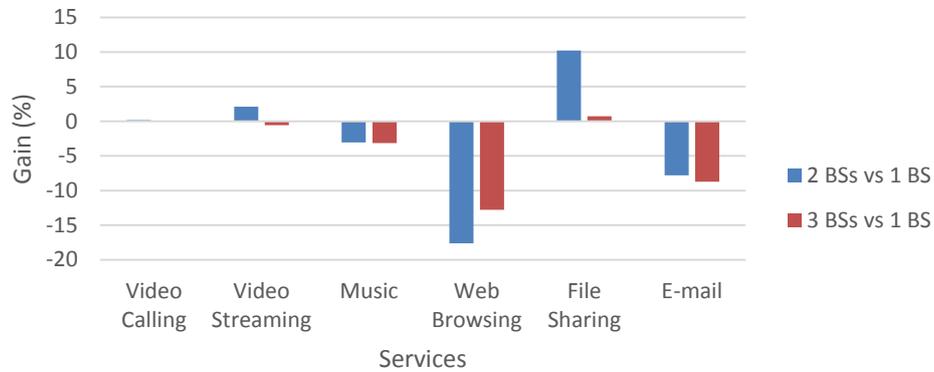


Figure 4.11. Throughput gain and loss between off-centre users who do not perform CoMP in a system with and without CoMP for the 2.6 GHz band.

The red and blue bars, in Figure 4.10 show similar results, however the situation for File Sharing is aggravated and losses are situated in 45%. In Figure 4.11, once again losses are minimal. A BS may have neighbouring BSs that interfere; an RB is interfering when is sent at the same instant that a non-interfering one. With CoMP, more RBs are used and for that reason interference can increase. However, this interference can be mitigated, but as explained in Chapter 3, the solution has not been applied. In Figure 4.12, it is possible to observe interference increasing, because SINR in CoMP is lower than without CoMP. Nevertheless, if interference was managed, and thus off-centre users' throughput improved, the mitigation of interference would be an extra feature to improve the obtained results.

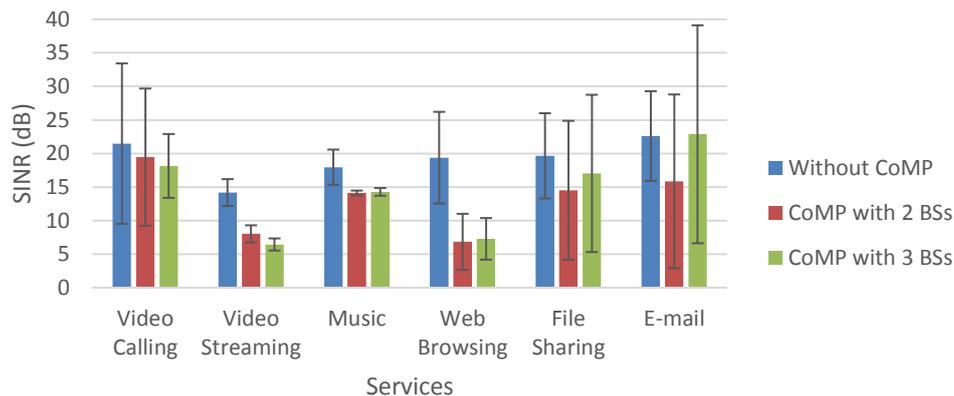


Figure 4.12. SINR without CoMP, and with CoMP with 2 and 3 BSs for the 2.6 GHz band.

In Table 4.7, one shows the number of users served in each algorithm. The first three services (Video Calling, Video Streaming and Music) are defined by duration, whereas the last three (Web Browsing, File Sharing and E-Mail) are by size. The former do not depend on throughput to finish faster, because the throughput only improves the QoS, but for the latter, if throughput increases, they are served faster, and stop consuming network resources. The services duration and size are generated randomly,

therefore it is difficult to draw a conclusion. However, it is possible to see that with CoMP more users that perform size defined services are served.

Table 4.7. Number of users served for the 2.6 GHz band.

Algorithm used	Users served						
	Video Calling	Video Streaming	Music	Web Browsing	File Sharing	E-Mail	Total
Without CoMP	10	10	15	27	20	17	99
CoMP with 2 BSs	10	14	13	35	26	21	119
CoMP with 3 BSs	11	12	14	33	28	21	119

For the 1800 MHz band, more users are covered than in 2600 MHz, as observed in Table 4.6, thus the load in BSs rises, and for this reason the outcome is affected. Without CoMP, results confirm previous ones. All centre users have a better throughput than off-centre ones. For File Sharing and E-Mail, the throughput of centre users doubles the one of off-centre users, Figure 4.13.

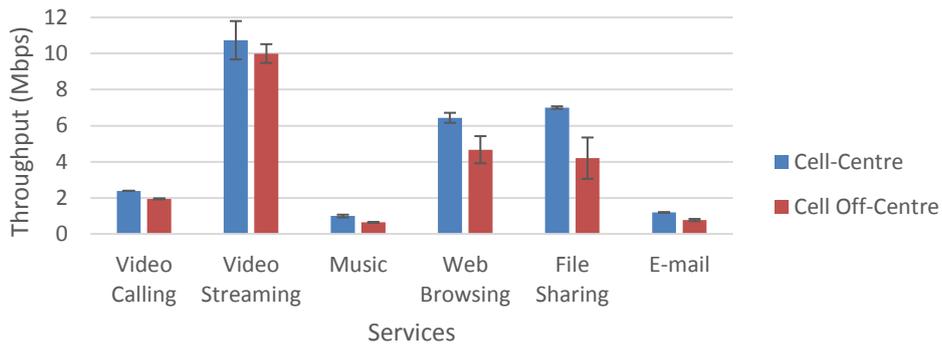


Figure 4.13. Centre users vs. off-centre users without CoMP for the 1.8 GHz band.

With CoMP, subsequently, a user can be connected to a maximum of two or three BSs. In Figure 4.14, one shows off-centre users' throughput increase and that off-centre users performing CoMP have a better throughput than centre ones.

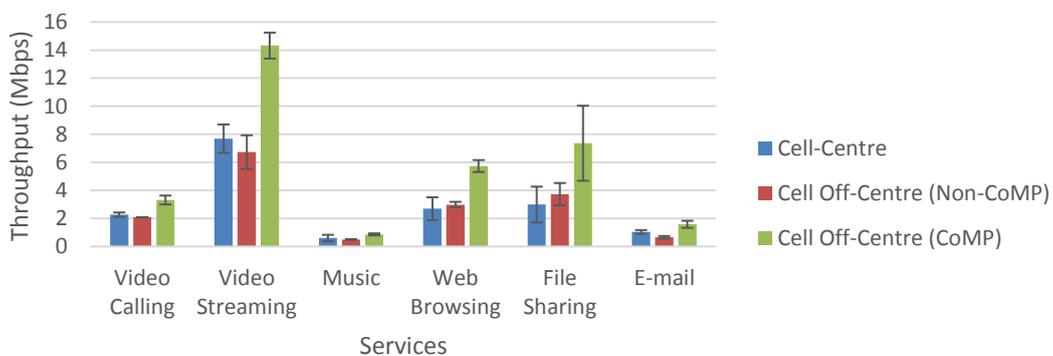


Figure 4.14. Centre users vs. off-centre users without and with CoMP (connected to 2 BSs simultaneous) for the 1.8 GHz band.

If an off-centre user is connected to a maximum of three BSs, results are very similar to one connected to a maximum of two BSs. However, in this band, off-centre users performing CoMP up to three BSs, in general, do not present a throughput larger than those with CoMP up to two BSs, Figure 4.15.

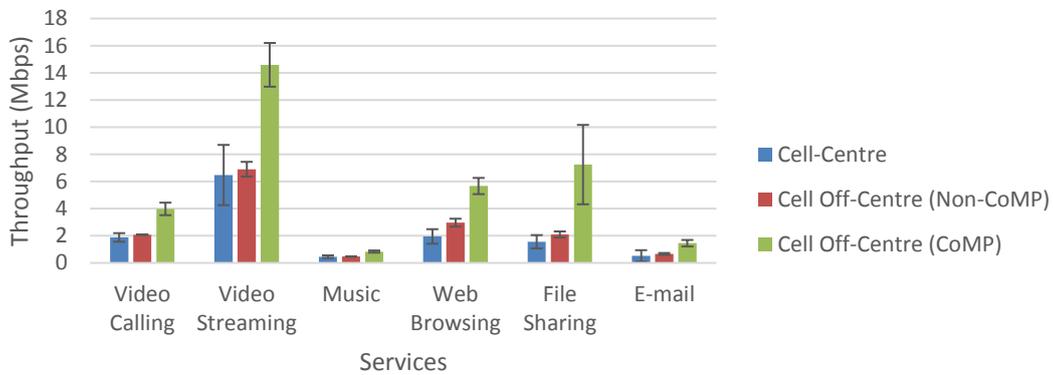


Figure 4.15. Centre users vs. off-centre users without CoMP vs. off-centre users with CoMP (connected to 2 or 3 BSs simultaneous) for the 1.8 GHz band.

In Figure 4.16, it is possible to observe the benefits of CoMP at the 1800 MHz band. Once again, CoMP introduces disadvantages in centre and off-centre users connected to one BS. In Figure 4.17 and Figure 4.18, one shows CoMP's influence in centre and off-centre users connected to one BS, respectively.

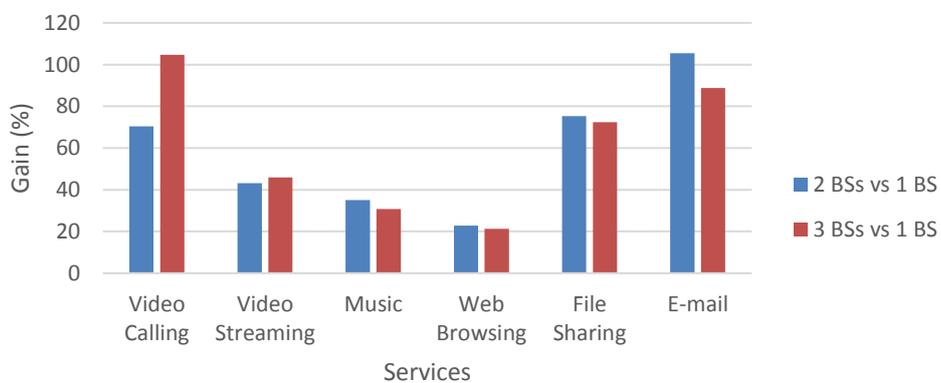


Figure 4.16. Throughput gain between off-centre users with and without CoMP for the 1.8 GHz band.

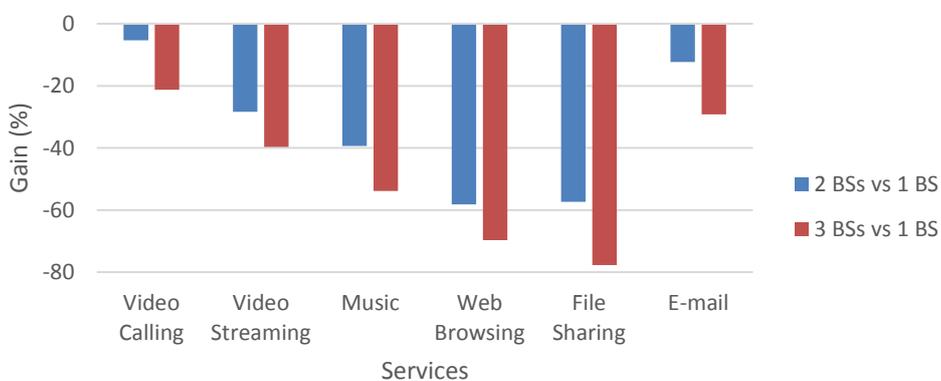


Figure 4.17. Throughput loss between centre users with and without CoMP for the 1.8 GHz band.

As with the 2600 MHz band, music losses should be ignored, once the throughput is above 320 kbps, as seen in Figure 4.14 and Figure 4.15. In contrast to the 2600 MHz band, the 1800 MHz band presents significant losses. In centre users, services as Web Browsing and File Sharing have losses above 50% compared with CoMP with two BSs and without CoMP. When an off-centre user that can be connected to three BSs is compared with a system without CoMP, losses are even worse, Figure 4.17.

In Figure 4.18, one compares off-centre users who do not perform CoMP in systems with CoMP with those that are in systems without CoMP. Again, in contrast to the 2600 MHz band, with the 1800 MHz band, users suffer more losses on the throughput gain, and with CoMP up to three BSs losses are even more significant, File Sharing services having losses of 50%.

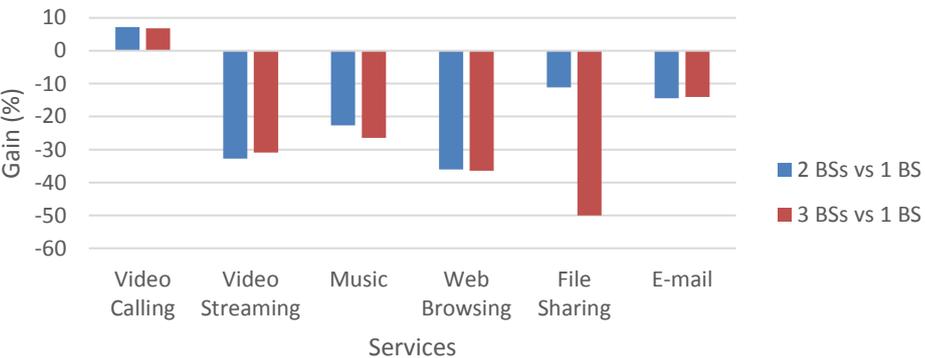


Figure 4.18. Throughput gain and loss between off-centre users who do not perform CoMP in system with CoMP and those in systems without CoMP for the 1.8 GHz band.

In this frequency band, when CoMP is used, SINR decreases massively. The coverage of this frequency band is larger than the one at 2600 MHz, with more interference, Figure 4.19. As stated before, interference can be managed and the negative impact less noticed.

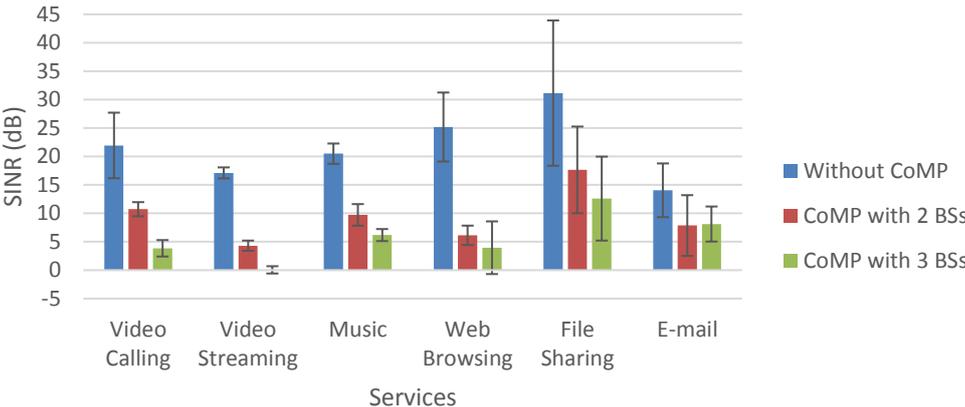


Figure 4.19. SINR without and with CoMP, with 2 and 3 BSs for the 1.8 GHz band.

As expected, in this frequency band more users are served than in 2600 MHz. In this case, the number of served users is identical between the cases, Table 4.8. Finally, for the 800 MHz band, even more users are covered, therefore the network has more load. In line with the results for 1800 MHz, all services in the cell-centre have throughputs better than in off-centre without CoMP, Figure 4.20.

Table 4.8. Number of users served for the 1.8 GHz band.

Algorithm used	Users served						
	Video Calling	Video Streaming	Music	Web Browsing	File Sharing	E-Mail	Total
Without CoMP	14	14	14	37	22	23	124
CoMP with 2 BSs	13	14	13	41	23	21	125
CoMP with 3 BSs	13	12	12	34	27	21	119

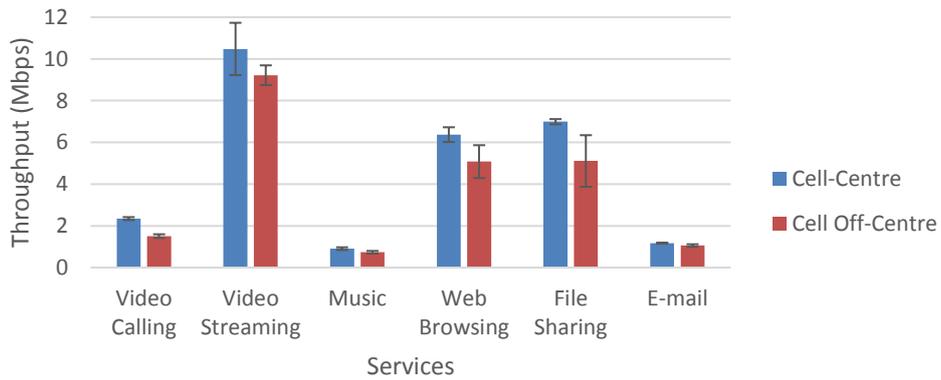


Figure 4.20. Centre Users vs. off-centre users without CoMP for the 800 MHz band.

As observed in Figure 4.21 and Figure 4.22, when CoMP is applied, off-centre users that have the capability to use CoMP experience better improvements. For three of the services (Video Streaming, File Sharing and E-Mail), off-centre with CoMP has a better throughput than in cell-centre.

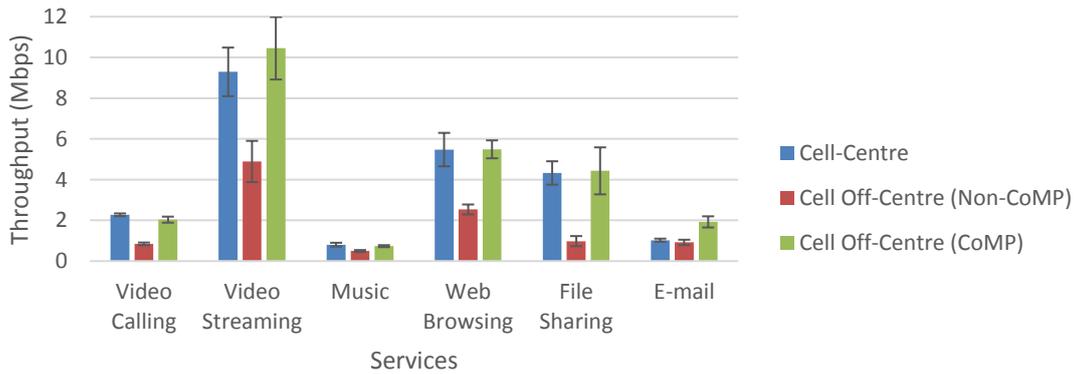


Figure 4.21. Centre users vs. off-centre users without and with CoMP (connected to 2 BSs simultaneous) for the 800 MHz band.

For the last case, if a user could be connected to two or three BSs, off-centre users' throughput would improve, however centre users would suffer a great impact on throughput. As for the 1800 MHz band, off-centre users who perform CoMP in systems with CoMP with three BSs, in general, do not present greater throughput than those in systems with two BSs. The explanation comes from the fact that this frequency band has less capacity, nonetheless a better explanation is given in the following pages.

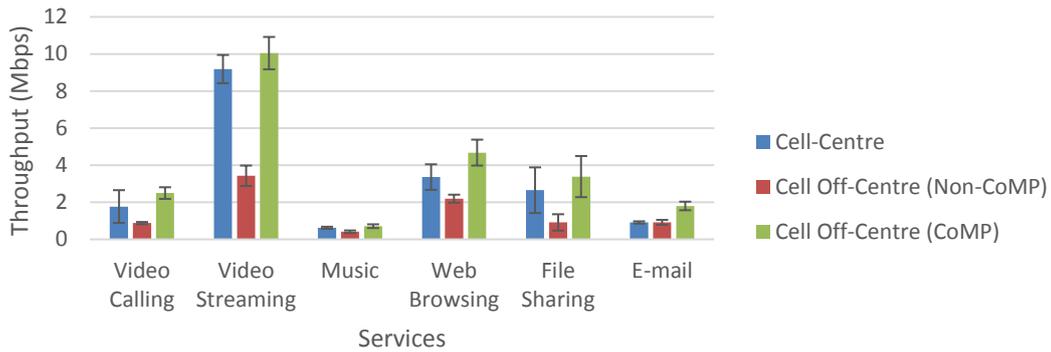


Figure 4.22. Centre users vs. off-centre users without and with CoMP (connected to 2 or 3 BSs simultaneous) for the 800 MHz band.

The 800 MHz band is the frequency band with the smallest bandwidth, 10 MHz, therefore, this band has a lower capacity than 1800 MHz and 2600 MHz. For the first time, there are losses in off-centre users that perform CoMP. When CoMP with three BSs is used, the situation gets worse, Figure 4.23. Since this frequency band has a larger coverage than the others, there are more users covered by two BSs.

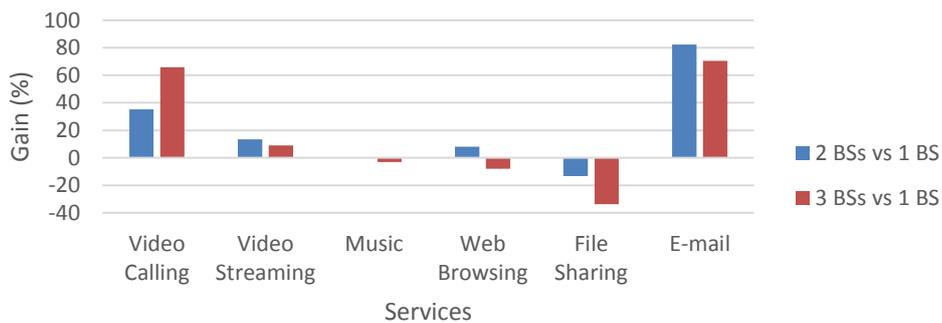


Figure 4.23. Throughput gain and loss between off-centre users with and without CoMP for the 800 MHz band

The losses of the music service can be ignored, since the throughput is above 320 kbps. As in the 1800 MHz band, 800 MHz has significant losses, Figure 4.24 and Figure 4.25.

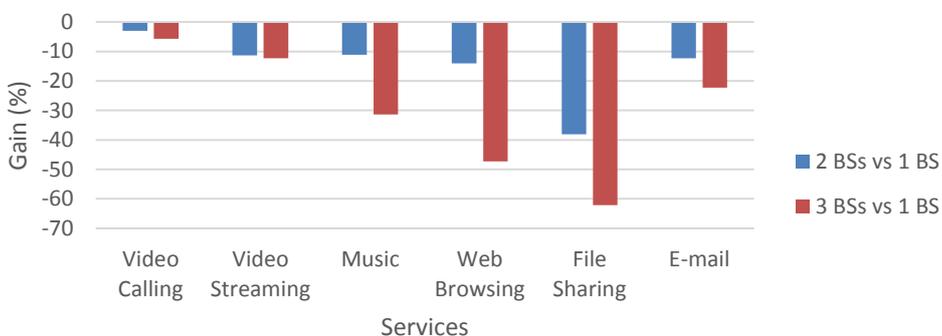


Figure 4.24. Throughput loss between centre users with and without CoMP for the 800 MHz band.

The losses between centre users with CoMP with two BSs and those without CoMP are around 10%, with the exception of File Sharing, that has a loss around 40%. A comparison between centre users in systems with CoMP with three BSs and those without CoMP shows even greater losses. Users who

perform Web Browsing and File Sharing have losses above 45%. These users are more harmed because they perform services with a lower priority, thus in case of overload they are more affected. The losses between off-centre users who do not perform CoMP in systems with CoMP and those in systems without CoMP are critical. In this case, systems with CoMP with two BSs presented dreadful results, as the systems with CoMP with three BSs. Even services with high priority have negative results, as in the case of Video Streaming with losses above 45%. The lack of capacity leads to very bad results hence, in this case CoMP does not bring advantages, because, in general, losses overcome gains.

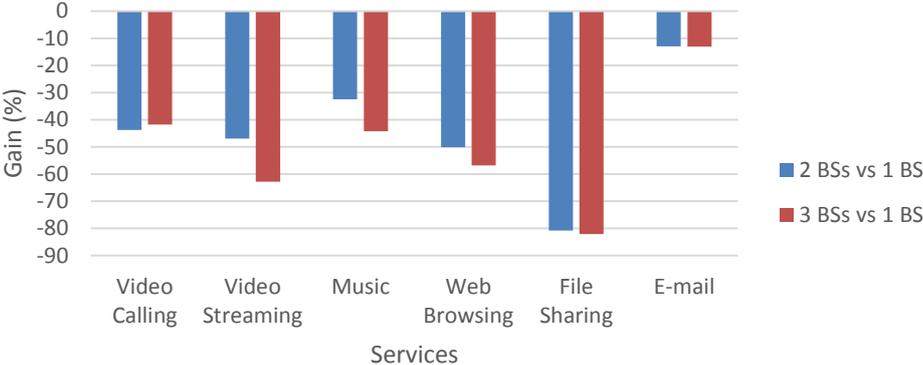


Figure 4.25. Throughput loss between off-centre users who do not perform CoMP in system with CoMP and those in systems without CoMP for the 800 MHz band.

As with the 2600 MHz and 1800 MHz band, the 800 MHz band with CoMP is affected by interference, thus SINR decreases. However, the behaviour is more similar with the 2600 MHz band, since the 1800 MHz band has worst results, because the 1800 MHz band covers almost the same users' positions than 800 MHz, and has more RBs, thus there are more RBs to interfere with each other. The results presented in Figure 4.26 are not a problem, because the interference is managed, as stated before.

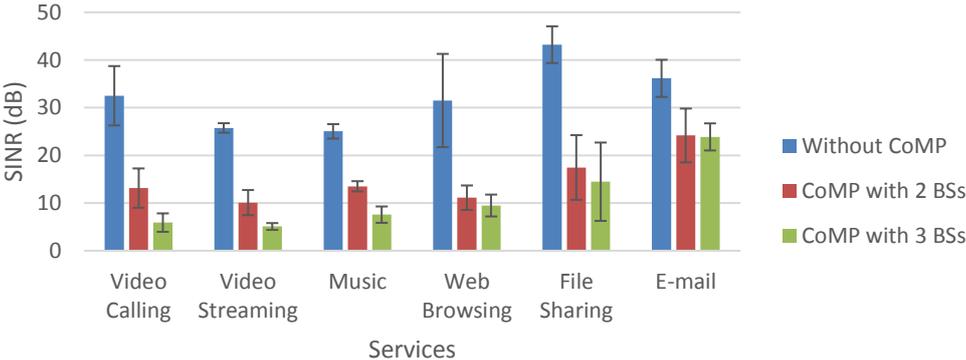


Figure 4.26. SINR without CoMP, and with CoMP with 2 and 3 BSs for the 800 MHz band.

As seen in Table 4.9, the 800 MHz band serves more users than other bands, because it is the band with a larger coverage, thus covering more users' positions. The number of users served is identical between cases.

In conclusion, for the 800 MHz band, there are no advantages of using CoMP with three BSs compared with two BSs, as seen in Figure 4.27. This bad result is enhanced with the results presented in

Figure 4.28 and Figure 4.29. For systems with CoMP with three BSs, the gain for off-centre users that perform CoMP is 16.8%, whereas, the other users (centre and off-centre users that do not perform CoMP) have losses of 30.2% and 50.1%, respectively. The results for CoMP with two BSs are not better, since off-centre users that perform CoMP have a gain of 21% compared with centre and off-centre users who do not perform CoMP and have losses of 15% and 44.5%, respectively.

Table 4.9. Number of users served for the 800 MHz band.

Algorithm used	Users served						
	Video Calling	Video Streaming	Music	Web Browsing	File Sharing	E-Mail	Total
Without CoMP	12	14	14	39	28	21	128
CoMP with 2 BSs	15	16	15	41	24	23	134
CoMP with 3 BSs	12	18	13	37	24	23	127

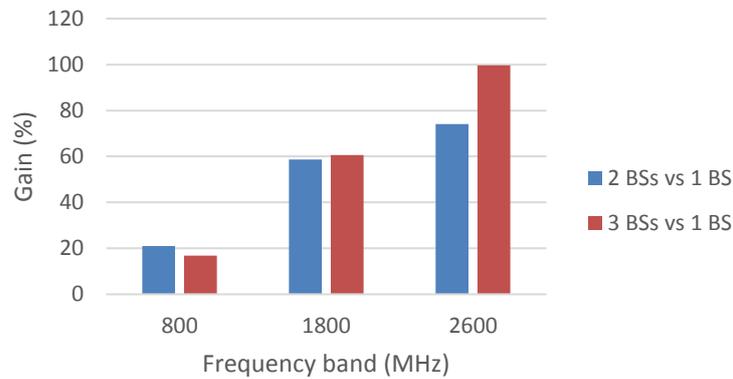


Figure 4.27. Throughput gain between off-centre users with CoMP and without CoMP.

For the 1800 MHz band, in terms of gain, using CoMP with two and three BSs is almost the same, differing from 58.7% against 60.6%. However, the losses with CoMP with three BSs are bigger than with two BSs. With two BSs, centre users' losses are about 33.4% and for off-centre users that do not perform CoMP are 18.3%. With three BSs, centre users' losses are 48.6% and for off-centre users that do not perform CoMP are 25.2%. This analysis was done in low load scenarios, therefore in this frequency band, in scenarios with more load, CoMP with three BSs can be harmful.

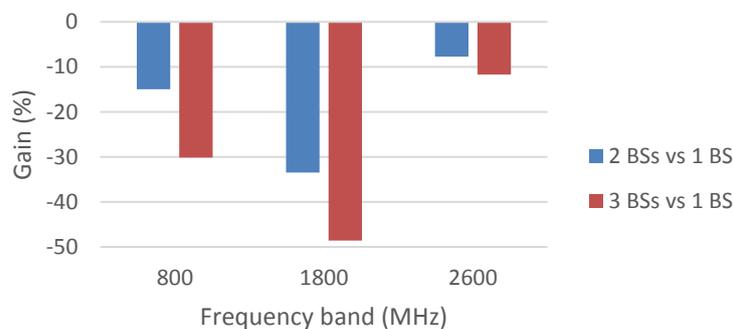


Figure 4.28. Throughput loss between centre users with CoMP and without CoMP.

Finally, the 2600 MHz band presents better results, being the one with more capacity and less covered users, consequently with more available RBs. In this band, off-centre users that perform CoMP have gains of 74% in systems with CoMP with two BSs and 99.6% those with three BSs. Centre users have small losses, 7.7% for two BSs and 11.7% for three BSs. Off-centre users that do not perform CoMP have minimal losses. In systems with CoMP with two BSs, losses are 2.7% and with three BSs are 4%. As 2600 MHz presents better results, in Section 4.4 it is tested for a scenario with mid load.

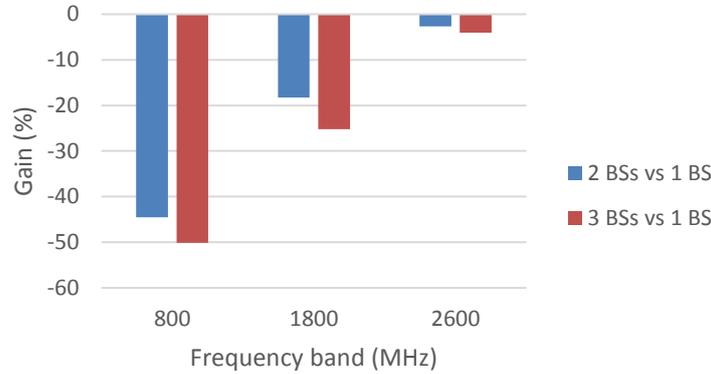


Figure 4.29. Throughput loss between off-centre users who do not perform CoMP in system with CoMP and those in systems without CoMP.

4.3.2 User Classification Analysis

Users are classified as cell-centre and off-centre, and the condition defining them is the received power. In the reference scenario, it was defined that all users with a received power above -80 dBm are classified as cell-centre ones. In this subsection, the threshold was modified to -100 dBm, therefore only cell-edge users can use CoMP. When the threshold decreases, there are less users available to perform CoMP, consequently there are less users using resource blocks in different BSs. The users' positions are the same as in the previous subsection, and the band chosen is 1800 MHz, since this band presents significant losses in centre users, and off-centre ones who do not perform CoMP, thus being interesting to study the network behaviour with less users performing CoMP, Figure 4.30.

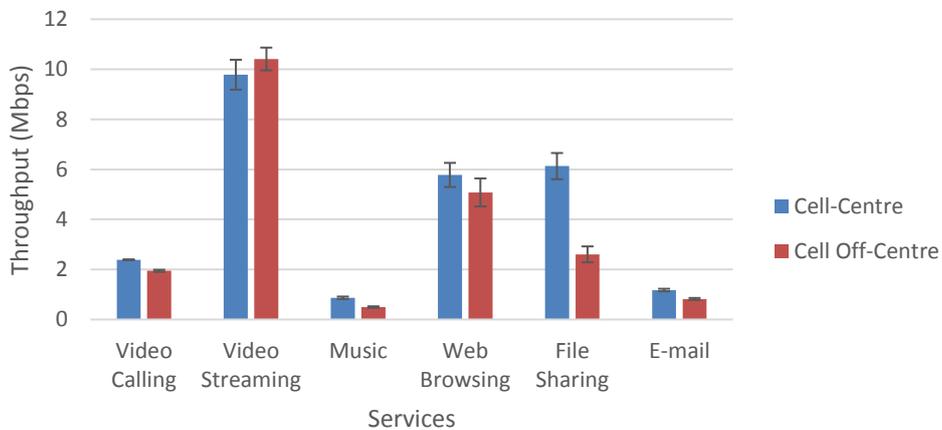


Figure 4.30. Centre users vs. off-centre users without CoMP in a new users' classification scenario.

Once again, it is possible to verify in Figure 4.30 that, in general off-centre users have worse throughput than centre ones. In this scenario, more users are included in the cell-centre category. Centre users' throughput in this scenario is, in general, lower than in the reference scenario, because there are more centre users in this scenario, with lower received power than centre users in the reference scenario.

Figure 4.31 and Figure 4.32 show that CoMP is effective in off-centre users, because the throughput increases. For off-centre users who perform CoMP in systems with three BSs, the majority of the services have a larger throughput than in the reference scenario. A good example is Video Streaming that has, on average, 18 Mbps while in the reference scenario it has 14.5 Mbps, because the network is less loaded, since only cell edge users perform CoMP.

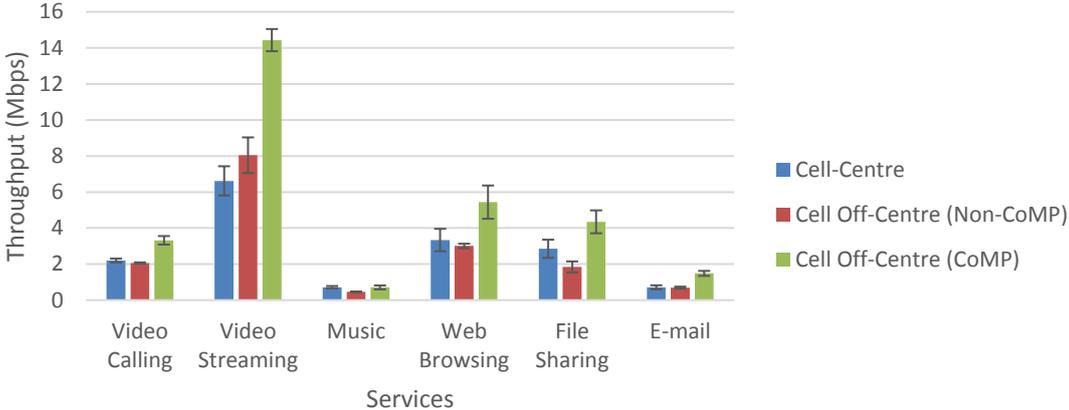


Figure 4.31. Centre users vs. off-centre users without and with CoMP (connected to 2 BSs simultaneous) in a new users' classification scenario.

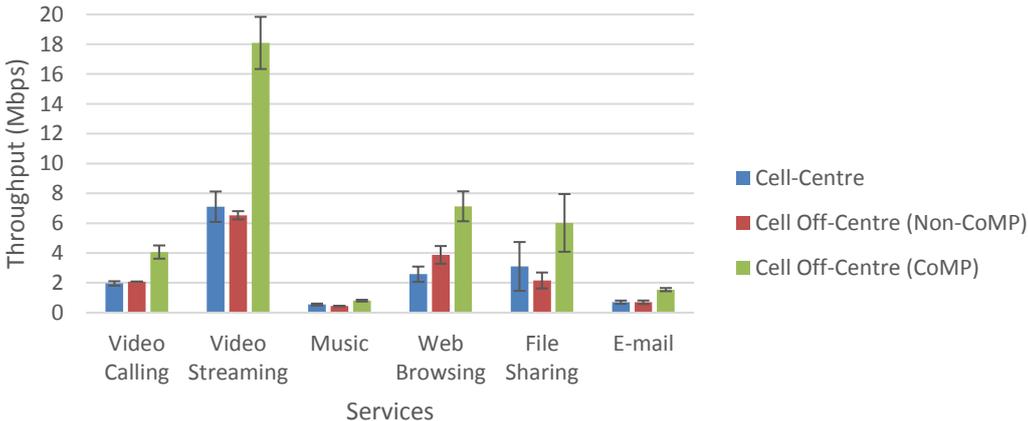


Figure 4.32. Centre users vs. off-centre users without and with CoMP (connected to 2 or 3 BSs simultaneous) in a new users' classification scenario.

In this scenario, SINR presents some improvements in relation to the reference one. Figure 4.33 can be compared with Figure 4.19, being visible that in this scenario systems with CoMP with three BSs have, in general, better SINR than in the reference one. Since there are less users performing CoMP, there is less interference and SINR improves.

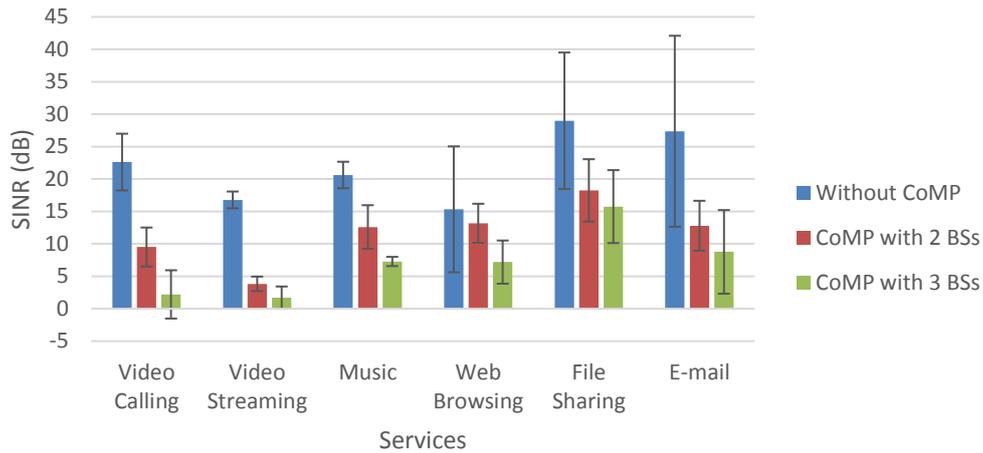


Figure 4.33. SINR without CoMP, and with CoMP with 2 and 3 BSs in a new users' classification scenario.

As in previous subsection, in the 1800 MHz band, off-centre users that perform CoMP have better results compared with those without CoMP. As seen in Figure 4.34, the gain with three BSs in this scenario is larger, being always greater than with CoMP with two BSs, in contrast with the reference scenario. In Figure 4.35 and Figure 4.36, it is possible to analyse the impact of CoMP in other users (centre and off-centre users that do not perform CoMP). A clear sign of improvement is that in Figure 4.35, any service has losses above 60%, in contrast with the reference scenario.

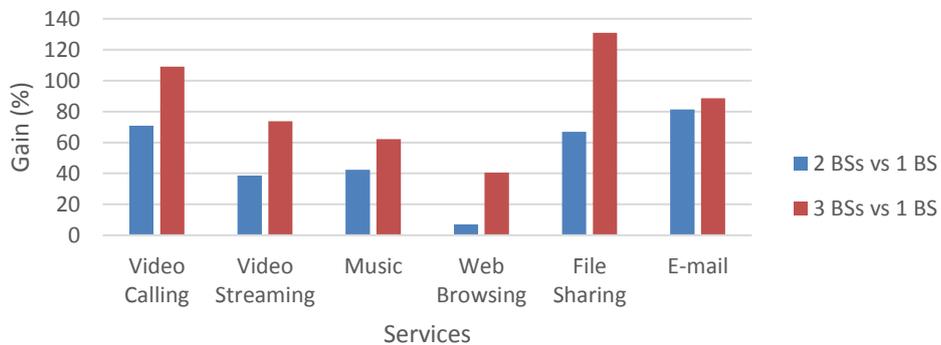


Figure 4.34. Throughput gain between off-centre users with CoMP and without CoMP in a new users' classification scenario.

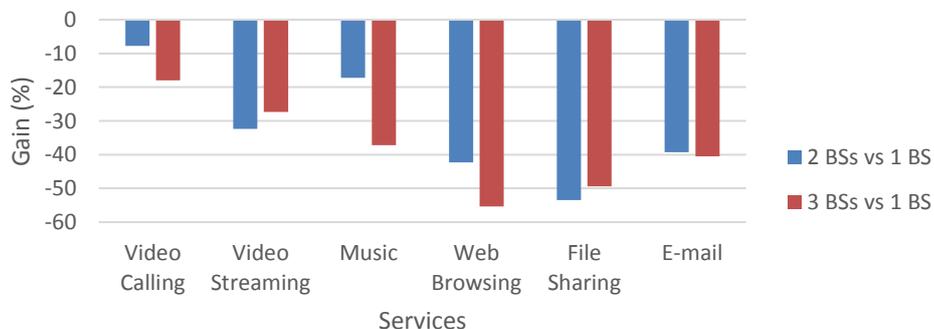


Figure 4.35. Throughput loss between centre users in system with CoMP and without CoMP in a new users' classification scenario.

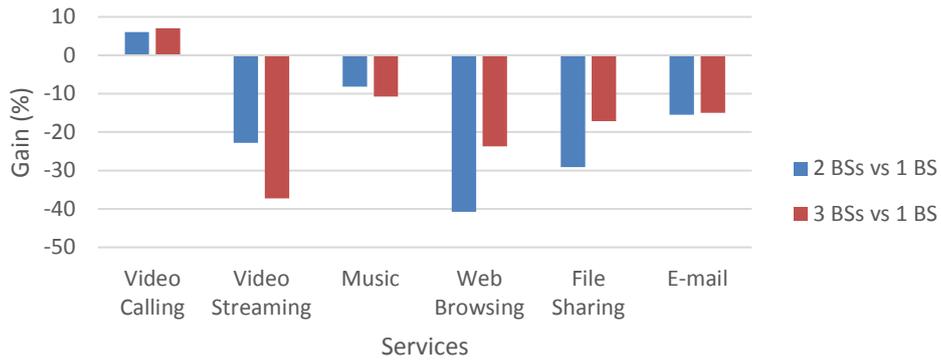


Figure 4.36. Throughput gain and loss between off-centre users who do not perform CoMP in system with CoMP and those in systems without CoMP in a new users' classification scenario.

However, in both cases, the scenario represented in this section and the reference one, systems with CoMP have a negative impact on the network. It is important to conclude if the gains are greater than the losses, global results being shown in Figure 4.37 and Figure 4.38.

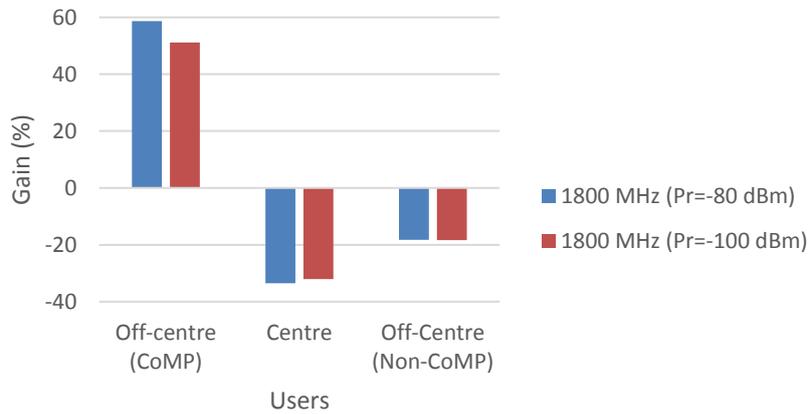


Figure 4.37. Throughput gain and loss between a system with CoMP with 2 BSs and a system without CoMP in the reference scenario and other scenario.

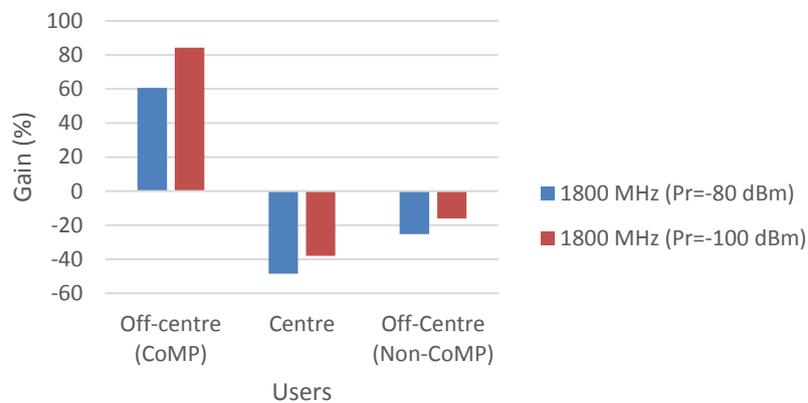


Figure 4.38. Throughput gain and loss between a system with CoMP with 3 BSs and a system without CoMP in the reference scenario and other scenario.

In this new scenario, the systems with CoMP with two BSs do not perceived the changes and results are similar to the reference scenario, as shown in Figure 4.37. However, for CoMP with three BSs, the changes have a positive effect, as observed in Figure 4.38. Off-centre users that perform CoMP in this new scenario have gained 84.2% against 60.6% of the reference one. Centre users and off-centre ones that do not perform CoMP suffer less losses. In the former, losses are 38% in new scenario against 48.6% in the reference one, while in the latter, losses are 16.2% in new scenario compared with 25.2% in the reference one. The changes done in the condition to classify users show that in case the system does not have the capacity to perform CoMP in all off-centre users, at least the cell-edge ones can have a better QoS, with less impact on the network.

4.3.3 Services Percentage Analysis

In this subsection, a comparison between the reference scenario and a different service profile is performed, taking a video centric test, because Video Streaming is one of the most demanding resource services, since it has a high priority and maximum throughput, thus it is interesting to observe how the network behaves. Only the 2600 MHz band is studied, since simulations take a long time. In Table 4.10, it is possible to observe the differences between the reference scenario service mix and the new scenario.

Table 4.10. Services mix scenarios [Guit16].

Service	Scenario [%]	
	Reference	Video Centric
Video Calling	8	8
Video Streaming	30	45
Music	20	9
Web Browsing	20	24
File Sharing	12	9
E-Mail	10	5

As expected, in general, centre users have better throughput than off-centre ones.

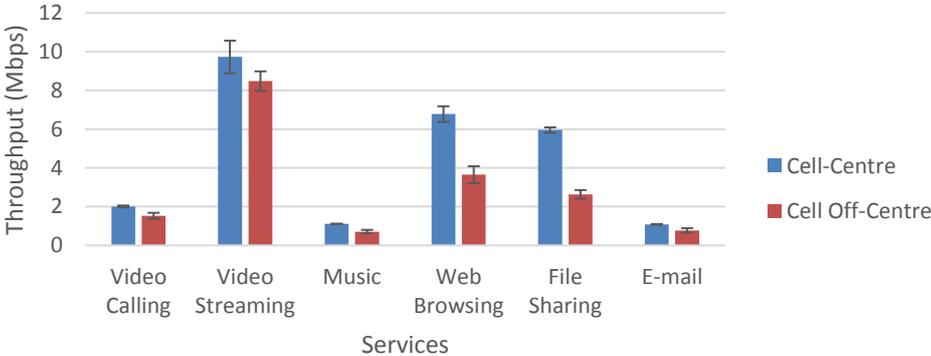


Figure 4.39. Centre vs. off-centre users without CoMP in a new service percentage scenario.

In Figure 4.39, it is possible to observe the difference between centre users and off-centre ones, where, in some cases, the former have twice the throughput, e.g., in Web Browsing and File Sharing. Again, with CoMP, the off-centre users' throughput increases, as shown in Figure 4.40 and Figure 4.41

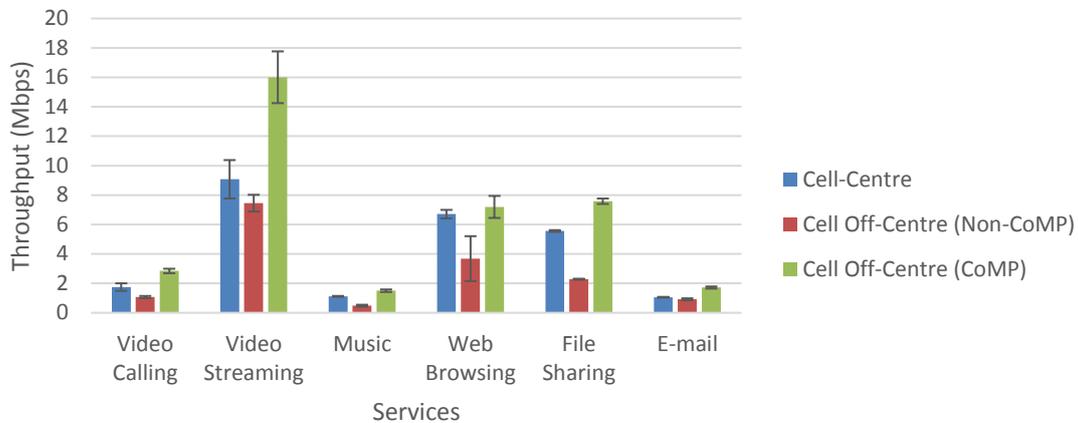


Figure 4.40. Centre users vs. off-centre ones without and with CoMP (connected to 2 BSs simultaneous) in a new service percentage scenario.

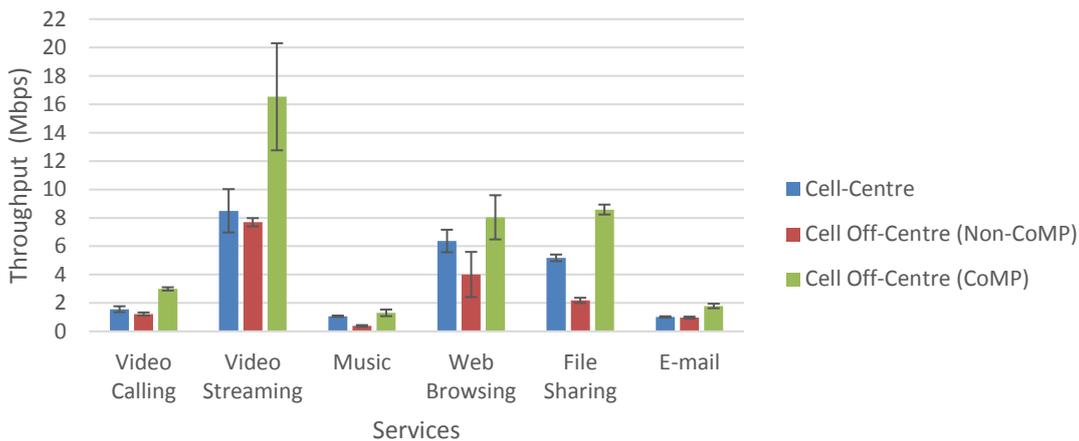


Figure 4.41. Centre users vs. off-centre ones without and with CoMP (connected to 2 or 3 BSs simultaneous) in a new service percentage scenario.

The total number of users in this scenario is the same as in the reference one, however, there is a concentration of users performing Video Streaming, therefore, some services such as Video Calling, Music, File Sharing and E-Mail have few active users, which translates into different results. In Figure 4.42, one presents the SINR in this scenario and results are similar to the ones obtained in the reference scenario.

The purpose of this scenario is to observe CoMP effects if the concentration of a given service exists. In Figure 4.43, it is possible to observe that the off-centre users' throughput increases compared with off-centre users without CoMP. In both cases, CoMP with two and three BSs present gains between 85% and 135% in five of the six services, whereas File Sharing presents gains exceeding 185%. Figure 4.44 and Figure 4.45 represent the impact of CoMP in centre users and off-centre ones that do

not perform CoMP, respectively. In centre users, the losses between the systems with CoMP with two BSs and those without CoMP are under 15%; in systems with CoMP with three BSs, results are a bit worse, however the worst service presents losses below 23%.

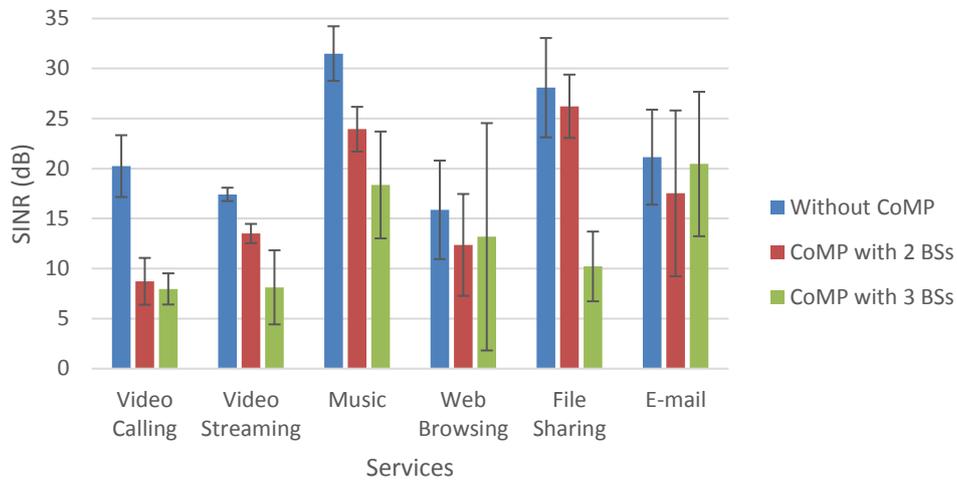


Figure 4.42. SINR without CoMP and with CoMP with 2 and 3 BSs in a new service percentage scenario.

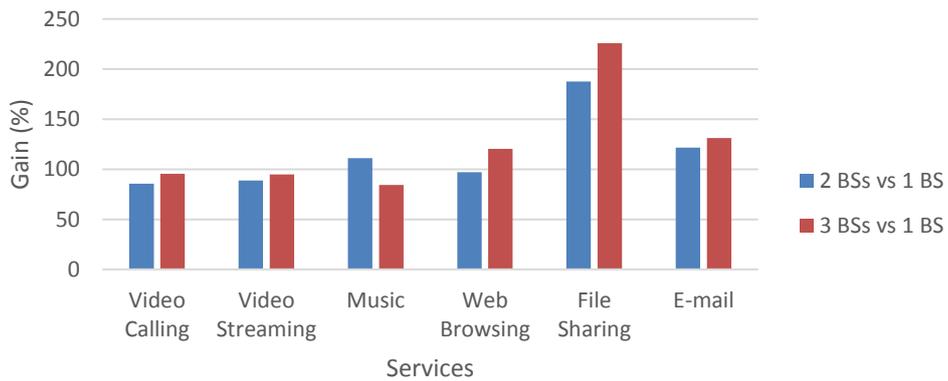


Figure 4.43. Throughput gain between off-centre users with and without CoMP in a new service percentage scenario.

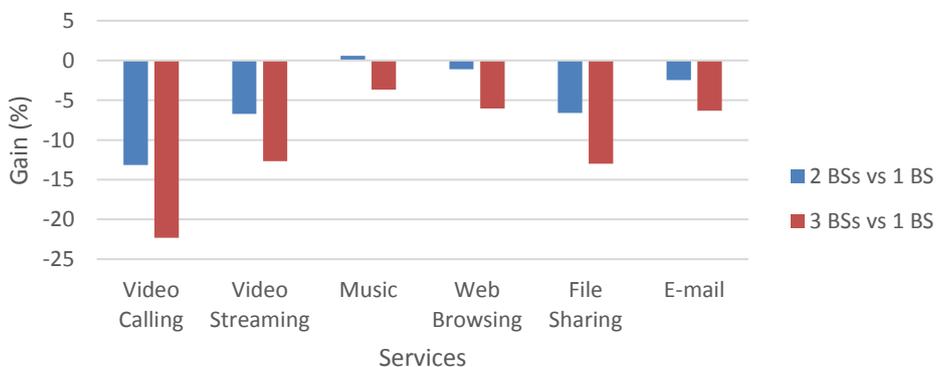


Figure 4.44. Throughput gain and loss between centre users with and without CoMP in a new service percentage scenario.

For off-centre users that do not perform CoMP the losses between the systems with CoMP with two BSs and without CoMP are below 32%. In systems with CoMP with three BSs results are similar, five of the six services having losses below 20%. Music users are the most affected ones, presenting losses of 45.8%, however their throughput is above 320 kbps.

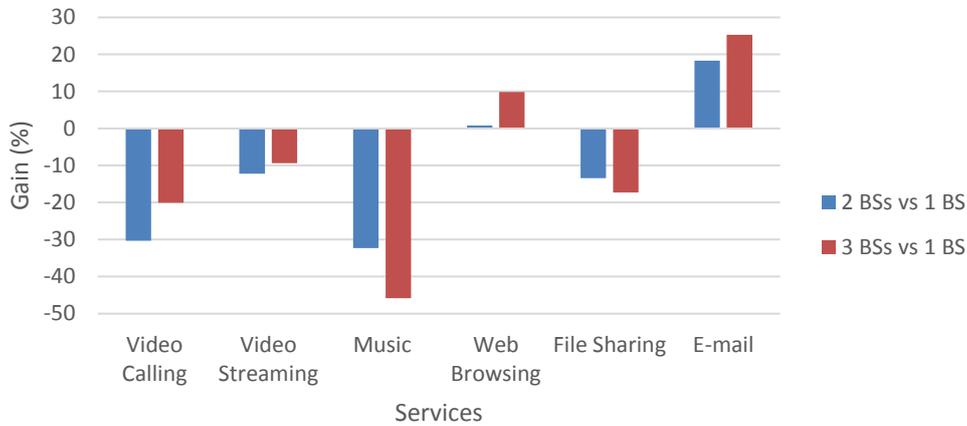


Figure 4.45. Throughput gain and loss between off-centre users who do not perform CoMP in system with CoMP and those in systems without CoMP in a new service percentage scenario.

Figure 4.46 presents an overview of the gains and losses in systems with and without CoMP; the benefits of CoMP are evident, where off-centre users exhibit gains above 100%, and centre and off-centre users that do not perform CoMP have losses below 12%.

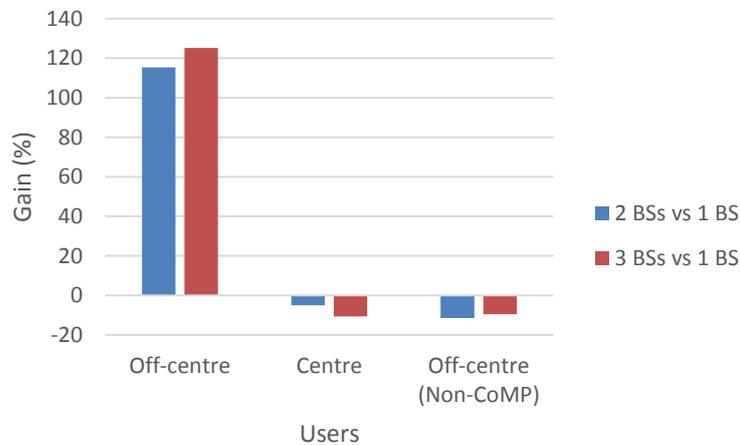


Figure 4.46. Throughput gain and loss between systems with and without CoMP in a new service percentage scenario.

4.4 CoMP Mid Load Analysis in Temporal Scenario

In this section, the number of geographic coordinates was increased, and subsequently the number of users also increases. A total of 150 geographic coordinates were generated, however 21 of them were

outside the service area boundaries, thus the analysis of the mid load scenario was performed for 129 locations. Due to the long simulation time, the tests for a mid load scenario were done only for one frequency band, the 2600 MHz one, because it offers the best capacity, covering 100 locations.

As expected, centre users have better throughput than off-centre ones in the network without CoMP, as seen in Figure 4.47. However, in this scenario the throughput decreases compared with the reference scenario. Video Streaming throughput is around 8 Mbps and in the reference scenario it is around 8.5 Mbps; another example is File Sharing, which in this scenario has a throughput below 5 Mbps and in reference one it is around 6 Mbps. As shown in Figure 4.48 and Figure 4.49, off-centre users who perform CoMP have, in general, better throughput than centre ones. As in Figure 4.47, throughput decreases for all services. In the reference scenario in systems with three BSs, the throughput of Video Streaming is around 14.6 Mbps, decreasing to 7.6 Mbps in this scenario. This scenario has a higher load, thus being normal that throughput decreases.

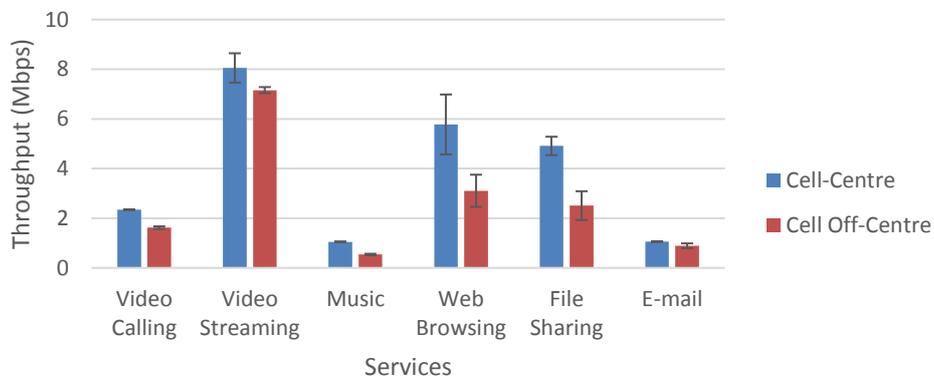


Figure 4.47. Centre vs. off-centre users without CoMP in mid load scenario.

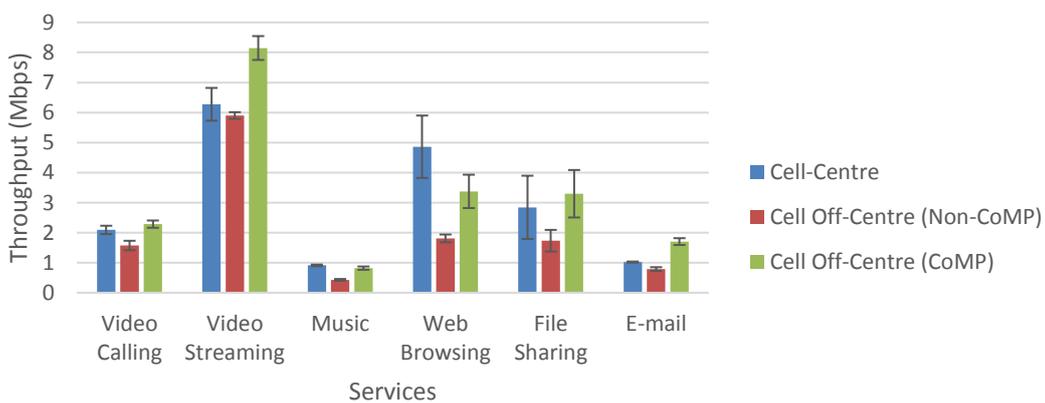


Figure 4.48. Centre users vs. off-centre ones without and with CoMP (connected to 2 BSs simultaneously) in mid load scenario.

It is also possible to observe that in some cases the systems with three BSs have worse throughput than those with two BSs. For example, in Video Streaming, which is a service with a high priority, off-centre users who perform CoMP and this service in systems with three BSs have a throughput lower than off-centre ones who perform CoMP in systems with two BSs. This phenomenon does not occur in low load scenarios, because there are more RBs available.

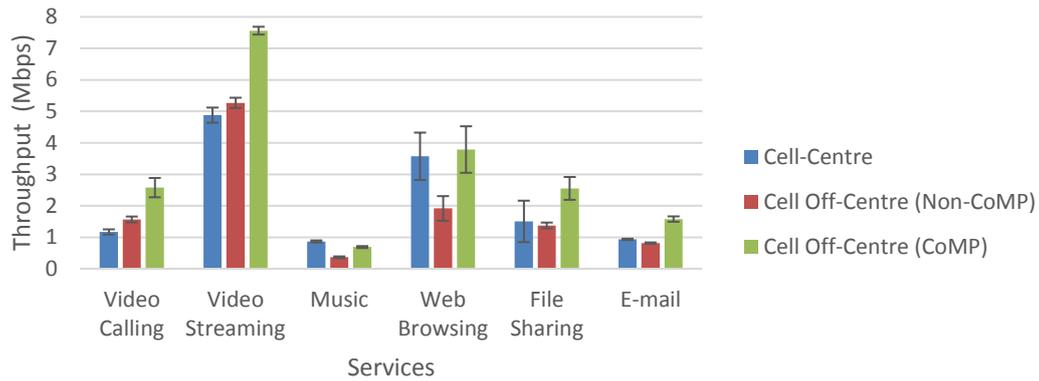


Figure 4.49. Centre users vs. off-centre ones without and with CoMP (connected to 2 or 3 BSs simultaneous) in mid load scenario.

SINR in this scenario has a behaviour equivalent to a low load scenario. Nonetheless, the standard deviation shows less oscillations, due to the existence of more load in the network, Figure 4.50.

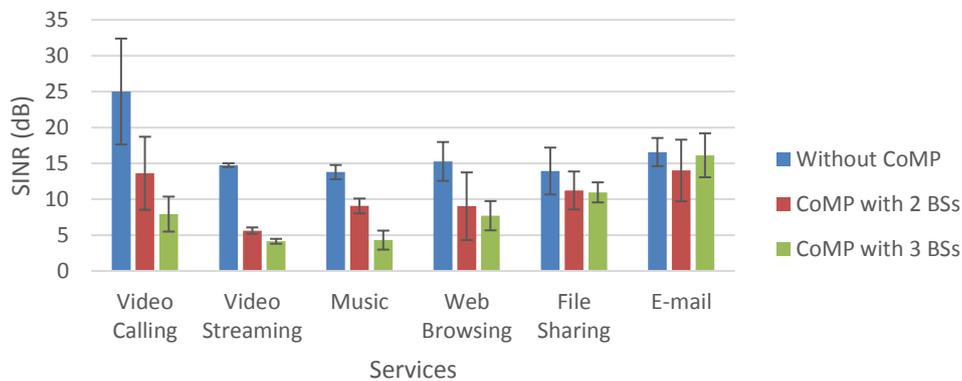


Figure 4.50. SINR without CoMP, and with CoMP with 2 and 3 BSs in a mid load scenario.

In Figure 4.51, one presents the gain between off-centre users who perform CoMP and the ones in systems without CoMP. In this scenario, gains are lower than in the low load scenario, and in three cases (Video Streaming, Music and File Sharing) the gains with three BSs are lower than with two, because CoMP with three BSs uses more RBs, and therefore the network becomes more loaded.

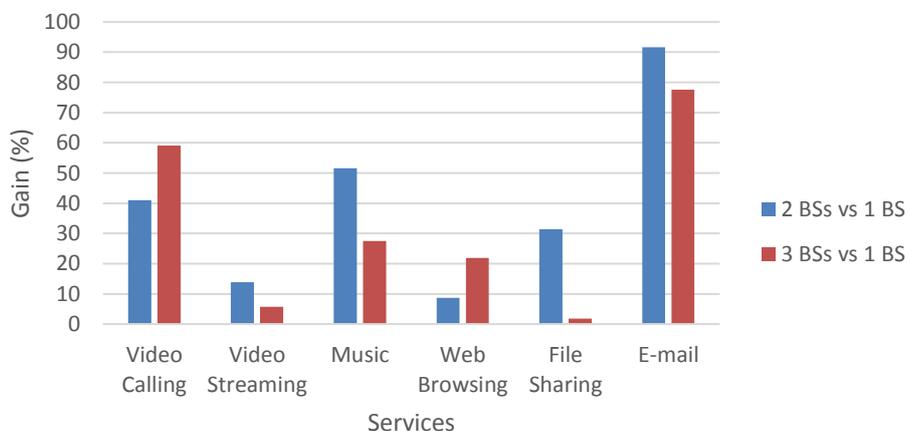


Figure 4.51. Throughput gain between off-centre users with and without CoMP in a mid load scenario.

Figure 4.52 and Figure 4.53 present the losses between centre users in systems with and without CoMP, and the losses between off-centre users who do not perform CoMP and the ones in systems without CoMP, respectively. It is perceived that in general with CoMP with three BSs there is a bigger loss than with two BSs, because the network is overload in the three BSs case.

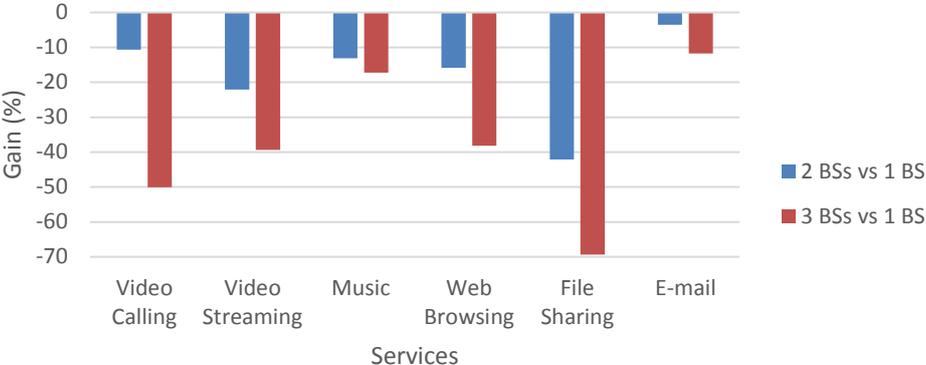


Figure 4.52. Throughput loss between centre users in the system with and without CoMP in a mid load scenario.

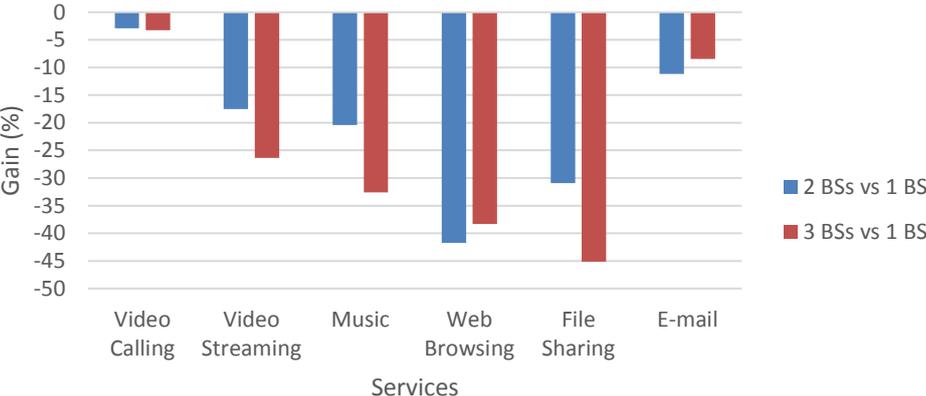


Figure 4.53. Throughput loss between off-centre users who do not perform CoMP in the system with CoMP and the ones in systems without CoMP in a mid load scenario.

Figure 4.54 presents throughput gain and losses between systems with and without CoMP.

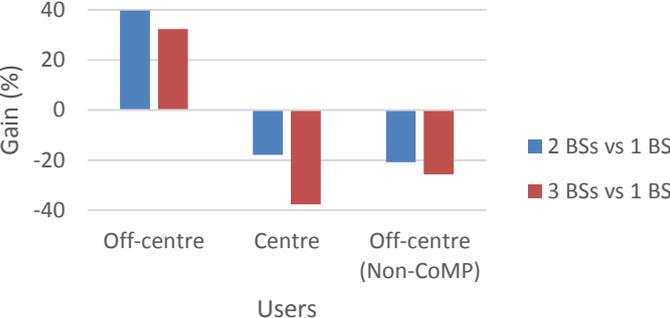


Figure 4.54. Throughput gain and loss between systems with and without CoMP in a mid load scenario.

In short, with this scenario, the most effective method is CoMP with two BSs, because it presents gains greater than losses. On average, off-centre users who perform CoMP have gains of 39.7%, centre ones have losses of 17.9%, and off-centre ones who do not perform CoMP losses of 20.8% in systems with CoMP with two BSs. In contrast, in CoMP with three BSs, off-centre users who perform CoMP have gains of 32.3%, centre ones have losses of 37.7% and off-centre ones who do not perform CoMP losses of 25.7%.

Chapter 5

Conclusions

This chapter finalises this work, summarising the main conclusions and pointing out aspects to be developed in future work.

The main goal of this thesis was the study of CoMP as a technique for the management of interference in off-centre users to improve their QoS. An initial analysis, in the city of Lisbon, was done in a static scenario to observe CoMP's possible gains. Afterwards, one analysed CoMP's behaviour in six BSs situated in Parque das Nações with low and mid loads.

In Chapter 1, a brief description of mobile communications systems evolution over time and of the growing consumer and traffic demand is provided, followed by a presentation on the motivation and contents of this thesis.

Chapter 2 presents a theoretical background on LTE's network architecture, radio interface, services, applications, and coverage and capacity aspects. Particular relevance is given to techniques for the management of interference, with special emphasis on CoMP. The two major categories of CoMP, JP and CS/CB, are explained in this chapter, which ends with a state of the art, providing some previous studies where CoMP was applied and on the impact the technique has on the network.

In Chapter 3, the model is fully described, with flowcharts for the most important algorithms and with detailed information on the parameters under study. The chapter starts with an overview of the developed model. Then, the parameters and the algorithms under study are presented, and justified with the relevant formulas and flowcharts. The considered parameters are SNR and SINR, antennas coverage, throughput and fading margin. Also, algorithms to classify the users and how they perform services over the time are presented. After that, model implementation is explained in its structural representation and in a more specific way, supported by diagrams. One describes the two versions (static and temporal) of the simulator using workflows, each one divided into three modules with different blocks that are justified. Finally, a model assessment is provided, confirming system stabilisation during the generation of users and providing the duration and number of simulations performed in each test.

Chapter 4 starts by providing a description of the scenarios used in this thesis, followed by the low and mid load scenarios analyses. This chapter contains all parameters used in the simulator such as, antenna parameters, services characteristics, frequency bands and bandwidths. The three frequency bands that were considered are the ones used by Portuguese mobile operators in LTE, 800, 1800 and 2600 MHz, each of them associated with a bandwidth that depends on the carrier frequency, i.e., 10, 20 and 20 MHz, respectively. Two different scenarios were considered for each version of the simulator. The first version of the simulator used 270 BSs distributed in Lisbon, and the second version used a smaller scenario in Parque das Nações with 6 BSs.

The static scenario was tested for the three frequency bands, with 399 users. Results prove that the frequency band with the best coverage is 800 MHz. In scenarios with more users (800 and 1800 MHz bands), CoMP may have a negative impact, since it can overload the network. CoMP performance was also tested, comparing its throughput with the best throughput connection. With this assumption, one intended to calculate the gain between systems with CoMP and those without it. In the 800 MHz band, systems with CoMP with two BSs have a gain of 47.8% and with three BSs of 73.4%. The 1800 MHz band, in systems with CoMP with two BSs have a gain of 42.5% and with three BSs of 62%. Finally, the

2600 MHz band, in systems with CoMP with two BSs present a gain of 32.6% and with three BSs of 45.8%. These results show CoMP capability, even though the scenario is not real, since it is a “snapshot” of the network. Therefore, for more reliable results a temporal scenario was tested.

The temporal scenario was tested for low and mid load scenarios. In a low load scenario, one analysed the variation of throughput for the different frequency bands. Note that, for this scenario, the condition to classify users was changed as well as the services percentage. As for the mid load test, only one frequency band in the reference scenario was used.

Simulations for the low load scenario for the different frequency bands presented different results for each one. The 800 MHz band is the one with better coverage, but with worst capacity, since its bandwidth is 10 MHz. With less RBs and more users, this frequency band presents the worst results. The gain between off-centre users who perform CoMP in systems with two BSs and in systems without CoMP, on average, is 20.9%. Centre users in systems with CoMP with two BSs can suffer losses of 15% compared with centre users in systems without CoMP. Furthermore, the loss between off-centre users who do not perform CoMP in systems with CoMP with two BSs and those in systems without CoMP is 44.5%. Results with CoMP with three BSs are even worse, because gains are even lower and losses bigger. The gain for off-centre users who perform CoMP is 16.8% and the loss for centre users and off-centre ones who do not perform CoMP is 30.2% and 50.1%, respectively. With this frequency band, CoMP does not offer any practical advantages, since losses overcome the gains.

The 1800 MHz band presents better results, nonetheless they are not optimal. The gain between the off-centre users who perform CoMP in systems with CoMP with two BSs and the ones in systems without CoMP, on average, is 58.7%. The loss between centre users in systems with CoMP with two BSs and those in systems without CoMP is 33.5%. As for the loss between off-centre users who do not perform CoMP in systems with CoMP with two BSs and the ones in systems without CoMP is 18.3%. For three BSs, the gain for off-centre users who perform CoMP is 60.6% and the loss for centre users and off-centre ones who do not perform CoMP is 48.6% and 25.2%, respectively. In this frequency band, gains between systems with CoMP with two and three BSs are similar, nonetheless losses with three BSs are more considerable, for this reason, in this frequency band, users should be connected to two BSs, in other words, they should perform CoMP with two BSs.

Finally, the 2600 MHz band is the one with the best capacity, leading to the best results in this scenario, since the gains of this band are large and losses minimal. The gain between off-centre users who perform CoMP in systems with CoMP with two BSs and the ones in systems without CoMP is 74%; with three BSs, the gain increases to 99.6%. As stated before, the losses are minimal: in centre users in systems with CoMP with two BSs compared with centre ones in systems without CoMP losses are 7.7%, and in CoMP with three BSs against centre users in systems without CoMP losses are 11.7%. The loss between off-centre users who do not perform CoMP in systems with CoMP with two BSs and the ones in systems without CoMP is 2.7%, and in systems with CoMP with three BSs rounds about 4%. In this frequency band, both systems have excellent results, due to the capacity of this band. However, with more load the scenario can change and, for this reason, a mid load scenario was tested.

Thereafter, the condition to perform CoMP was changed, i.e., initially, the threshold between centre and off-centre users is defined by a received power of -80 dBm, but in this scenario, all users with a received power above -100 dBm are considered centre ones. The purpose of this test is to observe network's behaviour if only edge-cell users perform CoMP. The test was performed with the 1800 MHz band, since in the reference scenario CoMP with three BSs indicates that the network starts to exceed its capacity. With less users to perform CoMP, less resources are used in the network. The results obtained for CoMP with two BSs are similar with the reference scenario, however with three BSs results are better in this scenario. The gain in off-centre users who perform CoMP in systems with two BSs is 51.2% and with three BSs is 84.2%. The loss in centre users in systems with CoMP with two BSs is 32% and with three BSs is 38%. Off-centre users who do not perform CoMP in systems with CoMP with two BSs, the loss is 18.4% and with three BSs is 16.15%. In comparison with the reference scenario, CoMP with three BSs has less impact in the system and cell-edge users better QoS.

The last test in the low load scenario was the video centric one. The frequency band was 2600 MHz, since it has the best capacity. Video Streaming is the most demanding resource services, since it has a high priority and maximum throughput, thus it is interesting to observe how the network behaves. Results in this scenario are similar to the ones obtained in the reference scenario, because gains are larger and losses are lower. The gain between off-centre users who perform CoMP in systems with two BSs and the ones in systems without CoMP is 115.3%, and with three BSs is 125.3%. The loss between centre users in systems with CoMP with two BSs and the ones in systems without CoMP is 4.9% and with three BSs is 10.7%. At last, the loss between off-centre users who do not perform CoMP in system with two BSs and the ones in systems without CoMP is 11.5%, and with three BSs is 9.6%. Once again, CoMP brings considerable benefits, and it shows that, with the concentration of the most demanding service, CoMP can be efficient in a low load scenario.

In the end, one considered a mid load scenario, with the network using the 2600 MHz band. As simulations taken a long time, the increase in the number of locations leads to longer simulations. As expected, with more load gains decrease and losses increase. Off-centre users who perform CoMP have gains of 39.7%, centre ones have losses of 17.9% and off-centre ones who do not perform CoMP losses of 20.8% in systems with CoMP with two BSs. In contrast, for the system with CoMP with three BSs, off-centre users who perform CoMP have gains of 32.3%, centre ones have losses of 37.7% and off-centre ones who do not perform CoMP losses of 25.7%. With more load, CoMP with three BSs is no longer effective, however the systems with CoMP with two BSs have positive results.

To summarise, CoMP in low load scenarios for 2600 MHz frequency band has excellent results in systems with two BSs and three BSs. In the 1800 MHz frequency band, CoMP should be only used with two BSs, because with three BSs it has some losses. However, if cell-edge users are the only ones to perform CoMP, results are good for both cases, i.e., CoMP with two and three BSs. In a low load scenario, the only frequency band that should not perform CoMP is the 800 MHz one, since gains are lower than losses. In a mid load scenario, the 2600 MHz band has a positive performance in systems with CoMP with two BSs. With this frequency band, CoMP with three BSs is not recommended.

Regarding future work, it is interesting to include a CoMP UL scenario. All tests performed in this thesis considered a CoMP DL scenario, because the simulator is based on previous theses, and to develop these two scenarios would involve more time than a M.Sc. thesis duration. In UL, CoMP is expected to have better performance, thus it is a stimulating feature to include in the model. Simulations are very slow with mid load, therefore the code should be optimised, so that in the future it is possible to test mid and high load scenarios more easily. Finally, interference should be mitigated with a technique such as DPS, with the objective to achieve better results. In this thesis, one has not included a technique for mitigation of interference, because simulation time would be increased significantly.

Annex A

Link Budget

This annex presents a brief description of the link budget equations, considering the losses between transmitter and receiver.

The link budget equations have an important role, being possible to calculate the power transmitted and received and the total path loss. All the equations presented in this annex were extracted from [Corr16].

The power available at receiving antenna is given by:

$$P_r[\text{dBm}] = P_{EIRP}[\text{dBm}] + G_r[\text{dBi}] - L_{p,total}[\text{dB}] \quad (\text{A.1})$$

where:

- P_{EIRP} : effective isotropic radiated power;
- G_r : gain of the receiving antennas;
- $L_{p,total}$: path loss.

The EIRP depends on the link. In DL, it is defined as follows:

$$P_{EIRP}[\text{dBm}] = P_{Tx}[\text{dBm}] - L_c[\text{dB}] + G_t[\text{dBi}] \quad (\text{A.2})$$

where:

- P_{Tx} : transmitter output power;
- L_c : losses in cable between transmitter and antenna;
- G_t : gain of the transmitting antennas.

For UL, it is expressed by:

$$P_{EIRP}[\text{dBm}] = P_{Tx}[\text{dBm}] - L_u[\text{dB}] + G_t[\text{dBi}] \quad (\text{A.3})$$

where:

- L_u : losses due to user.

The power at the receiver, in DL, is given by:

$$P_{Rx}[\text{dBm}] = P_r[\text{dBm}] - L_u[\text{dB}] \quad (\text{A.4})$$

where:

- P_{Rx} : power at the input of the receiver.

The power at the receiver, in UL, is given by:

$$P_{Rx}[\text{dBm}] = P_r[\text{dBm}] - L_c[\text{dB}] \quad (\text{A.5})$$

The total path loss can be calculated by:

$$L_{p,total}[\text{dB}] = L_p[\text{dB}] + M_{FF}[\text{dB}] + M_{SF}[\text{dB}] \quad (\text{A.6})$$

where:

- L_p : path loss from the COST 231 Walfisch-Ikegami model;
- M_{FF} : fast fading margin;

- M_{SF} : slow fading margin.

SNR can be computed using the signal and noise power available at the receiver antenna:

$$\rho_N[\text{dB}] = P_{Rx}[\text{dBm}] - N[\text{dBm}] \quad (\text{A.7})$$

where:

- N : Average noise power at the receiver.

The average noise power is expressed by:

$$N[\text{dBm}] = -174 + 10 \log(N_{RB} \times B_{RB}[\text{Hz}]) + F[\text{dB}] \quad (\text{A.8})$$

where:

- N_{RB} : number of RBs;
- B_{RB} : bandwidth of one RB, which is 180 kHz;
- F : noise figure.

SINR can be calculated by following expression:

$$\rho_{IN}[\text{dB}] = 10 \log\left(\frac{P_{Rx}[\text{mW}]}{N[\text{mW}] + I[\text{mW}]}\right) \quad (\text{A.9})$$

where:

- I : Interference power at the receiver.

Annex B

COST 231 Walfisch-Ikegami

This annex provides a description of the propagation model used to determine the path loss in Lisbon (urban environment).

In this thesis to calculate the path loss was used the COST 231 Walfisch-Ikegami propagation model, which is applied with urban and sub-urban environments. Figure B.1 illustrates some parameters used in this model. This annex is based on [Corr16].

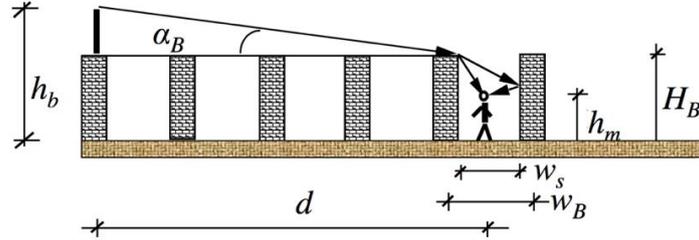


Figure B.1. COST 231 Walfisch-Ikegami model parameters (extracted from [Corr16]).

For LoS propagation in a street, the path loss is given by:

$$L_p[\text{dB}] = 42.6 + 26 \log d_{[\text{km}]} + 20 \log f_{[\text{MHz}]}, d > 0.02 \text{ km} \quad (\text{B.1})$$

where:

- d : distance between the BS and the UE;
- f : signal carrier frequency.

For all other cases, path loss is defined as:

$$L_p[\text{dB}] = \begin{cases} L_0[\text{dB}] + L_{rt}[\text{dB}] + L_{rm}[\text{dB}], & L_{rt} + L_{rm} > 0 \\ L_0[\text{dB}] & , L_{rt} + L_{rm} \leq 0 \end{cases} \quad (\text{B.2})$$

where:

- L_0 : free space propagation path loss;
- L_{rt} : attenuation due to propagation from the BS to the last rooftops;
- L_{rm} : attenuation due to diffraction from the last rooftop to the UE.

The free space propagation path loss is given by:

$$L_0[\text{dB}] = 32.44 + 20 \log d_{[\text{km}]} + 20 \log f_{[\text{MHz}]} \quad (\text{B.3})$$

The propagation from the BS to the last rooftops is obtained from:

$$L_{rt}[\text{dB}] = L_{bsh}[\text{dB}] + k_a + k_d \log d_{[\text{km}]} + k_f \log f_{[\text{MHz}]} - 9 \log w_B[\text{m}] \quad (\text{B.4})$$

where:

- L_{bsh} : loss due to the height difference between rooftop and the antennas;
- k_a : increase of path loss for the BS antennas below the rooftops of the adjacent buildings;
- k_d : controls the dependence of the multi-screen diffraction loss versus distance;
- k_f : controls the dependence of the multi-screen diffraction loss versus frequency;
- w_B : distance between buildings' centres.

The loss due to the height difference between rooftop and the antennas is obtained from:

$$L_{bsh[\text{dB}]} = \begin{cases} -18 \log(h_{b[m]} - H_{B[m]} + 1), & h_b > H_B \\ 0 & , h_b \leq H_B \end{cases} \quad (\text{B.5})$$

where:

- h_b : height of the BS antenna;
- H_B : height of the buildings.

Other correction factors are obtained from:

$$k_a = \begin{cases} 54 & , h_b > H_B \\ 54 - 0.8(h_{b[m]} - H_{B[m]}) & , h_b \leq H_B \wedge d \geq 0.5 \text{ km} \\ 54 - 1.6(h_{b[m]} - H_{B[m]})d_{[\text{km}]} & , h_b \leq H_B \wedge d < 0.5 \text{ km} \end{cases} \quad (\text{B.6})$$

$$k_d = \begin{cases} 18 & , h_b > H_B \\ 18 - 15 \frac{h_{b[m]} - H_{B[m]}}{H_{B[m]}} & , h_b \leq H_B \end{cases} \quad (\text{B.7})$$

$$k_f = \begin{cases} -4 + 0.7 \left(\frac{f_{[\text{MHz}]}}{925} - 1 \right), & \text{urban and suburban scenarios} \\ -4 + 1.5 \left(\frac{f_{[\text{MHz}]}}{925} - 1 \right), & \text{dense urban scenarios} \end{cases} \quad (\text{B.8})$$

The loss due to diffraction from the last rooftop to the UE is given by:

$$L_{rm[\text{dB}]} = -16.9 - 10 \log w_{s[m]} + 10 \log f_{[\text{MHz}]} + 20 \log(H_{B[m]} - h_{m[m]}) + L_{ori[\text{dB}]} \quad (\text{B.9})$$

where:

- w_s : width of the streets;
- h_m : height of the UE.

The loss due to the street orientation is obtained from:

$$L_{ori} = \begin{cases} -10.0 + 0.354 \phi_{[^\circ]} & , 0^\circ < \phi < 35^\circ \\ 2.5 + 0.075(\phi_{[^\circ]} - 35), & 35^\circ < \phi < 55^\circ \\ 4.0 + 0.114(\phi_{[^\circ]} - 55), & 55^\circ < \phi < 90^\circ \end{cases} \quad (\text{B.10})$$

where:

- ϕ : angle of incidence of the signal in the buildings, on the horizontal plane.

The COST 231 Walfisch-Ikegami model is valid for the following values:

- $f_{\text{[MHz]}} \in [800, 2000]$;
- $d_{\text{[km]}} \in [0.02, 5]$;
- $h_{b\text{[m]}} \in [4, 50]$;
- $h_{m\text{[m]}} \in [1, 3]$;

The standard deviation of the model takes values between [4, 7] dB, and the error increases when h_b decreases relative to H_B . Although the presented frequency range does not contain all the frequency bands analysed in this thesis, it is possible to use this model. However, one should understand that the results may present higher relative errors than expected.

Annex C

SNR and Throughput

This annex provides an overview of the SNR and the throughput in LTE.

This annex is based on [Alme13], considering three expressions derived from three different modulation types in DL: QPSK, 16-QAM and 64-QAM. In order to have a more realistic approach to a real network, were chosen three Modulation and Coding Scheme (MCS) with the following coding rates:

- QPSK with a coding rate of 1/3;
- 16-QAM with a coding rate of 1/2;
- 64-QAM with a coding rate of 3/4.

For 2x2 MIMO, QPSK and coding rate of 1/3, throughput per RB and the corresponding SNR in the DL can be given by:

$$R_{b[\text{bps}]} = \frac{2.34201 \times 10^6}{14.0051 + e^{-0.577897\rho_{N[\text{dB}]}}} \quad (\text{C.1})$$

$$\rho_{N[\text{dB}]} = -\frac{1}{0.577897} \ln\left(\frac{2.34201 \times 10^6}{R_{b[\text{bps}]}} - 14.0051\right) \quad (\text{C.2})$$

For 2x2 MIMO, 16-QAM and coding rate of 1/2, throughput per RB and the corresponding SNR in the DL can be given by:

$$R_{b[\text{bps}]} = \frac{47613.1}{0.092628 + e^{-0.295838\rho_{N[\text{dB}]}}} \quad (\text{C.3})$$

$$\rho_{N[\text{dB}]} = -\frac{1}{0.295838} \ln\left(\frac{47613.1}{R_{b[\text{bps}]}} - 0.092628\right) \quad (\text{C.4})$$

For 2x2 MIMO, 64-QAM and coding rate of 3/4, throughput per RB and the corresponding SNR in the DL can be given by:

$$R_{b[\text{bps}]} = \frac{26405.8}{0.022019 + e^{-0.24491\rho_{N[\text{dB}]}}} \quad (\text{C.5})$$

$$\rho_{N[\text{dB}]} = -\frac{1}{0.24491} \ln\left(\frac{26405.8}{R_{b[\text{bps}]}} - 0.0220186\right) \quad (\text{C.6})$$

Annex D

User's Manual for MapInfo

This annex provides an overview of the simulator, along with an explanation on how to run a simulation.

When UMTS_Simul.mbx is executed, it opens a window, as it can be observed in Figure D.1, asking for the following files:

- DADOS_Lisboa, which holds information about the city of Lisbon, namely its districts;
- ZONAS_Lisboa, which contains information about the areas characterisation.

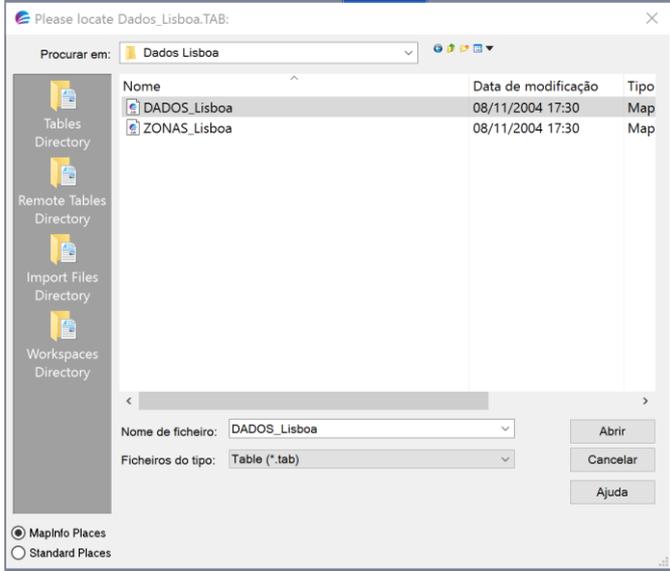


Figure D.1. Generated window for selecting the information of the city of Lisbon.

Thereafter, one should access the tab called “System” on the upper bar of MapInfo and select the “ACMIL” option. Inside of this option there are eight options: “Propagation Model”, “Network Settings”, “Traffic Properties”, “Services”, “CoMP Options”, “Insert Users”, “Deploy Network” and “ACMIL Run”.

The “Propagation Model” window is presented in Figure D.2. It provides the appropriate choices to select the propagation model parameters such as the height of the BS antennas, the height of the buildings, street width, distance between buildings’ centres, departing angle from the closest building, height of the UE and type of environment (urban or dense urban).

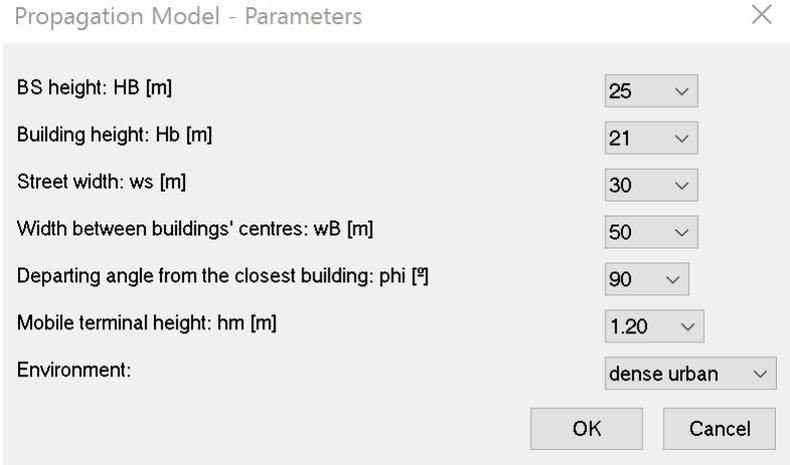


Figure D.2. Propagation model parameters.

The “Network Settings” window is represented in Figure D.3. This option allows to choose more parameters for the scenario demanded.

ACMIL Settings

Reference Service [Mbit/s] : 0,5

Antenna Parameters

- Horizontal Half-Power Beam Width [Deg] : 63
- Vertical Half-Power Beam Width [Deg] : 4,2
- Front-to-back Attenuation [dB] : 50
- Sidelobe Attenuation [dB] : 20
- Electrical Downtilt [Deg] : 6
- Mechanical Downtilt [Deg] : 0
- BS Antenna Gain [dBi] : 17,5

DL Transmission Power [dBm] : 43

UE Antenna Gain [dBi] : 1

User Losses [dB] : 1,5

Cable Losses [dB] : 2

Noise Factor [dB] : 7

Alfa r [dB] : 3

MIMO order : 2

Slow Fading Margin [dB] : 8,8

Bandwidth [MHz] : 20

Frequency Band [MHz] : 2600

Resource Allocation

- Localised
- Distributed

OK Cancel

Figure D.3. ACMIL settings.

In the “Traffic Properties” window is possible to select the priority of services and the minimum and maximum throughput requested for each service considered. This window can be observed in Figure D.4.

Traffic Properties

Type of Service	Priority	Bit Rate [Mbit/s]	
		Min.	Max
Voice	1	0,0053	0,064
Video Calling	2	0,064	2
Video Streaming	3	0,5	13
Music	4	0,016	0,32
Web Browsing	5	0,4	6
File Sharing	6	0,4	6
E-Mail	7	0,4	1

OK Cancel

Figure D.4. Traffic Properties.

The “Services” window allows to choose colours for the different services, as can be seen in Figure D.5.

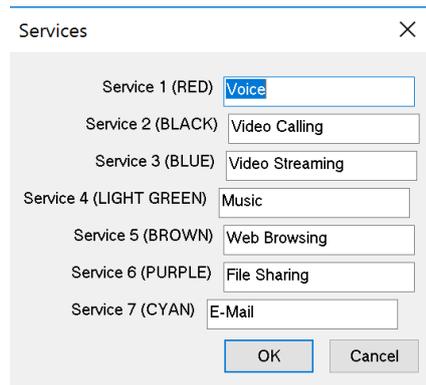


Figure D.5. Services options.

In the “CoMP Options” window is possible to choose the simulation and pause duration and the maximum number of BSs that a user can be connected. All options are represented in Figure D.6.

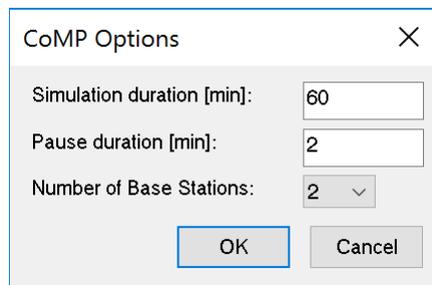


Figure D.6. CoMP options.

Finally, “Insert Users” window becomes available, being selected in order to import a .txt file containing the users positioning along the city of Lisbon or the Parque das Nações area. After that, the “Deploy Network” option also becomes selectable, and it allows to choose the file with BSs’ identification and position. When the “ACMIL Run” is executed, it is generated inside of temp5 folder two files, the data.dat and definitions.dat. These two files are subsequently read by third module of the simulator.

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