



Small Cell Deployment Evaluation on LTE

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To all my family.

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Abstract

This dissertation focuses on the study of a realistic scenario where a small area of a cluster is analysed with and without small cells deployment. The network is tested in terms of performance, analysing coverage, capacity and interference with all main LTE elements. Different characteristic scenarios are put into test, where one distributes users evenly throughout the area under analysis and the other concentrate users in critical coverage zones over special event days. The small cells are strategically deployed over this critical zones and their impact is evaluated for both scenarios. With no surprise, small cells prove to be extremely useful for a macro-cell based network, when various users concentrate in the same region, delivering a much higher network throughput and serving significantly more users in each deployment. Although a capacity improvement of small cells has been verified, also varied scenarios were tested. For example, frequency reuse schemes were applied and their performance was assessed. Over a well-planned network, on an overall level, these schemes prove to be less efficient than those already used in nowadays, but good results were obtained from the global interference cancelation analysis viewpoint.

Keywords

Small Cells, LTE, Heterogeneous Networks, Urban Scenario, FRS, Interference

Resumo

O objectivo principal deste trabalho consistiu em analisar uma pequena área específica de uma rede real com e sem células pequenas. Testou-se a rede em termos de desempenho, analisando cobertura, capacidade e interferência com todos os elementos principais implementados do LTE. Testaram-se diferentes cenários característicos, em que no primeiro se distribui utilizadores uniformemente pela rede e no segundo os utilizadores se concentraram em zonas críticas, semelhante ao que acontece num dia de um evento especial. As células pequenas foram colocadas estrategicamente nessas zonas críticas e o impacto da sua implementação foi avaliado. Sem surpresas, as células pequenas provam ser uma ferramenta extremamente útil para uma rede de macro-células já implementada, principalmente para o segundo cenário, conectando um muito maior número de utilizadores e produzindo um débito de dados por segundo instantâneo total na rede muito bom. Embora a otimização em termos de capacidade tenha sido verificada, alguns outros cenários foram também testados. Por exemplo, esquemas de reutilização de frequências foram aplicados e o seu desempenho foi aferido. Numa rede bem planeada, como a que se colocou em estudo, estes esquemas provam ser ineficazes em comparação a não utilização de nenhum esquema implementado. No entanto, bons resultados foram obtidos do ponto de vista do cancelamento de interferência.

Palavras-chave

Células pequenas, LTE, Redes Heterogéneas, Cenário Urbano, FRS, Interferência

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List of Acronyms

3GPP	3 rd Generation Partnership Project
ACIR	Adjacent Channel Interference at the Receiver
AMC	Adaptive Modulation and Coding
BF	Beamforming
CoMP	Coordinated Multipoint
CP	Cyclic Prefix
DeNB	Donor eNB
DL	Downlink
eICIC	enhanced ICIC
eMBMS	evolved Multimedia Broadcast Multicast Service
eNodeB	evolved Node B
eNB	eNodeB
EPC	Evolved Packet Core
E-UTRAN	Evolved UTRAN
FDD	Frequency Division Duplexing
FFR	Fractional Frequency Reuse
GSM	Global System for Mobile Communications
HeNB	Heterogeneous eNB
HeNB-GW	Home eNB Gateway
HSS	Home Subscription Server
IC	Interference Cancellation
ICIC	Inter-Cell Interference Coordination
IRC	Interference Rejection Combining
LoS	Line of Sight
LTE	Long Term Evolution
MBSFN	Multicast/Broadcast Single Frequency Network
MCL	Minimum Coupling Loss
MIMO	Multiple-Input and Multiple-Output
MME	Mobility Management Entity
MRC	Maximal Ratio Combining
MT	Mobile Terminal
MU-MIMO	Multi-User MIMO
NLoS	Non Line of Sight

OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PAPR	Peak to Average Power Ratio
PBCH	Physical Broadcast Channel
PCC	Policy and Charging Control
PCRF	Policy and Charging Resource Function
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PRACH	Physical Random Access Channel
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
P-GW	Packet Data Network Gateway
P-SCH	Primary Synchronisation Signals
S-SCH	Secondary Synchronisation Signals
SINR	Signal to Interference plus Noise Ratio
SNR	Signal Noise Ratio
QoS	Quality of Service
RAN	Radio Access Network
RB	Resource Block
RN	Relay Node
RS	Reference Signal
SAE	System Architecture Evolution
SAE GW	SAE Gateway
SC-FDMA	Single Carrier Frequency Division Multiple Access
SINR	Signal to Interference Noise Ratio
SU-MIMO	Single-User MIMO
S-GW	Serving Gateway
TDD	Time Division Duplexing
TDM	Time Division Multiplexing
TE	Terminal Equipment
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UTRAN	UMTS Terrestrial Radio Access Network
UMTS	Universal Mobile Communications Systems

List of Symbols

Δf	Subcarrier spacing
μ	Average value
$\rho_{IN\ i,n}$	Signal interfering plus noise ratio for a macro-cell user i on a subcarrier n
$\rho_{IN\ f,n}$	Signal interfering plus noise ratio for a small cell user i on a subcarrier n
ρ_N	Signal noise ratio
σ	Standard deviation
ϕ	Angle of incidence of the signal in the buildings, in the horizontal plane
a_{pd}	Average power decay
d	Distance between the BS and the MT
$d_{2D,indoor,}$	Distance between user and base station that is indoor the apartment the base station is installed
f	Carrier frequency
F	Serving small cell
F'	Neighbour small cell
F_N	Noise figure at the receiver
G_t	Gain of the transmitting antenna
G_r	Gain of the receiving antenna
h_b	Base station height
H_B	Buildings height
h_m	Height of the mobile terminal
i	Number of outdoor walls of apartments penetrated between user and base station
I	Total interference power at the receiver
I_j	Interference power received from transmitter j
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 pathloss
L_{bsh}	Loss due to the height difference between the rooftop and the antennas
L_c	Losses in the cable between the transmitter and the antenna
L_{iw}	Attenuation of indoor wall between apartments
$L_{ow,j}$	Attenuation of outdoor wall of apartment
L_{ori}	Street orientation loss

L_p	Path loss
$L_{p,COST\ 231\ WI}$	Path loss from the COST 231 Walfisch-Ikegami Model
$L_{p,environment}$	Path loss from the user environment
L_{rm}	Loss between the BS and the last rooftop
L_{rt}	Loss between the last rooftop and the MT
L_u	Losses due to the user's body
m	Order of the modulation considered, depends on the link condition
M	Macro-cell serving the user
M'	Neighbour macro-cell
M_{SF}	Slow fading margin
n	Number of floors penetrated between user and base station
N	Average noise power at the receiver
N_0	White noise power spectral density
N_{RB}	Number of RB allocated to the user
$N_{streams}$	Number of streams, in case of MIMO
N_t	Number of interfering signals reaching the receiver
N_U	Number of users served by the base station
N_{sc}^{RB}	Number of subcarriers per resource block, depends on subcarrier spacing being the normal value 12 (for 15 kHz of subcarrier spacing)
N_{RB}^u	Number of user resource blocks, depends on how much RBs the eNodeB will allocate for the current user
N_{symb}^{SF}	Number of symbols per sub-frame, depends on the type of CP deployed being 14 symbols for normal CP or 12 for extended CP
N_z	Number of samples
$P_{i,F,n}$	Received power by user i of neighbouring small cell on subcarrier n
$P_{i,M,n}$	Received power by user i of serving macro-cell on subcarrier n
$P_{i,M',n}$	Received power by user i of neighbouring macro-cell on subcarrier n
PL	Path loss due to the small cell propagation model
P_r	Power available at the receiving antenna
$P_{r,min}$	Power sensitivity at the receiver antenna
P_t	Power fed to the antenna
P_{Rx}	Receiver input power
q	Number of indoor walls between apartments penetrated between user and base stations
R	Distance between user and base station
R_{max}	Maximum range of coverage of a cell
$R_{b,BS}$	Total throughput transmitted by the base station
$R_{b,T}$	Total throughput for a single user
$R_{b,T,i}$	Total throughput for the user i
$R_{b,i}$	Throughput for RB i calculated based on signal interference plus noise ratio

T_{SF}	Sub-frame period, 1 ms for LTE
w_B	Buildings separation distance
w_s	Width of the street
\bar{Z}	Average value of the population Z
z_i	Value of sample i

List of Software

Microsoft Word	Text Editor Software for overall thesis writhing
Microsoft Excell	Calculation and Graphic software
Microsoft Visio	Schematic generating software to design diagrams and figures
MapInfo	Geographic Information System software
MapBasic	Programming Software to compile and create programs over the same name programing language.
Borlands C++ Builder 6	C++ Integrated Development Environment Software

Chapter 1

Introduction

This chapter introduces this thesis theme, situating the matter under study on a global aspect and concept. The motivation and structure of the thesis are also presented.

1.1 Overview

Over the last few years, the world watched the mobile communications technology development and its immeasurable growth in terms of importance and usability. The number of connected devices has grown exponentially over the recent years, where the diversification of smart phones, data dongles or mobile communication integrated tablet devices keeps on growing. In an everyday more connected world, societies accept mobile communications as one of the most important milestones to invest. The present technology taken this investment, and profited from the most advanced mobile communications system the world has ever seen. The record levels of performance achievable by present day systems seduced operators to high level investments as a response to the continuous growth of data capabilities required for today's network.

In Europe in particular, there has always been through time a huge crescent tendency of using mobile communication on a regular day basis. The described growth was already verified in the past and many systems were developed to address this necessity, namely the Global System for Mobile Communications (GSM), referred commonly as 2nd Generation (2G) technology, Universal Mobile Communications Systems (UMTS), in the latest High Speed Packet Access Evolved (HSPA+) version, often referred as the 3rd Generation (3G) technology, and finally the well-known Long Term Evolution (LTE) also often referred as the 4th Generation (4G) technology, [Moto10]. A comparison among these 3 technologies is presented in Figure 1-1 (a), where the perspective of 2G being replaced by 3G will start to be a reality in future years. The same will happen between 3G and 4G in a more distant future. This figure also confirms the expected growth of mobile communications devices. The same goes for Figure 1-1 (b), where the same vision is done for the volume of data. Notice that still having a lower number of devices in 2012, 4G already presents a 76% volume of all mobile communications data. In the future, data growth is expected to grow exponentially, and 4G will keep on being leader on overall volume of data.

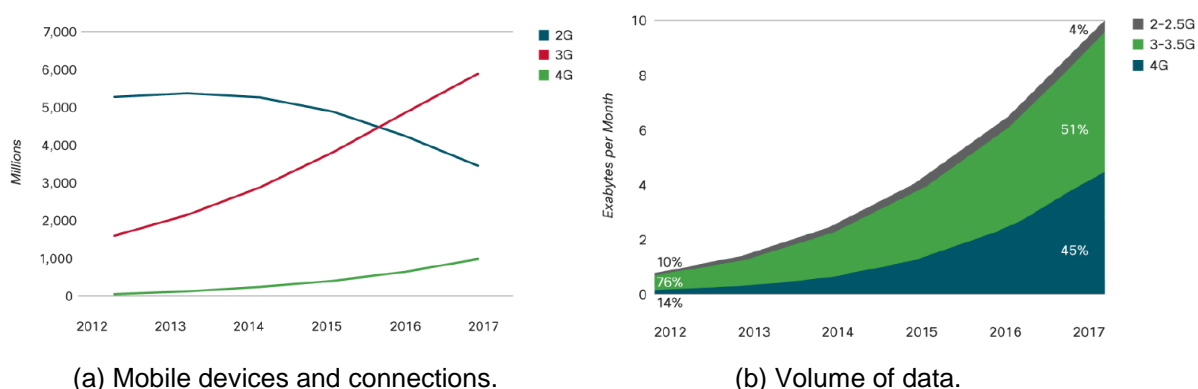


Figure 1-1 Global results of 2G, 3G and 4G in different aspects (extracted from [Cisc13]).

The same growth in the number of connect mobile devices is also observed in a global view by the growth of data transmission over mobile communications as seen in Figure 1-1 (b). This is a consequence of 3G, which enabled the mobile devices to use heavy data services, resulting in users to exploit this with a rapid growth rate. One of LTE's major motivations was to address this rapid data

growth. One can observe this growth in a global view in a more detail view in Figure 1-2, where 4 main services are shown: mobile file sharing, mobile machine to machine (M2M), mobile Web/Data and mobile video. This results on categorising the mobile video service as one of the biggest trends for the future for mobile communications, [Cisc13].

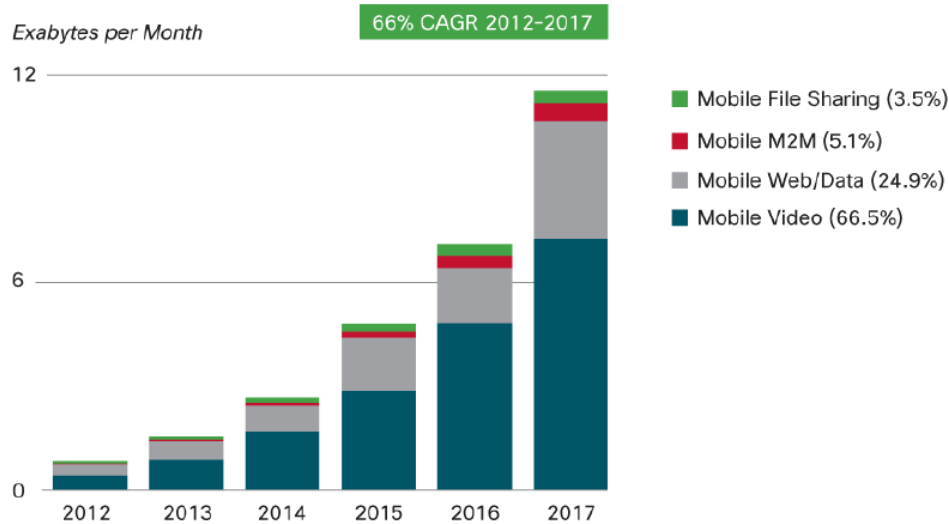


Figure 1-2 Global mobile data traffic growth per year (adapted from [Cisc13]).

The future of LTE is already known and 3GPP is already outlining future concept technologies. LTE was first released on the 3GPP Release 8 and further advancements were presented on Release 9. Release 10 introduced LTE Advanced (LTE-A), the next evolution phase for LTE, where many new features are first mentioning, such as carrier aggregation and enhanced multi-antenna transmission based on an extended more flexible structure of reference signals, for a higher number of antennas than before. Until Release 11, the LTE-A concept has been overdeveloped but beyond this release, new concept and requirements have start being identified. Sometimes referenced as LTE-B, [Eric13], Release 12 and possible further ones start to present new potential technologies and grasp different concepts of what is already known. A schematically evolution of the Releases by 3GPP is shown in Figure 1-3. This thesis only considers the LTE technology with all the features defined for it, ignoring all evolution concepts beyond it.

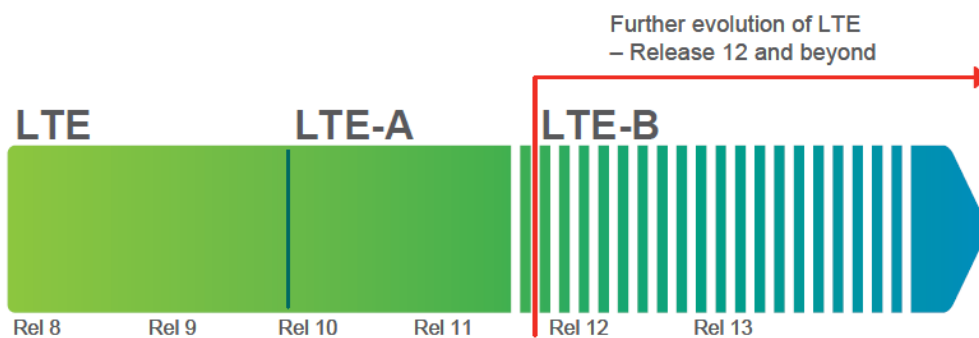


Figure 1-3 The evolution of LTE beyond LTE-A (extracted from [Eric13]).

The technology feature under study in this thesis, applied to LTE, is the one of small cells. These low

power base stations provide a replication of a macro-cell layer, but with an extremely more limited range of coverage. Although cover is shorter, small cells can still provide more resources to users, thus improving network capacity and usability. Various types of installations are possible for small cells and there is a very big variety of scenarios small cell can actually prove to be an extremely cost effective optimisation. In LTE, there is a need to study and explore these new features. The small cells subject will be continuously referred and detailed over this thesis. There is a global world tendency to use small cells as presented in Figure 1-4: the authors define public access small cells as small base station devices that form an integral part of the mobile operator's 3G and 4G networks and are therefore accessible to all the operator's customers.

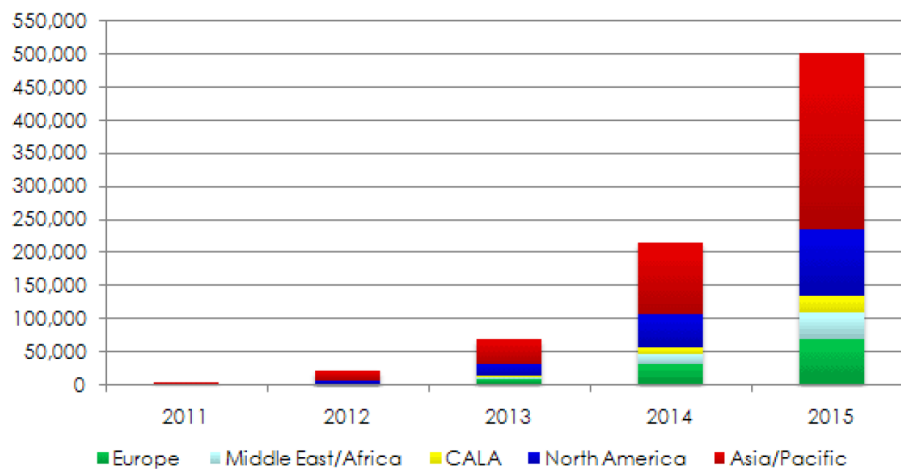


Figure 1-4 Public Access Small Cell Forecast (extracted from [Tella12]).

1.2 Motivation and Contents

The main scope of this thesis is to analyse the small cell deployment over a typical urban scenario, in a realistic LTE network. Throughout a described methodology, the various characteristics of the technology are analysed in detail and the most critic points are therefore segmented and applied for proper analysis. The objective is to analyse small cells in terms of coverage, capacity and interference for the downlink.

Small cells are not a new concept, and have already been addressed and studied for previous technologies such as 3G. The focus is on the high data capabilities tested throughout small cells connections inserted macro-cell layers. A comparison among different scenarios is done in order to address when small cells are useful to address network problems.

This thesis was developed in collaboration with Optimus, a Portuguese mobile operator. This partnership proved to be extremely useful, since a realistic study on a specific zone was possible.

The thesis is composed of 5 chapters, including the present one. Chapter 2 makes an introduction to LTE in technical terms and the overall concept of small cells for LTE. Every concept is approached

and a theoretical analysis of known concepts and literature was made along with the state of the art. First, the network architecture used by LTE is presented in detail, then the radio interface aspect is approached, where all details about how LTE works in terms of frame structures and applied frequencies are analysed. The small cells concept and the integration with LTE is also analysed, and small cells are studied in terms of architecture and radio interface. The relays alternative to small cells is also reviewed in this chapter. Other very important aspects, such as interference, services and applications, are also described and a bridge is made to LTE and the small cell paradigm. Last, the state of the art is presented, where studies from the current literature related to small cells and the topics in study over LTE are analysed and described.

In Chapter 3 the model description takes place. First, the description is made for all aspects regarding the most important factors under study. The model development is addressed and explained how the propagation models are applied, and how they are taken into consideration. One presents a bridge between the theoretical information presented in the previous chapter and the implementation into a simulator, after which the simulator description is made. This chapter ends with the assessment of the simulator. Concepts like SNR and SINR are addressed and explained in how they are calculated and how they are used.

Chapter 4 presents the results obtained from simulation, analysed and explained. The major outline of all simulations is drawn and the specific realistic network is described with all parameters. All options are explained and justified. For the two studied reference scenarios, the various performance aspects are analysed after the results are presented. Variations to the settings were made and different case scenarios are compared to draw specific conclusions on how the parameters affect the system.

Chapter 5 concludes the present dissertation, a critical analysis of the results being shown, followed by the main work conclusions. It finalises with many follow-up notes to future work. Finally, a set of annexes closes this thesis, being needed to complement most of the explained thoughts.

Chapter 2

LTE Basic Concepts

This chapter develops the basic technical concepts related to LTE, small cells usage and relays deployment. First, the LTE network architecture and radio interface are explained, then, small cells and relays are described referring the differences in system architecture and radio interference in their implementation, plus a performance analysis for each. This chapter end with coverage, capacity and interference in general and some references to small cells and relays approach.

2.1 Network Architecture

This section describes LTE's basic network architecture, being based on [3GPP12a] and [HoTo09].

LTE has an overall simplification in the architecture compared with older systems, which promoted network architecture evolution towards a simpler and more effective new flat system. LTE aims at optimisation for packet switched services in general, support for higher throughput required for higher end user bit rates, and improvement in the packet delivery delays. It was also considered the optimisation of inter-working with other platforms, such as different access networks from 3GPP.

Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) is used at the base station level, consisting of intelligent base stations called evolved Node B (eNodeB). E-UTRAN corresponds to a simple grid of eNodeBs interconnected by the X2 interface.

Figure 2-1 shows the basic network architecture when using only E-UTRAN. There are four main high level domains: User Equipment (UE), E-UTRAN, Evolved Packet Core Network (EPC), and Services. The first three form the Internet Protocol Connectivity Layer (or Evolved Packet System) with the purpose of providing IP based connectivity, highly optimised, offering all services over IP, eliminating the need of circuit switched nodes and interfaces, present in older 3GPP systems.

UEs, normally referred to as mobile terminal or Terminal Equipment (TE), interact with eNodeBs via LTE-Uu interface.

The EPC contains the following elements: Mobility Management Entity (MME), responsible for security and authentication, mobility management, and subscription profile management and connectivity; Serving Gateway (S-GW), responsible for UP tunnel management and switching; Packet Data Network Gateway (P-GW), performing traffic gating and filtering functions, and usually acting as the IP point of attachment for the UE; Policy and Charging Resource Function (PCRF), responsible for Policy and Charging Control (PCC), making decisions on how to handle the services in terms of QoS; and the Home Subscription Server (HSS), which is the subscription data repository for all permanent user data. All communications between EPC and E-UTRAN are performed by the S1 interface. When connecting a eNodeB to MME, the interface is called S1-MME and in case of a connection between eNodeB and S-GW it is S1-U.

An alternative deployment scenario is to combine S-GW and P-GW into an element called System Architecture Evolution Gateway (SAE GW), as indicated in Figure 2-1, but the standards define the interface between them, and all operations have also been specified for when they are separate.

The Services Domain, along with EPC, E-UTRAN and UE form the Services Connectivity Layer. This domain consists of various types of sub-systems, which may contain several logical nodes. From the architectural point of view, its structure remains intact compared with previous 3GPP systems, but the functional evolution has also continued in those areas.

A different image of LTE's Network Architecture is shown in Figure 2-2.

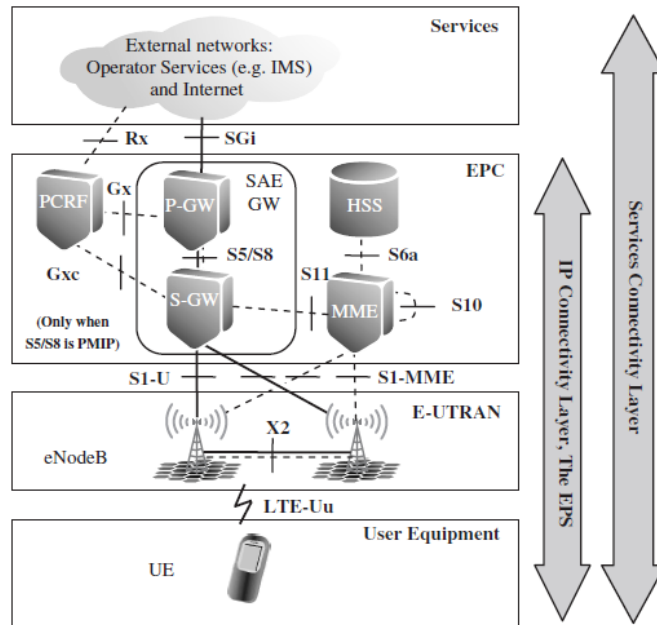


Figure 2-1 System architecture for E-UTRAN only network (extracted from [HoTo09]).

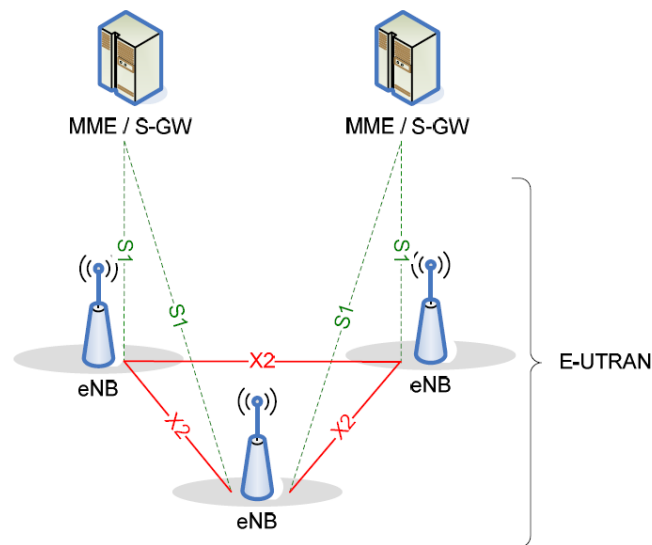


Figure 2-2 Network Architecture (extracted from [3GPP12a]).

2.2 Radio Interface

This section addresses LTE's Radio Interface based on [3GPP12] and [HoTo09].

The approach used on LTE's access techniques consists of using Orthogonal Frequency-Division Multiple Access (OFDMA) for the downlink (DL) and Single Carrier Frequency Division Multiple Access (SC-FDMA) for the uplink (UL), both with Cyclic Prefix (CP). CP is a simple prefix added to the

Orthogonal Frequency-Division Multiplexing (OFDM) symbol, copied from the end of the same symbol. The signal will gain a periodic nature, allowing discrete Fourier operations, hence avoiding Inter-Symbol Interference. CP usage is addressed in the frame structure later on. In an OFDM system, the available bandwidth is divided into various sub-carriers that can be modulated independently.

The main reason that justifies different access techniques for the UL and DL is the fact that SC-FDMA optimises range and power consumption at the UE, while OFDMA minimises receiver complexity and enables frequency domain scheduling with flexibility in resource allocation. OFDMA is a multi-carrier transmission scheme in opposition to SC-FDMA. Both allow multiple user access, depending on the available bandwidth, by dynamically allocating each user to a specific time-frequency resource, depending on which duplexing is deployed. OFDM requires a large dynamic range due to high Peak to Average Power Ratio (PAPR). Since SC-FDMA is OFDM with pre-coding, the usage of SC-FDMA reveals a 2 dB optimisation of PAPR compared to OFDMA, [Zeme08].

The main difference between an OFDM system and an OFDMA one is represented in Figure 2-3. The different colours represent different users using resources. In OFDM, users are assigned to resources in the time domain only, while in OFDMA, users can be assigned also in the frequency domain, optimising resource usage. This resource allocation is done by using a Resource Block (RB) system being explained later on.

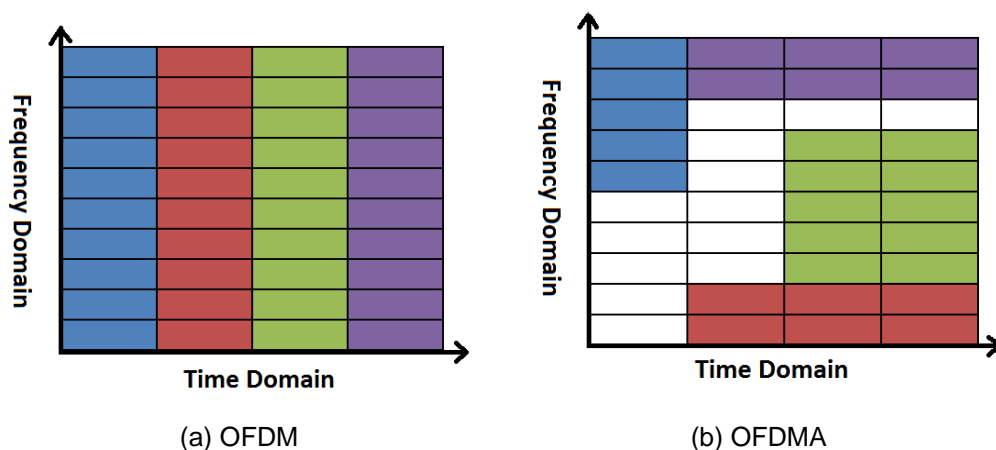


Figure 2-3 Difference between OFDM and OFDMA resource by user allocation.

Two types of duplexing, Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD), are supported by LTE, although FDD is the most adopted technique in the majority of European networks, [Carrei11]. Concerning the physical channels, there are only two types of frame structures: the Type 1, applicable to FDD; and the Type 2, applicable to FDD. Each radio frame has 10 ms duration and the specific description of Type 1 frame structure is presented later on.

3GPP specifications indicate that there are 17 frequency FDD bands and 8 TDD ones. ANACOM (the Portuguese entity that regulates spectrum usage) issued an auction for the 450 MHz, 800 MHz, 900 MHz, 1800 MHz, 2.1 GHz and 2.6 GHz frequency bands, to be used by mobile operators to deploy LTE. This auction resulted on the three mobile operators buying exactly the same number and size slots in 800 MHz with 2 x 10 MHz, 1800 MHz with 2 x 14 MHz and 2.6 GHz with 2 x 20 MHz (being this last band specifically for FDD). Vodafone also acquired one extra slot in 900 MHz and another

one in 2.6 GHz for TDD, [ANAC12].

Regarding transmission bandwidth, LTE has plenty of options when it comes to channel bandwidth selection, including selectable channels ranging from 1.4 to 20 MHz, with sub-carrier spacing of 15 kHz. When evolved Multimedia Broadcast Multicast Service (eMBMS) is enabled, a sub-carrier spacing of 7.5 kHz is available. In Table 2.1, all LTE available bandwidths are discriminated in terms of size in RB. For instance, a bigger bandwidth will have more RBs available.

LTE uses QPSK, 16QAM and 64QAM modulation schemes. Much like other 3GPP systems, LTE has Adaptive Modulation and Coding (AMC), which greatly improves data throughput. The variation of the downlink modulation coding scheme, based on the channel condition for each user, results in one of LTE's greatest features: self-optimisation. With the capability of changing the modulation scheme to a higher order (more bits per symbol) when the link condition is good, the network capacity is increased.

User data, control and information are carried by physical channels to higher layers. Physical signals do not communicate with higher layers and are used for cell search and channel estimation purposes.

DL main physical channels are the Physical Broadcast Channel (PBCH), Physical Downlink Control Channel (PDCCH) and Physical Downlink Shared Channel (PDSCH). DL main signals are the Reference Signal (RS), and the Primary and Secondary Synchronisation Signals (P-SCH, S-SCH). Figure 2-4 illustrates a Type 1 DL frame structure. A radio frame has 10 ms duration, and is composed of 20 slots of 0.5 ms duration each. Two of these slots are called a sub-frame, with 1 ms duration, also designated as the Transmission Time Interval (TTI). Systems tend to evolve to shorter TTIs, which will reduce latency at the cost of a more demanding UE processor. In Figure 2-4, it can be observed in which symbol the physical signals and channels are used, and also the usage of CP in the frame and the predominant data space represented in yellow.

UL main physical channels are the Physical Uplink Control Channel (PUCCH) and the Physical Uplink Shared Channel (PUSCH). UL main physical signals are the demodulation reference signal and the Physical Random Access Channel (PRACH). In terms of UL frame structure, Type 1 is basically the same as DL when it comes to its lengths (frame, slot and sub-frame). CP will have a direct impact on the number of symbols that will form a slot. In a frame structure Type 1 for the UL, a slot is composed of 7 symbols, the fourth symbol being a reference signal used for demodulating purposes.

Resource allocation in DL is made with the help of a resource grid composed of RBs. When allocating time-frequency resource units, the smallest unit possible is called a resource element, which is one symbol in one sub-carrier. Aggregating 12 contiguous sub-carriers (referring to frequency domain, 12 sub-carriers x 15 kHz spacing) and one time slot (referring to time domain, 12 sub-carriers x 7 symbols) one has an RB. An RB is composed of 84 resource elements and this size is the same for all the transmission bandwidth. RB is the basic unit when allocating data to the UE. Figure 2-5 represents this description of the relation between RB and frequency.

Table 2.1 LTE key parameters (adapted from [RoCh13]).

Frequency Bands	450 MHz, 800 MHz, 900 MHz, 1800 MHz, 2.1 GHz and 2.6 GHz					
Channel bandwidth 1 RB = 180 kHz	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
	6 RB	15 RB	25 RB	50 RB	75 RB	100 RB
Modulation Schemes	Downlink: QPSK, 16QAM, 64QAM Uplink: QPSK, 16QAM, 64QAM (optional for handset)					
Multiple Access	Downlink: OFDMA Uplink: SC-FDMA					
MIMO technology	Downlink: Wide choice of MIMO configuration options for transmit diversity, spatial multiplexing, and cyclic delay diversity (max. 4 antennas at base station and handset) Uplink: Multi user collaborative MIMO					
Peak Data Rate	Downlink: 150 Mbps (UE category 4, 2x2 MIMO, 20 MHz) 300 Mbps (UE category 5, 4x4 MIMO, 20 MHz) Uplink: 75 Mbps (20 MHz)					

2.3 Small Cells

Small cells are a reliable option to use throughout present-day mobile communications systems. They consist of base stations with a smaller working range. The indoor and outdoor use of this type of cells offers many advantages in cellular coverage and capacity, overcoming building penetration loss and assisting frequency reuse.

LTE's requirements and specifications for small cells are being discussed in 3GPP and may suffer changes in the future. The last released filed in this matter (in Nov. 2012) still is in draft version 0.2.0, [3GPP12d], but for the moment, there are various types of small cells that vary according to their range, Figure 2-6. From a larger range to a smaller one, there are micro-, metro-, pico- and femto-cells. Small cells deployment results in a heterogeneous network, [3GPP12c]. When referring to small cells in a network, 3GPP uses the nomination Heterogeneous eNB (HeNB).

The network architecture suffers some changes when considering HeNB, presented in Figure 2-7 with the logical architecture of E-UTRA with HeNB deployment. The available interfaces are presented, with S1 defined to communicate between HeNB and the core network for S1-U, as well between HeNB and a new network element: Home eNB Gateway (HeNB-GW) for S1-MME. To increase HeNB deployment in a scalable manner, HeNB-GW serves as a concentrator for the S1-MME interface, terminates the S1-U interface and allows the S1-U interface to be terminated by the S-GW, if needed. X2 is also used between HeNBs independently if they are connected or not to the HeNB-GW.

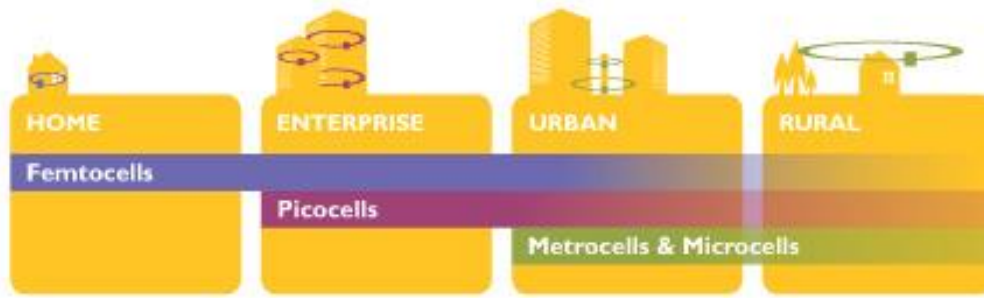


Figure 2-6 Small cells types and where they are used (extracted from [SCF12]).

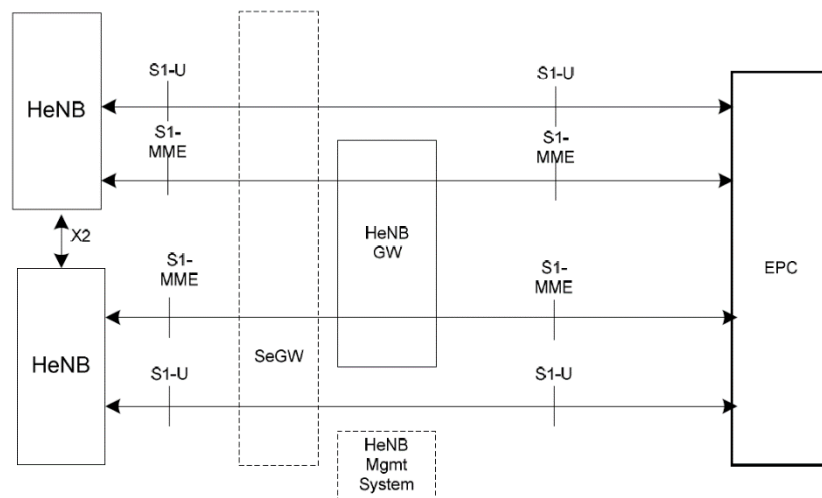


Figure 2-7 E-UTRAN HeNB Logical Architecture (extracted from [3GPP12a]).

To the MME, the HeNB-GW appears as an eNB and to the HeNB, the HeNB-GW appears as an MME. The S1 interface will always remain the same between HeNB and the EPC, even if the HeNB is connected to a HeNB-GW or not. The functions supported by a HeNB should be the same as the ones supported by a normal eNB and all communications to EPC shall be the same as the ones between an eNB and EPC. Note that HeNB will only serve one cell, so HeNB-GW will have to establish a connection to the EPC in a way that allows inbound and outbound mobility, so no inter MME handovers are required. In Figure 2-8, an overall view of the network architecture is provided. There are various aspects that are expected from the integration of small cells into the network, one of them being that small cells must support most functionalities of the eNB, such as MIMO or the 20 MHz bandwidth.

Small cells deployment should target any situation that it proves to be useful. 3GPP considers indoor and outdoor deployments as target scenarios, with and without macro-cell coverage, and even ideal or non-ideal backhaul situations. 3GPP also highlights considering sparse and dense small cells deployments, [3GPP12d].

When referring to small cells deployments, there are some requirements defined by 3GPP to allow small cell enhancement. For instance, a mobile operator that installs and maintains a set of small cells should support enhancements, but a user that deploys a small cell only needs to support small cell

enhancement with a lower priority, [3GPP12d].

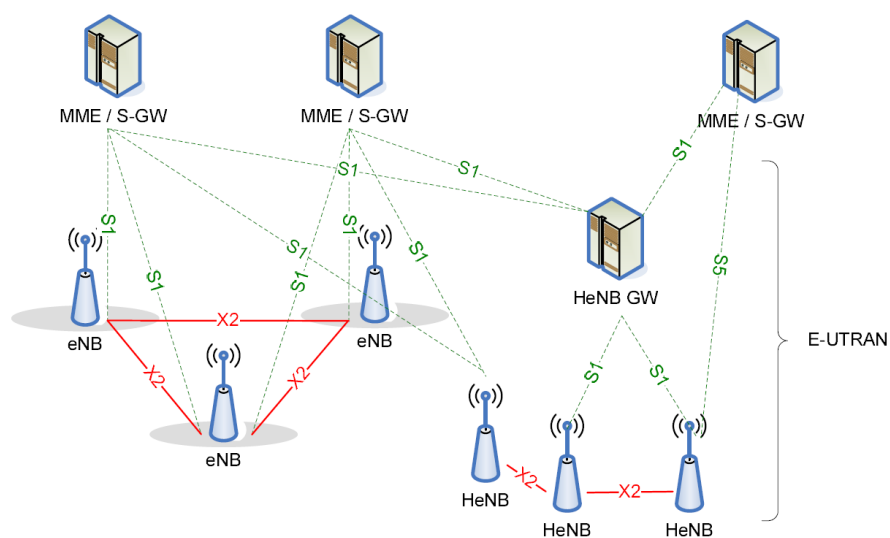


Figure 2-8 Overall E-UTRAN Architecture in a heterogeneous network (extracted from [3GPP12a]).

The radio interface does not suffer major changes when considering HeNB instead of eNB, but some spectrum considerations are needed. When deploying small cells in a scenario with macro-cell coverage, the two will normally have different frequency bands assigned to each one, but co-channel deployment will also be considered by 3GPP. Three configuration examples are given:

- Carrier aggregation in the eNB with band X and Y, when the HeNB has only X.
- HeNB supporting carrier aggregation bands and these are co-channel with the eNB.
- HeNB supporting carrier aggregation bands and these are not co-channel with the eNB.

Preferably, small cells should work in frequency bands that, at least locally, are only used for small cell deployments. Also, since small cells should work in all available bands, there is a special focus on higher frequency bands, e.g., the 3.5 GHz one, to enjoy the available spectrum and the wider bandwidth, [3GPP12d].

The main reason for small cell deployment is capacity and the improvement of user throughput. Anyway, small cells can also be used to improve indoor coverage at low cost. They are designed to support higher user throughputs, both for UL and DL, with the main focus on typical or average user throughput, given a reasonable system complexity. Feedback on coverage user experience is highly important, so that small cells enhancement keeps the fairness among users for the throughput for UL and DL. Also, the impact of the current backhaul delays should be evaluated, so that these will not impact negatively on system performance, [3GPP12d].

3GPP is conducting some studies regarding performance of mobility in heterogeneous networks, [3GPP12c]. This is essential for further advancement over the deployment study. To ensure user mobility, successful handover is one of the most critical points in small cells good performance.

When addressing small cells deployment, backhauling is one of the biggest concerns for operators and service providers. The backhaul link of a small cell is the physical connection between the small cell and all the upper layers of the network, and it has to be planned properly, [RoHi12]. The way the

two layers communicate is through the S1 interface, the backhaul referring to the link itself. There is no optimal solution for small cells backhauling, since small cells are emerging now, and industry is looking for options. There are plenty of types of backhauling with different costs and efficiencies. It all comes down to how much money an operator is willing to pay to achieve better quality of service, [RoHi12]. The major types of backhauling are:

- **Fibre:** the best solution when it comes to performance, but extremely hard and expensive to deploy. Even with the present fibre network, it is still difficult to have fibre to specific indoor locations.
- **DSL:** the same as fibre, but with a worse performance. Although, it is a bit less difficult to deploy than fibre and also less expensive, if one has to choose between the two, it makes more sense to use fibre instead.
- **Microwave:** a good alternative when one is forced to use wireless backhauling. There is plenty of spectrum available in the 10GHz-60GHz bands, which represents lots of capacity. Nowadays, it is a mature technology for fixed links.
- **E-band:** regulators have made the spectrum around 71-81GHz available to promote innovation, and using it for backhauling is also a possibility.

The next step to be considered, after the type of backhauling has been chosen, is what type of network topology to deploy. There are four types of topologies, as seen in Figure 2-9, and they are quite self-explanatory.

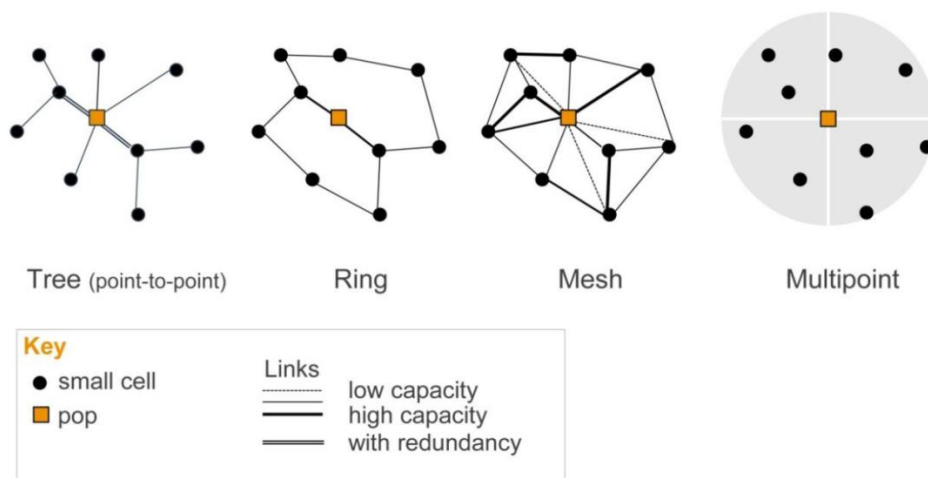


Figure 2-9 Topologies for backhaul networks (extracted from [RoHi12]).

2.4 The Relay alternative

Relays are low range wireless access points similar to small cells, but do not require a physical connection to the network. They work by retransmitting radio waves from an eNodeB with the purpose of solving coverage and range problems. Since they are not connected to the network and they only

redirect information, all data must be received from the eNodeB, which disables relays to solve capacity problems, since they do not increase the available resources like small cells. That is one of the main reasons why relays are not studied in this thesis. On the other hand, relays aim to improve carrier-to-noise power ratio plus inter-cell interference, resulting in an enhanced throughput close to cell edge. They are referred to as a solution to achieve self-backhauling of radio communications between eNodeB and UE, [lwTa10].

There are different types of relays defined by 3GPP for LTE, [lwTa10]: Layer 1, Layer 2 and Layer 3. Their overview and features are presented in Figure 2-10. Layer 1 consists of a simple repeater that receives DL from an eNodeB and retransmits it to a UE and vice-versa with the UL. It will improve signal power to the end-user but also amplifies noise. Layer 2 produces the same effect as Layer 1 with the property of eliminating noise by demodulating/decoding and modulating/encoding the signal. This will result in an improved signal compared with Layer 1, but with a higher latency, consequence of the signal functions processing delay. Layer 3 is an improvement in Layer 2 functionality by adding corrective functions and user data regeneration in the demodulated signal.

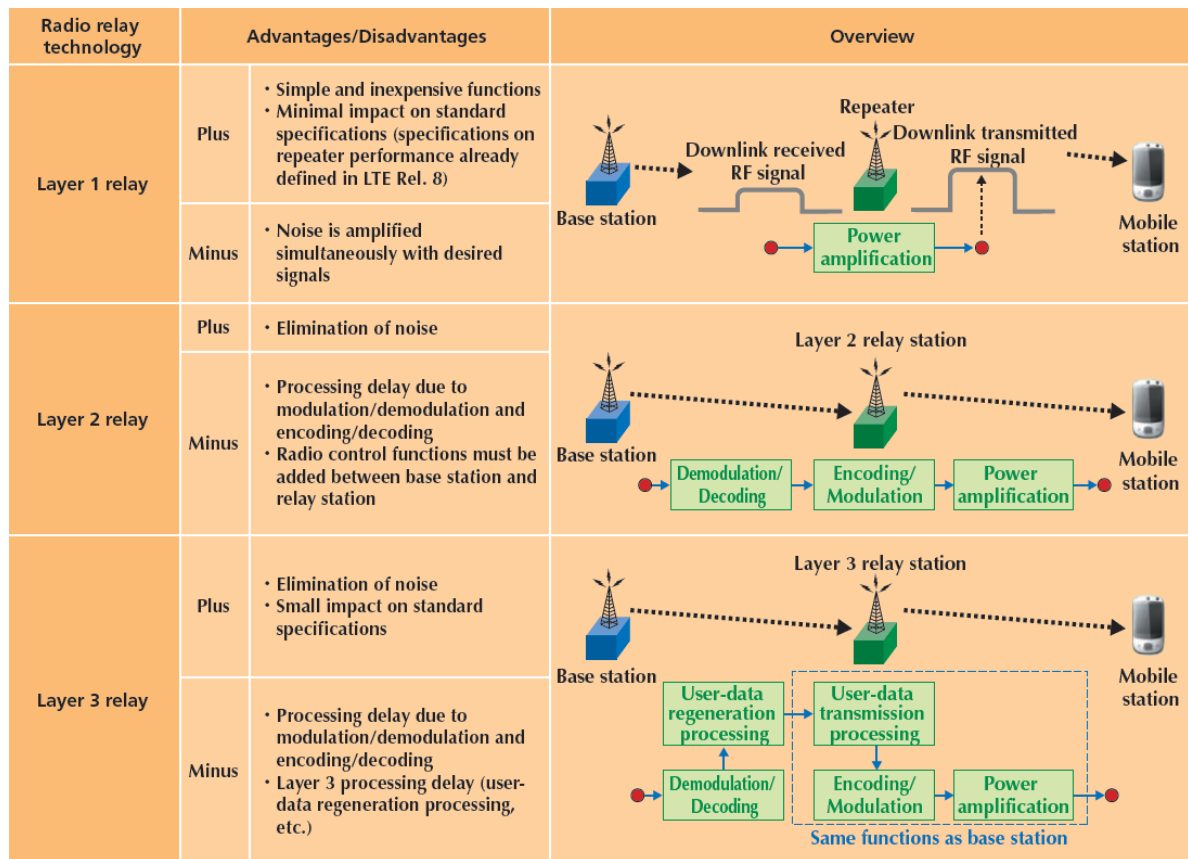


Figure 2-10 Relays Types and Features (extracted from [lwTa10]).

One already referred that the way E-UTRAN supports relaying is by having a Relay Node (RN) wirelessly connected to an eNB. This node is called Donor eNB (DeNB) and serves the RN via a modified version of radio interface called Un interface, allowing the RN to support all functionalities of an eNB, specifically the E-UTRA radio protocols, and the S1 and X2 interfaces. Note that inter-cell handover of the RN is not supported, [3GPP12a].

Figure 2-11 shows an overall E-UTRAN Architecture containing RNs. The proxy functionalities between RN and other network nodes (other eNBs, MMEs and S-GWs) is guaranteed by DeNB making it appear as an MME (for S1-MME), an eNB (for X2) and an S-GW (for S1-U) to the RN. On the other hand, the rest of the network sees RN as a new cell under the DeNB. All Gateway-like functionality of the RN is also provided by DeNB, which creates sessions and manages EPS bearers for the RN. These bearers mapping is based on existing QoS mechanisms defined for the UE and the P-GW. The MME functionality for the RN is provided by the MME, as it would be an eNB.

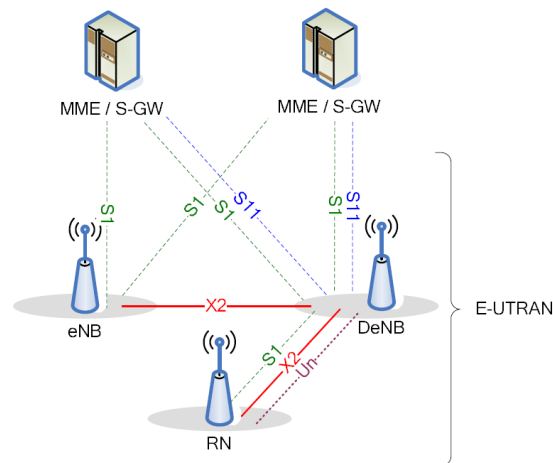


Figure 2-11 Network Architecture supporting RNs (extracted from [3GPP12a]).

3GPP also discusses scenarios in which the introduction of RNs would prove to be useful. The most common ones are the coverage extension problem at cell edge and providing backhaul communication.

The RN radio interface does not suffer any changes from the specifications in Radio Interface, discussed in Section 2.2, when working with different frequencies, named outband relay, [3GPP10]. The DeNB and RN try to transmit and receive information at the same time resulting in a problem when different frequencies are not available. The interference caused by the same frequency reuse, inband, would compromise RN usefulness. This is why when operating in inband, the wireless-backhaul-link and radio-access-link provided by the RN must be configured to work in Time Division Multiplexing (TDM) providing enough isolation between receiving and transmission.

Relay operating band and channel arrangement is the same as the one considered in present 3GPP release specifications for E-UTRA, [3GPP12b].

Radio Frame Configuration for relays must take account TDM so, to this end, 3GPP studied the usage of Multicast/Broadcast Single Frequency Network (MBSFN) sub-frames configuration received by the RN from the DeNB, Figure 2-12. In this method, a reference signal and control signals are placed at the header of the frame taking up only two symbols at most. These symbols can provide the UE radio quality measurement plus the perception that there will be no data transmission from the RN. Through this, DeNB can transmit data to the RN safely, [IwTa10].

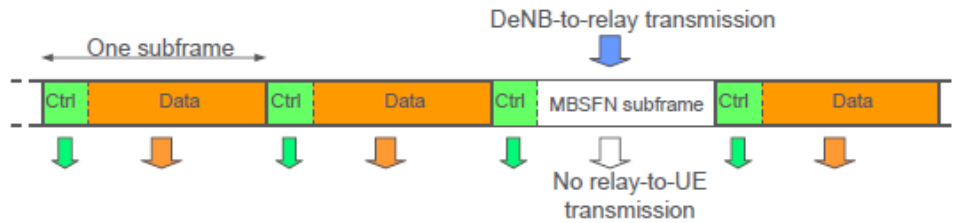


Figure 2-12 Radio frame configuration for RN (extracted from [Hoym10]).

Relaying, for the inband, improves coverage and cell-edge bit rate due to signal regeneration, reduces peak rate for relay users due to backhaul subframes, and degrades data throughput for non-relay users due to increased interference. For the outband, relaying improves capacity but with the disadvantage of larger spectrum demand, [Hoym10].

Several studies are being made in relay performance. These studies obviously depend on the types of relay deployments and various situational factors. In [MiKe11], various deployment scenarios are taken into account and explained, and some studies are made considering average effective Signal to Interference Noise Ratio (SINR).

2.5 Interference

This section is based on [Paol12], where the majority of the aspects around interference are addressed.

Currently, mobile operators try to aggressively increase network capacity to meet the wireless traffic fast growth. Since spectrum does not grow in the same proportions, mobile operators try various techniques to improve network capacity. These techniques include adopting a frequency reuse of one (reusing the entire spectrum for adjacent sectors) and the usage of the already discussed small cells, creating heterogeneous networks. But these come with a substantial consequence: interference increase.

High interference is shown by lower SINR and seriously degrades system performance, decreasing network efficiency. User throughput is directly proportional to system performance, forcing operators to compensate for the decrease in SINR. But if operators augment frequency reuse to avoid interference, network capacity is decreased.

There are three major types of interference in LTE, being presented and explained in Figure 2-13. Obviously, the type of interference one wants to focus in this thesis is inter-cell interference, related to macro-/small cells signals. A few techniques, described below, to coordinate frequency reuse between the macro-cell layer and small cells were implemented with the objective to study the impact of these interference mitigation techniques on the overall system performance.

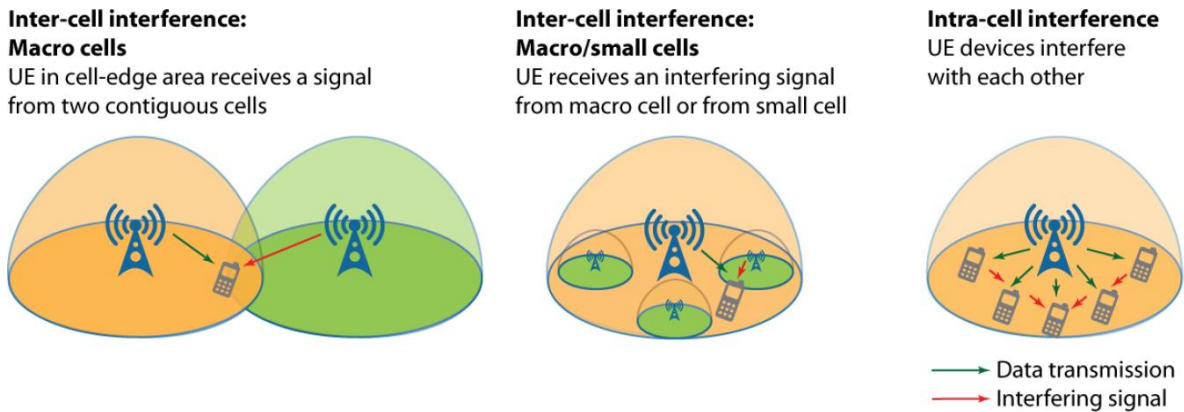


Figure 2-13 Types of interference (extracted from [Paol12]).

There are various techniques operators can use for interference managing:

- **Within the Radio Access Network (RAN):** Inter-Cell Interference Coordination (ICIC), enhanced ICIC (eICIC) and Coordinated Multipoint (CoMP) transmission and reception.
- **Coordinating between RAN and UE:** Multiple-Input Multiple-Output (MIMO) enhancement, including Multi-User MIMO (MU-MIMO) and Single-User MIMO (SU-MIMO).
- **Within the UE:** they depend directly on the UE type and if they are supported or not, including Maximal Ratio Combining (MRC), Interference Rejection Combining (IRC), and Interference Cancellation (IC) with receiver Beamforming (BF).

2.6 Services and Applications

This section approaches the services and applications available in LTE. The first main objective was to assure a voice service with quality to any user connected to the network. This was not a difficult task, since voice is a very predictable service, with a constant bit rate, allowing operators to assure its performance without much effort. The subsequent problem started to be spectral efficiency in order to boost network capacity, but system and society evolution brought operators goal towards LTE boosting mobile communications operability, capacity and functionality. This raised a lot of new challenges and the service and application approach suffered tremendous evolution in LTE.

Voice was, and still is, one of operators' most important services, but nowadays the paradigm has changed drastically. With the development of mobile communications in general and the continuous growth of smartphone users, data communications services in mobile terminals are starting to gain importance over voice. This has pushed developers to optimise the technology with the objective to respond to demanding new features, now possible thanks to smartphones. Even before smartphones, data started to have its relevance with Short Message Service (SMS) and email features, which are extremely popular among users. But new services, like web browsing, video streaming and video calls, take data share of the overall traffic to an all new level. The voice service started to be optimised with the purpose of allowing a better spectral efficiency to respond to these demanding data services.

One example of this optimisation is the transition of voice to a packet-based service (VoIP) allowing more spectrum to be used in data services, [3GPP12e].

The proper planning and parameterisation had to be defined in order to respond to these challenges. 3GPP had already done this in UMTS, and the same approach is used to LTE. In order to define performance parameters, 3GPP has specified different QoS classes related to the desired type of service and quality. These traffic classes can be observed in Table 2.2 along with some characteristics. The four available classes are: Conversational, Streaming, Interactive and Background. One of the key factors that differentiate them is the fact that the first two are real time services, while the last two are not, obviously. This gives a total different approach to the service when it comes to how delay sensitive the traffic effectively is, because in a real time service the user expects a real time response, [3GPP12f].

Table 2.2 3GPP service classes and characteristics (extracted from [Serra12]).

		Traffic class			
		Conversational	Streaming	Interactive	Background
Fundamental Characteristics	Connection delay (main attribute)	Minimum fixed	Minimum variable	Moderate variable	High variable
	Buffering	No	Allowed		
	Bandwidth	Guaranteed bit rate		No guaranteed bit rate	
	General Characteristics	Symmetric traffic, delay sensitive, low emphasis on signal quality	Asymmetric traffic, delay variation sensitive, not sensitive to transmission errors	Asymmetric "request-response" traffic, low round trip delay, high signal quality required	Asymmetric non-real time traffic, high signal quality required
	Real Time	Yes		No	
	Typical Applications	Voice, video telephony, interactive games	Audio streaming, video demand	Voice messaging, FTP, Web browsing	E-mail, SMS, MMS, Fax

Along with defining traffic classes, the restrictions and limitations of the air interface have to be taken into account, since it is not reasonable to define complex mechanisms as have been in fixed networks, due to different error characteristics of the air interface, [3GPP12f]. The restrictions once produced by legacy systems prior to LTE were very big compared with the present day case, and the service and application range of effectiveness was much more limited.

The development of the System Architecture Evolution (SAE) bearer model came along with the QoS concept. Due to the extensive QoS attributes available, it was agreed that for SAE, only a reduced set of QoS parameters and standardised characteristics would be specified. It was also established that the bearer set-up logic would be so that the network resource management is solely network

controlled, and the network decides how the parameters are set. The main bearer set-up logic consists of only one signalling transaction from the network to the UE and all interim network elements, [HoTo09].

The limited set of signalled QoS parameters are included in the specifications. These were optimised for SAE and, as specified in [HoTo09], they are:

- **QoS Class Identifier (QCI):** It is an index that identifies a set of locally configured values for three QoS attributes: Priority, Delay and Loss Rate. QCI is signalled instead of the values of these parameters. Ten pre-configured classes have been specified in two categories of bearers, Guaranteed Bit Rate (GBR) and Non-Guaranteed Bit-Rate (Non-GBR) bearers. In addition, operators can create their own classes that apply within their network. The standard QCI classes and the values for the parameters within the class are shown in Table 2.3.
- **Allocation and Retention Priority (ARP):** It indicates the priority of the bearer compared to other bearers. This provides the basis for admission control in bearer set-up, and further in a congestion situation if bearers need to be dropped.
- **Maximum Bit Rate (MBR):** It identifies the maximum bit rate for the bearer. Note that a Release 8 network is not required to support differentiation between the MBR and GBR, and the MBR value is always set to be equal to the GBR.
- **Guaranteed Bit Rate (GBR):** It identifies the bit rate that will be guaranteed to the bearer.
- **Aggregate Maximum Bit Rate (AMBR):** Many IP flows may be mapped onto the same bearer, and this parameter indicates the total maximum bit rate a UE may have for all bearers in the same PDN connection.

Table 2.3 presents the QoS parameters that are part of the QCI class, and the nine standardised classes. Also, as defined in [HoTo09], the QoS parameters are:

- **Resource Type:** It indicates which classes will have GBR associated with them.
- **Priority:** Used to define the priority for the packet scheduling of the radio interface.
- **Delay Budget:** It helps the packet scheduler to maintain sufficient scheduling rate to meet the delay requirements for the bearer.
- **Loss Rate:** It helps to use appropriate RLC settings, e.g., number of re-transmissions.

Table 2.3 QoS parameters for QCI (extracted from [HoTo09]).

QCI	Resource type	Priority	Delay budget	Loss rate	Example application
1	GBR	2	100	1e-2	VoIP
2	GBR	4	150	1e-3	Video call
3	GBR	5	300	1e-6	Streaming
4	GBR	3	50	1e-3	Real time gaming
5	Non-GBR	1	100	1e-6	IMS signaling
6	Non-GBR	7	100	1e-3	Interactive gaming
7	Non-GBR	6	300	1e-6	Application with TCP:
8	Non-GBR	8			browsing, email, file, download,

2.7 State of the art

This section addresses the current studies related to small cell deployment and their impact on the overall system performance. All studies address dense urban scenarios, which is precisely the framework of this thesis. Half of the presented studies aim at demonstrating capacity improvements related to small cell usage, while the other half focuses on the interference problem and interference mitigation techniques.

In [BrCo12], a study of LTE small cells performance is made by simulating a realistic urban 3D scenario of a heterogeneous network, with small and macro-cells together and isolated. The authors' goal is to analyse spectral efficiency, thus network capacity improvement, by deploying small cells in the scenario. The average achieved throughput is also determined for each considered scenario. The 3D analysis is made by introducing extra floors in each building. The result is, as expected, higher floors have less macro-cell coverage, inducing less interference in small cells communications. The simulation is conducted by defining multiple DL traffic load and introducing 3D path-loss matrices, obtaining results at each UE location. The coverage statistics are analysed and since the simulations are made with small and macro-cells together and isolated, a comparison between the different deployment techniques is possible. The presented results are in terms of spectral efficiency for indoor and outdoor static users. Concerning both types of users, the worse spectral efficiency is obtained by using macro-cell only coverage. The deployment of small cells leading to a two-tier network provides much better spectrum efficiency for both cases than macro-cell only coverage. The best results are obtained for small cells only, but bear in mind that this is a very specific study for static users only. The authors admit future work in the same simulator giving a different result assessment.

Other study related to spectral efficiency in a heterogeneous network dense urban scenario was made in [CoHu12]. Realistic three-dimensional propagation characteristics are used in the simulation as the previous paper, but different small cell deployment strategies are used in this case and also a different spectrum allocation scheme is used. The simulation results are obtained for DL network outage, which is denoted as the percentage of users whose experienced throughput is below 1 Mbps, and is given in terms of offloaded users from a macro- to a pico-cell only, femto-cell only, pico-/femto-cell deployment and some considerations regarding coverage vs. throughput. Some interference considerations are taken into account. The work concludes that the massive offload of traffic taken from the macro-cell layer that is achieved at heterogeneous networks proves amazing network capacity improvements. These improvements can be seen in Figure 2-14 with a percentage of offloaded users from macro- to small cells and analysis of network outage.

Similar to the two previous studies, [SaEl12] demonstrates network capacity's improvement with the introduction of small cells, offloading the macro-cell. This has the particularity to be specific to LTE-Advanced, introducing an analysis in energy efficiency to overall power consumption at the network level. An open scenario is taken into account and the DL throughput is calculated relating it with inter-cell interference. The conclusion is not surprising: small cell deployment provides a much higher capacity to the overall system. Although not related to this thesis, the paper also provides very

interesting considerations on power consumption improvement with small cells deployment.

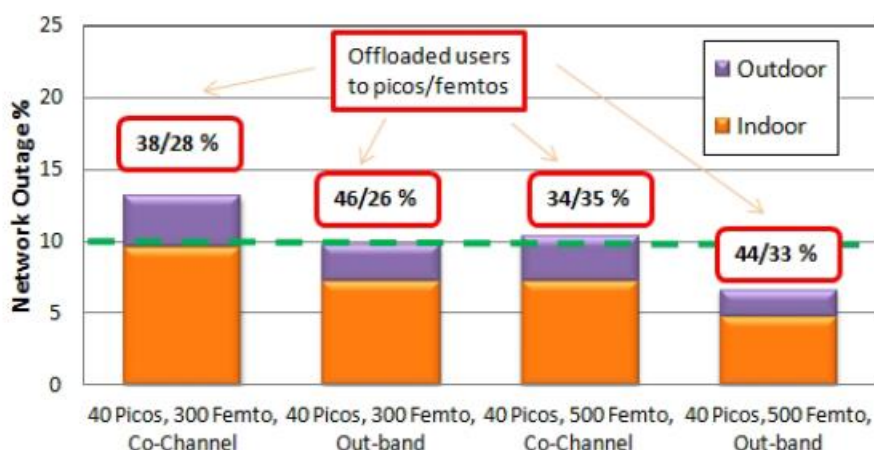


Figure 2-14 Network Performance for joint pico-femto deployment (extracted from [CoHu12]).

As stated earlier, interference is one of the main degradation factors in system performance when heterogeneous networks are taken into account. An interference analysis is conducted in [LaHa12], evaluating its effect on the overall system performance for both FDD and TDD. The study concentrates on DL and UL throughput from the eNB to UE, analysing the effect on interference. It is presented in terms of throughput percentage loss and Adjacent Channel Interference at the Receiver (ACIR), which measures the interference caused by different systems. Only performance is evaluated according to multiple scenarios and simulation parameters. No technique to correct the problem is proposed other than coordinating efforts between macro- and small cells to avoid additional interference. The paper shows serious degradation of signal quality related to the coexistence of different LTE systems. Its conclusion enhances the importance of interference mitigation techniques usage when small cells are deployed.

Other study that addresses interference related problems on heterogeneous networks is presented in [CaFe12]. The paper has two major objectives to study: first Inter-Cell Interference Management and second Mobility Management due to increasing handover related to small cells deployment. The first objective is achieved by using an interference handling system inspired by the Multi Armed Bandit solutions in Reinforced Learning. The technique used to mitigate system interference is an autonomous ICIC technique. The second objective is obtained analysing techniques of handover management and simulating their performance into different parameters and factors. The paper does not conclude on best solutions, and only refers the importance of interference mitigation techniques and the lack of handover related studies related to this topic.

Another study related to the interference problem is [WeSt12]. It is focused on LTE-Advanced small cells cellular network and addresses the related problems due to interference. After addressing and proving all stated problems, offers the main current solution to these problems: Enhance Inter-cell Interference Coordination (eICIC) and a discussion related to different scheduling strategies for this technique: strict scheduling and dynamic scheduling. Different load conditions and scenarios are simulated, being used to draw conclusions. In Figure 2-15, some simulation results are presented,

proving the usefulness of eICIC when considering higher network loads.

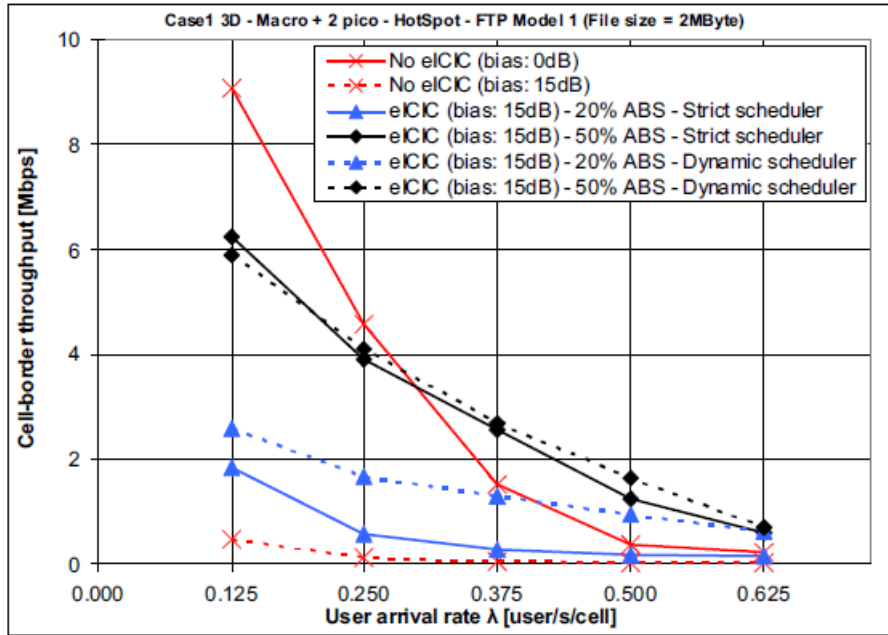


Figure 2-15 Load-dependent cell-boarder throughput (extracted from [WeSt12]).

The study concludes on major advantages of using this system. Like this work, there are many others that present eICIC as the present-day best solution to mitigate inter-cell interference on a heterogeneous network. Its study is being taken seriously by the research community, and there is no doubt that one will see more advanced studies related to this coming in the future.

A great example of these advanced studies is done in [SaHo11]. This paper exploits three state of the art ICIC techniques derived from Fractional Frequency Reuse (FFR). These techniques consist of different ways of reusing frequency related to the small cell placement in macro-cells. In Figure 2-16, it is possible to observe these in (a) strict FFR, (b) soft FFR, (c) FFR-3 and (d) a proposed scheme by the authors. The study concludes on which scenario each solution is more favourable, totally promoting this technique, referring its essential to usage in small cell deployment scenario.

To finalise the state of the art, a Ph.D. thesis is also referred, [Serra12]. The topic is Joint Radio Resource Management in Heterogeneous Networks and the author addresses different types of access techniques and their influence on resource management. Various models and algorithms are taken into account, and are analysed on a consisting manner with the particularity of MIMO enhancement to the network.

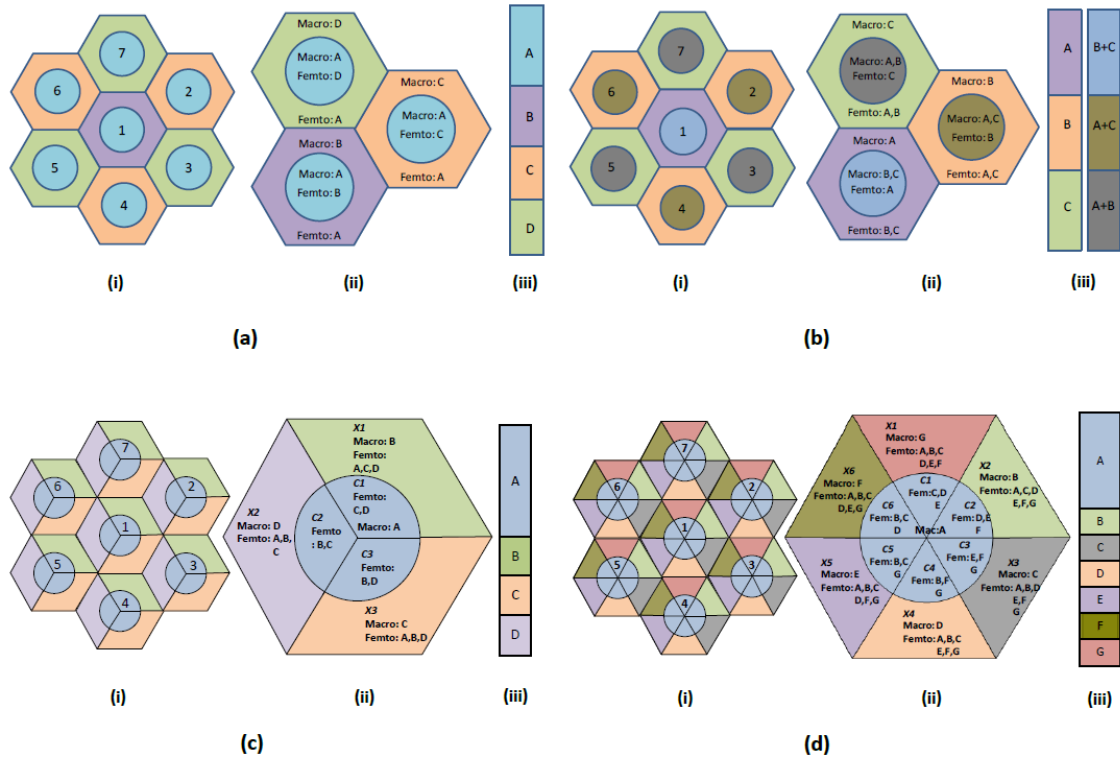


Figure 2-16 Different FFR deployment schemes (extracted from [SaHo11]).

Chapter 3

Models Description

This chapter describes the theoretical models used in this thesis plus details over their implementation and results assessment. The models are presented in full, detailing all functionality aspects and how one should apply them. The major considered aspects are also referred to, and a very detailed description of how the simulator was developed is done. This chapter ends with an overall assessment of the output data.

3.1 Model Development

This section provides an overview of the propagation and radio interface models used in this thesis that were implemented into the simulator. Most expressions are based on [Corr09] and [HoTo09], the first being related to basic mobile communications and the second to LTE.

3.1.1 Propagation Models

This thesis is focused on urban scenarios. The used propagation models are defined for this scenario in order to get the most realistic results. The specific scenario description is presented later on.

Path loss is calculated by using COST 231 Walfisch-Ikegami Model. This model is explained in detail in Annex A, and is valid for Line of Sight (LoS) and Non Line of Sight (NLoS). It is also possible to apply this model to an indoor user, taking into account building penetration with an attenuation margin explained in the next section. So, this is the model used to calculate the path loss in macro-cell.

When considering a connection in small cells, a statistic model is used for calculating the path loss based on [3GPP12g]. This is defined by the following equation:

$$L_{p[\text{dB}]} = \max(15.3 + 37.6 \log_{10}(R), 38.46 + 20 \log_{10}(R)) + 0.7 d_{2D, \text{indoor}} + 18.3 n^{\left(\frac{n+2}{n+1} - 0.46\right)} + q \cdot L_{iw} + \sum_{j=1}^i L_{ow,j} \quad (3.1)$$

where:

- R : distance between user and BS;
- $d_{2D, \text{indoor}}$: distance between user and the indoor BS;
- n : number of floors penetrated between user and BS;
- q : number of indoor walls between apartments penetrated between user and BS;
- L_{iw} : attenuation of indoor wall between apartments;
- $L_{ow,j}$: attenuation of outdoor wall of apartment;
- i : number of outdoor walls of apartments penetrated between user and BS.

The two presented propagation models allow path loss calculation with a realistic value in the desired scenarios. Path loss calculation is essential for the future calculations regarding the performance parameters that this thesis evaluates (throughput and capacity). Equation (3.1) is used in a variety of studies such as [CoHu12] and [BoKa12].

3.1.2 Signal Noise Ratio and Signal to Interference plus Noise Ratio

The Signal Noise Ratio (SNR) and Signal to Interference plus Noise Ratio (SINR) are key factors to determinate which BS the user connects to, and has a vital part in throughput calculation. Deploying

small cells on an already established macro-cell network will produce extra interference that has to be taken into account when calculating throughput. Added to this, there is also sector overlapping between different macro-cells for some cases, and same cell sectors also form a frontier region where they overlap. In this thesis, it is essential to study SINR; only by having a proper interference analysis one can have realistic conclusions about the effect of small cells deployment over an established macro-cell network.

In a first phase, the SNR is calculated for each user, using the equations from Annex B. This is possible using the average received signal power and the noise power at the receiver. The purpose is to estimate the number of RB necessary to satisfy the throughput required by the users. This average signal power is calculated using the propagation models described earlier, combined with the link budget (B.1) and the noise power at the receiver can be calculated by (B.8). With these, one can finally use (B.7) to estimate the SNR. Statistical deviations on signal power calculations are taken into account with the slow fading margin in (B.6). Also, other margins are taken into account that are explained in the next section.

To account for system interference and analyse its effect on network functionality, the SINR is calculated and used to determinate performance parameters. Normally, this is achieved by dividing the average received signal power by the sum between the noise power and the interfering power at the receiver location. Generically, one can calculate the total interference power at the receiver with:

$$I_{[\text{mW}]} = \sum_{j=1}^{N_t} I_{j [\text{mW}]} \quad (3.2)$$

where:

- I_j : interference power from transmitter j ;
- N_t : number of interfering signals reaching the receiver.

When calculating SINR, one can use (B.9). The contribution of power to interference can be taken into account by combining (3.2) and (B.9). For simplification purposes, and also to simplify the analysis, one can use the following expression, adapted from [BoKa12], to calculate SINR for a macro-cell user i in a subcarrier n :

$$\rho_{IN_{i,n}} = \frac{P_{i,M,n} [\text{W}]}{N_0 [\text{W/Hz}] \Delta f [\text{Hz}] + \sum_{M'} P_{i,M',n} [\text{W}] + \sum_F P_{i,F,n} [\text{W}]} \quad (3.3)$$

where:

- M : macro-cell serving the user;
- M' : neighbour macro-cell;
- F : neighbour small cell;
- $P_{i,M,n}$: received power by user i of serving macro-cell in subcarrier n ;
- $P_{i,M',n}$: received power by user i of neighbouring macro-cell in subcarrier n ;
- $P_{i,F,n}$: received power by user i of neighbouring small cell in subcarrier n ;
- N_0 : white noise power spectral density;
- Δf : subcarrier spacing.

The same is possible for a small cell user f in a subcarrier n . One can calculate SINR for this case using the similar expression, adapted from [BoKa12]:

$$\rho_{INf,n} = \frac{P_{f,F,n} [W]}{N_0 [W/Hz] \Delta f [Hz] + \sum_M P_{f,M,n} [W] + \sum_{F'} P_{f,F',n} [W]} \quad (3.4)$$

where:

- M : neighbour macro-cell;
- F : serving small cell;
- F' : neighbour small cell.

The powers received by the user in (3.3) and (3.4) are also calculated using (B.1) combined with the path loss models described earlier. These are used for each user to calculate the SINR for each used RB. With all the calculated values, a mapping of SINR is made to provide further user throughput calculation and determinate the possible modulation scheme. The next sub-section describes how calculating SNR and SINR can determine throughput.

3.1.3 Throughput

Throughput is the most important performance parameter to be calculated. It is vital for a proper network analysis that the throughput enhancement is evaluated and related to the deployment of small cells. This cannot be done without taking interference into consideration.

Generically, it is possible to determinate an approximation of throughput for the DL using, [Carrei11]:

$$R_{b[Mbps]} = \frac{N_{sc}^{RB} \cdot N_{RB}^u \cdot N_{symb}^{SF} \cdot \log_2(m) \cdot N_{streams}}{10^3 \cdot T_{SF}[ms]} \quad (3.5)$$

where:

- N_{sc}^{RB} : number of subcarriers per resource block; depends on subcarrier spacing being the normal value 12 (for 15 kHz of subcarrier spacing);
- N_{RB}^u : number of user resource blocks; depends on how much RBs the eNodeB will allocate for the current user;
- N_{symb}^{SF} : number of symbols per sub-frame; depends on the type of CP deployed being 14 symbols for normal CP or 12 for extended CP;
- m : order of the modulation considered; depends on the link condition;
- $N_{streams}$: number of streams, in case of MIMO;
- T_{SF} : sub-frame period, 1 ms for LTE.

As one can see in (3.5), many parameters take part in how users receive data. Besides all the presented factors, there is also interference, synchronisation messages and reference signals, apart from application throughput that are not taken into account.

The method used in this thesis to calculate user throughput is to determinate throughput for each RB assigned to the user separately. The interference power at the receiver varies with the RBs that are being used, and when there are collisions between adjacent sectors or small cells. It is highly possible

that the same user experiences different throughputs for different RBs in the same conditions and BS, due only to interference.

The expressions in Annex C to determinate RBs throughput based on SINR were used in several previous studies, like [Duar08], [Jaci09], [Carrei11] and [Pires12], and were used in this thesis in a first phase. Annex C has many expressions based on 3GPP measurements, specifically for LTE. The explanation of each case plus how to use each expression is also present in this annex. This includes the modulation scheme determination due to the condition of the link. Later these expressions were updated to most recent ones.

The total throughput for a single user is the sum of the various throughputs calculated for each RB providing a more realistic value then (3.5). This is possible using the equations in Annex D, which relate a previous calculated value of SINR of a RB with its designated throughput, similar to Annex C. Using the previously explained mapping of SINR calculated for each RB, it is possible to obtain the total user throughput. These equations were dimensioned by [Alme13]: all manufacture values were taken, relating SNR and throughput, and an average value was calculated relating all. Further details are explained in both Annex D and [Alme13].

The following expression defines the total throughput for a single user, through the use of the SINR mapping and Annex D:

$$R_{b,T[\text{Mbps}]} = \sum_{i=1}^{N_{RB}} R_{b,i[\text{Mbps}]} \quad (3.6)$$

where:

- $R_{b,i}$: throughput for RB i calculated with SINR and Annex D
- N_{RB} : number of RB allocated to the user;
- $R_{b,T}$: total throughput experienced by the user.

3.1.4 Capacity

When analysing capacity, there are a variety of different ways of looking to the same problem. With the evolution of the mobile communication paradigm, capacity became a difficult term to define. Capacity defines a quantity, the key issue being “quantity of what?”. In LTE, as presented previously, the smallest allocation unit is an RB and a user can have various RBs allocated to him depending on the requested service. The definition of capacity for previous systems, as the number of users connected to the network (making phone calls, for example), is an outdated concept for LTE, where data services dependent of RB, leading the analysis to a different view.

In the past, it made sense to determinate the number of users one can connect to a BS in terms of capacity. In LTE, it is possible to calculate it through the following expression, [Gonca11]:

$$N_u = \frac{N_{SC}^{RB} \cdot N_{RB} \cdot N_{sym}^{SF} \cdot \log_2(m) \cdot N_{streams}}{R_b \cdot T_{SF[s]}} \quad (3.7)$$

where:

- N_{RB} : Number of resource blocks

In LTE, the available RBs in a BS are the most important limiting factor, for both UL and DL. It makes sense to analyse how much throughput is possible to achieve for a specific BS, rather than to analyse the number of served users. When considering capacity in terms of total throughput, the randomness of results due to the different resources quantities requested by the different services is avoided. A user can request different throughput values, and it would be hard to analyse capacity in terms of users but, most important, it would be extremely difficult to draw conclusions. So, by defining capacity on how much throughput the system can have in a cell, one can define the total throughput transmitted by the BS with the following expression, combining the results from (3.6):

$$R_{b,BS}[\text{Mbps}] = \sum_{i=1}^{N_U} R_{b,T,i}[\text{Mbps}] \quad (3.8)$$

where:

- $R_{b,T,i}$: total throughput for user i ;
- N_U : number of users served by the BS;
- $R_{b,BS}$: total throughput transmitted by the BS.

The deployment of small cells influences the total network capacity, increasing the available RBs of the system. It is a key factor to see how much capacity small cells increase into the system in terms of RBs but, most important, in terms of throughput. In this thesis, throughput calculation is done considering interference, so it would be possible to analyse a point where small cells are not enhancing system performance, but decreasing throughput due to interference. Another important factor to analyse is how many users or how much throughput small cells deployment offload from the macro-cell BS, consequently increasing capacity.

In terms of resource allocation, since the simulation is a snapshot analysis of the system, there is no possibility of studying a temporal distribution of the RBs to users. Thus, implementing a scheduling algorithm in its full complexity is not considered in the present simulator. Taking into account the Proportional Fair Scheduling (PFS) algorithm, an approximation of this is implemented in the simulator. This algorithm provides an excellent relationship between system throughput and fairness between users, selecting users with the highest instantaneous throughput relative to its average throughput. The con is that in every block, the scheduler informs the UEs about their allotted slot positions of RB, resulting on overhead and scheduler complexity, [SwMo13]. The approximation is to serve first the users that present the best channel conditions, emulating the selection of the users described before. When the simulator initiates, the resources have to be distributed and there is no previous data in user data rate, so starting in the user with the best channel condition makes a good approximation considering the type of simulator.

3.1.5 Coverage

The target scenario is a specific cluster, which is described in Section 4.1, and one assumes that all locations are completely covered due to the nature of the cluster. The analysis focuses on throughput

and, consequently, in capacity gains leaving the small cell deployment to address these two factors, not considering the feature of small cells to deliver coverage to blind coverage spots due to the target scenario.

When the objective is to determine the maximum range of coverage of a cell, one can use the following expression:

$$R_{\max} [\text{km}] = 10^{\frac{P_t[\text{dBm}] + G_t[\text{dBi}] - P_{r,\min}[\text{dBm}] + G_r[\text{dBi}] - L_p[\text{dB}]}{10 a_{pd}}} \quad (3.9)$$

where:

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

In the simulator described later on, cell radius is calculated allowing one to know what users are in range to make a connection to the BS. A coverage region is created in the simulator to help this analysis.

3.1.6 Frequency Reuse Schemes

Frequency Reuse Schemes (FRS) are the main tool used in networks for interference cancelation and avoidance. As already explained, interference can have devastating effects on the user link, destructing the signal power due to collisions from other BS links. The default frequency reuse scheme used in systems, and also in this thesis, is the simple reuse of 1, meaning the whole spectrum is used by all sectors. It is also often referred to as Universal Frequency Reuse, or for short, Reuse of 1. This technique naturally produces interference degrading the overall system performance. To proper address the interference problem cause by this default allocation, in this thesis one used two different popular FRS, based on other studies. They were implemented in the simulator and their effect on performance is studied.

The small cell problem address in this thesis is relative to small area of a specific cluster. Small cells are by definition a small area problem, where high level of knowledge about local morphology and distribution is required. The interference phenomenon that will be determined by simulation, and observed might not seem as devastating as the same phenomenon observed on larger areas of much bigger and concentrated networks. This specific area of the cluster in analysis is limited in the number of sectors and proper planning was elaborated by a mobile operator to determine the orientations of antennas or azimuths, antenna height, locations and number of sectors. One can assume that this planning was properly done, and the deployment made of small cells was into regions that do not already suffer a lot of interference by the macro-cell layer. Hence, the expected interference effect might prove ineffectiveness to the following presented schemes. Nevertheless, the study of these

schemes is essential to a proper overall analysis in every aspect of the system.

The first presented alternative to the Reuse of 1 is the mechanism of a simple reuse of 3, meaning that each sector of a macro-cell is assigned 1/3 of all spectrum. This scheme is commonly referred to as Reuse of 3. Theoretically, one can say that the overall network capacity is reduce to a third compared to the default technique, nevertheless, this technique allows for a total interference cancelation produced by same cell sectors overlap, and the same goes for neighbouring cells sector overlap. In Figure 3-1, the scheme is illustrated and it is possible to observe this first overlap cancelation. When in some cases, neighbouring cells also overlap this interference is also cancelled by the frequency reuse if proper planning of the sectors is made. In this thesis, each macro-cell is assigned manually their frequency, where a microscopic plan was necessary. Some macro-cells only have 2 sectors and one must assure that the small overlaps that occur are assigned different spectrum parts. This contributes for better results and a more realistic approach of what would happen in a realistic scenario, where no operator would restrict a sector available spectrum blindly, without any planning. Small cells are deployed in specific sectors and in this scheme they are assigned part of the rest of the spectrum that is not allocated in the respective sector. For instance, if a small cell is deployed in the first sector of a cell and this cell uses the first 1/3 of spectrum, the small cell will have available another third different from this to avoid more interference. This scheme will achieve maximum results in cases that interference is the most degrading factor, extremely normal in dense urban scenarios as said. Allowing for a total cancelation in this dense network, this scheme allows for a very aggressive deployment of a macro-cell layer solving many capacity issues by its own. The purpose of this study is to see the impact this takes when done with small cell deployment. One could argue, beforehand, that the major handicap this scheme has is the lack of spectrum efficiency, but if it is proven that by using less spectrum, it is possible to provide similar throughputs, small cells can prove to be a very interesting optimisation tool. Again, this thesis is concentrated in a specific region of the network, and a different a more wide range of study would be necessary to fully undertake the analysis of total usefulness or not of the scheme.

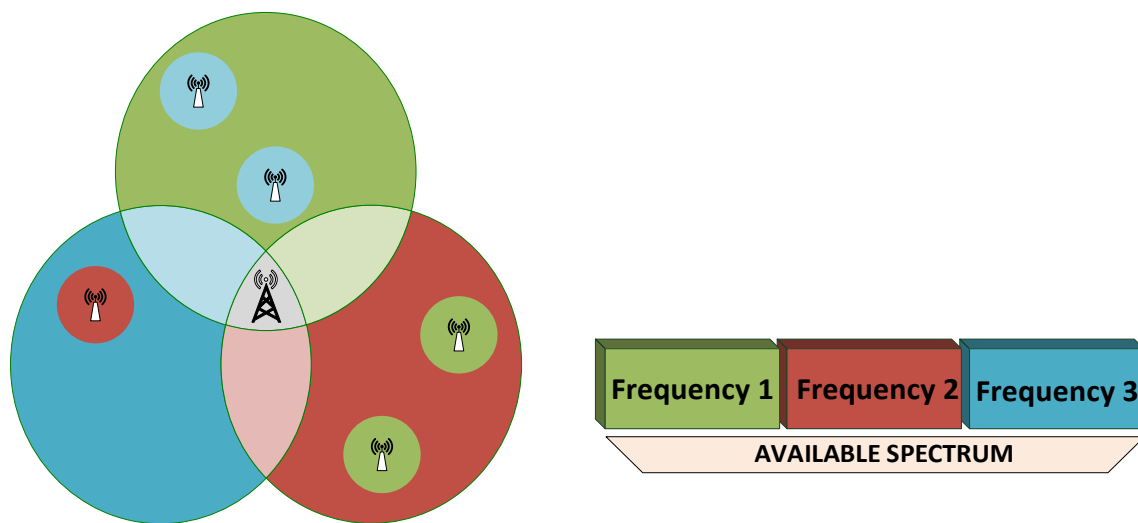
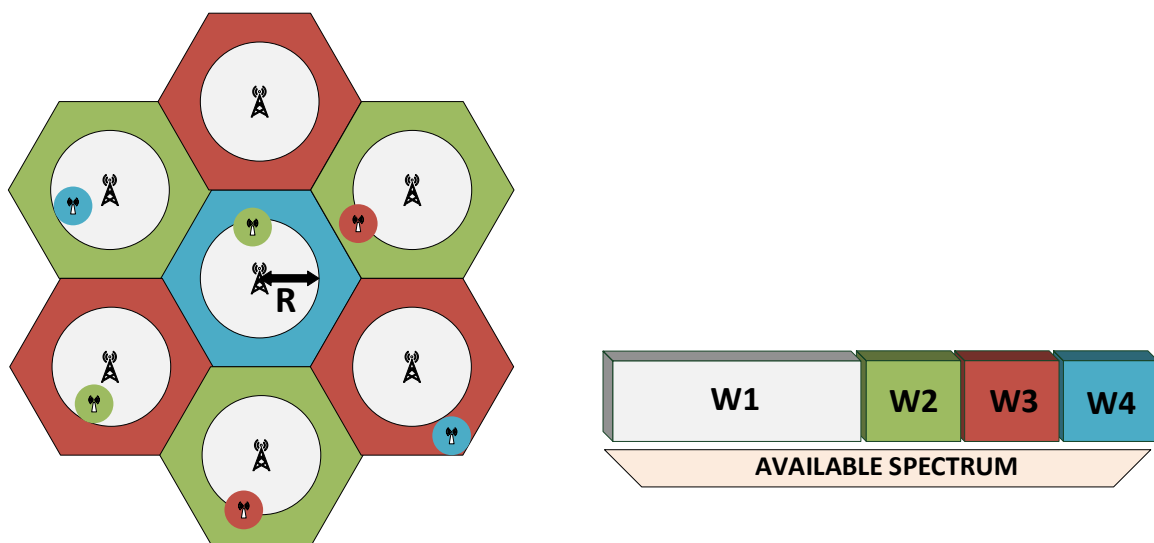


Figure 3-1 Frequency Reuse of 3.

The second scheme is a mechanism based on [BoKa12], designed specifically for heterogeneous networks. For the sake of simplification, this scheme is addressed as the Proposed Scheme for the rest of the thesis. In this scheme, spectrum is divided into four groups: one major group and three equally distributed ones. The major group is used to serve users on the macro-cell centre, while one of the other three serves cell edge users of that cell. The same frequency spectrum interval is used for all the sectors edge of the same cell and is reutilised for the neighbouring cells, as one can observe in Figure 3-2. Similar to the last scheme, neighbouring cells overlapping are the ones that ultimately benefit from this. Edge regions of cells are always critical points where it is difficult to guarantee good coverage. They are also the regions where most of the interference is created, where the same user can receive from different cells the same power. By allowing this edge regions to reutilise frequency, one can benefit from the great advantage of Reuse of 3 to cancel interference, but also keeping the cell centre with optimal capacity on the contrary to Reuse of 3. In Figure 3-2, it is also visible an R , which is the designated value to distinguish between cell centre and cell edge. This value must be studied by simulation and determinates the value that maximises system performance. The same happens to the size of the spectrum groups, which is also studied with the simulator. For this scheme, one can observe that the same cell sector interference consequence of overlapping is not avoided, proving to be its major handicap on overall performance.

Small cells have assigned spectrum that is not used in their current macro-cell, i.e., small cells have one of the three equal intervals available ($W2$, $W3$ and $W4$) that necessarily are not used in the current macro-cell where the small cells are. By doing so, one can avoid and mitigate every interference produced by small cells deployment, leaving the capacity aspect to increase aggressively with deployment maximisation. This can also be observed in Figure 3-2 (a), where the colours represent the assigned spectrum. Since the focus of this thesis is to evaluate various aspects related to small cells from different natures, an extensive study of this scheme was not made in order to exploit this aggressive deployment referred.



(a) Cluster overview after spectrum distribution

(b) Spectrum divided by 4 groups

Figure 3-2 Proposed FRS adapted from [BoKa12]

To fully implement this technique, in the procedure described in [BoKa12], one must firstly study what is the best value for R . This is done by simulation, so that the simulator compare different values in terms of performance and determines one to use for the rest of the simulation. The next step is to set what is the best spectrum division to apply with the designated R . In this thesis, the procedure is changed to fully simulate every possible combination, thus having the best system performance overall. The procedure of determinate the best spectrum division is repeated for different reasonable R values, therefore obtaining the best combination of division values and R value.

To determinate the best RB division, one considers 2 different groups composed of RBs, A and B, where A corresponds to the cell centre (W1) and B to the three groups of cell edge spectrum (W2, W3 and W4). The second one divides the spectrum equally by all three groups. Having for example the 20 MHz bandwidth of the 2600 MHz band, there is a total of 100 RBs at use. At a first stage, one considers 97 RBs available in A and only 3 in B. The B group is then divided into 3 by W2, W3 and W4, giving 1 RB to each. The simulator analyses performance and the second stage of the cycle is to pass another 3 RBs from A to B. Performance is then again measured and so on until there is only 1 RB in A and 99 in B, totalling 33 RBs in W2, W3 and W4. If all this process is repeated to all possible R values, one can achieve the maximum performance enhancement produced by this mechanism.

Through various simulations, the previous described process to determine the spectrum interval is repeated for different R values varying from 50 m, and for each simulation, it was incremented by 50 m. The values of R that were considered to maximise system performance are approximately 300 m and the value for the division is 20, meaning that W1 has 40 RBs and W2, W3 and W4 have each one assign 20 RBs. These are the values used in the results later shown in this thesis.

3.2 Simulator Development

In this section, an overview of the simulator is presented regarding all utilised modules followed by the description of the specific implementation details.

3.2.1 Overview and Structure

The simulator overview and structure is presented in

Figure 3-3. It consists of three main distinct modules, one programmed in MapBasic for geographic computation and the other two programed in C++ to generate input user files and simulate an LTE system for the DL. MapBasic is a programming language similar to VisualBasic and is used to implement functions and programs into the MapInfo program. First, the User Generator creates the *users.txt* file to be used as input in the MapInfo Simulator. Then, using the *users.txt* and *network.tab* input files, this MapInfo simulator deploys the network and performs a single user analysis to determinate areas of coverage, generating two output files to be used on the C++ Simulator, *data.dat* and *defenitions.dat*. Lastly, this simulator performs a DL analysis obtaining the final *output.xls* file,

containing all results. Other debug output files are generated to guarantee simulator functioning. This debug files are vital so that one can observe immediately why a given result is wrong or to assure overall well-functioning of the simulator, ensuring simulator credibility.

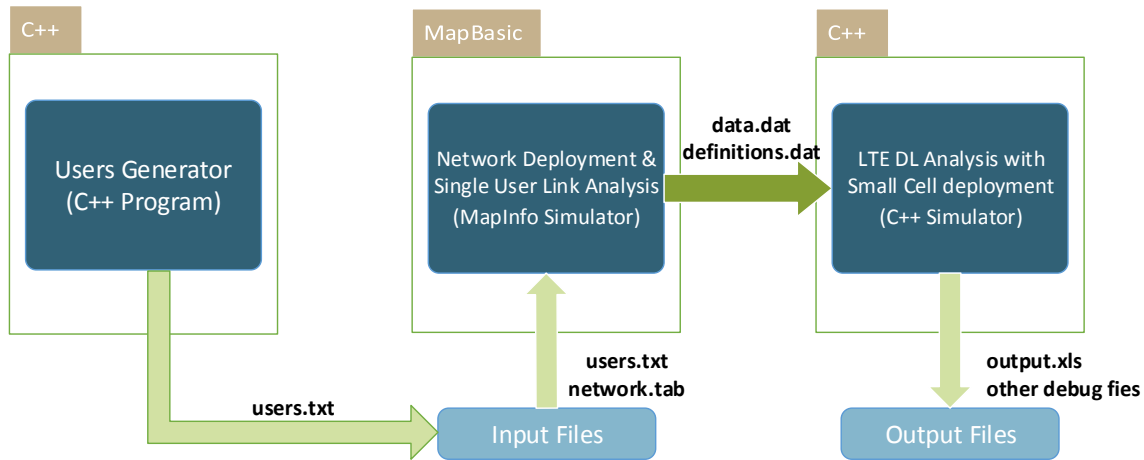


Figure 3-3 Simulator Overview.

The User Generator was originally called SIM and was developed by [Lope08] and [Salv08]. The User Generator used in this thesis was reprogrammed in C++ to obtain more restrict values of the geographic positioning of the users. For the present study, the output files generated by the old SIM where not in sync with the specific cluster used, which is presented later on. So, the old format of the input file *users.txt* is preserved and users are randomly generated assigning them services and scenarios.

There are 7 types of services and simulation distribution of users through these can be specified, referred as penetration margins. There are 4 different possible scenarios in this thesis: pedestrian, vehicular, indoor with low losses and indoor with high losses. The impact of user service and scenario is addressed later on. The main aspect that motivated this new user generator is the feature that allows to specify the area of concentration of most users. One can then simulate, for example, an event day that would attract many users to that specific place. This is explained over the next section when the scenarios are presented in detail.

The MapBasic simulator has been adapted from the one developed in [CoLa06], [Lope08], [Salv08] and [Duar08]. The main structure of this module was left almost unchanged, only adapting the LTE code to allow small cell deployment and the network deployment function to allow specific azimuth definition and sector numbering. This simulator has a lot of integrated functions that were not used, mainly related to prior versions of LTE.

The users and network deployment procedure in MapBasic is described in detail in [CoLa06] as well the various functions to calculate coverage and radius of cells. This has been developed to support UMTS and was later adapted to support LTE by [Duar08]. This document provides the functional description of how MapBasic output files are generated (*data.dat* and *definitions.dat*). The way the simulator from [CoLa06] inputs macro-cells creates always three sectors with the same azimuth for the whole network. Since this thesis addresses specific clusters, as it is explained later, all macro-cell sectors and azimuths are inserted in the code, using a real cluster network with proper antenna

orientation. The specific code for cell deployment developed by [Duar08] was changed to allow small cell deployment. The user of the simulator specifies how many small cells are to be considered, and according to the *network.tab* input file, they are deployed in the positions indicated by the file. The omnidirectional small cell antennas are taken into account as the different DL transmitting power when it comes to determinate cell range. This cell range is determine using (3.9) for both small and macro-cells. The user interface was also implemented based on the previous interface, but eliminating previous non-related functions and adding specific functions. The simulator user's manual is presented in Annex F.

3.2.2 LTE System Implementation with Small Cell enhancement

The C++ simulator was originally developed by [CoLa06], [Lope08], [Salv08], [Duar08], [Jaci09], [Carrei11] and [Pires12], starting with UMTS and since [Duar08] adapted to LTE, lately being expanded to multi-cell modules, interference calculation, soft-frequency reuse schemes and a variety of other functions.

To maximise accuracy, the stats simulation and algorithms were completely redone, and the previous ones discarded. The only part kept from the old simulator is the structure of .cpp files and the different classes defined in them. The content of these classes was changed and algorithms were implemented. All classes' variables that were not used by these algorithms were deleted. New variables and methods were defined to all classes and one applied a policy of memory over cycles, meaning that the possibility to minimise cycles is always taken by using more memory in the range of reasonable values.

The simulator starts by opening the input *.dat* files, updating simulator system variables with *definitions.dat* and creating users connected to sectors with *data.dat*. For the sake of simplification and flow of explanation, when the word sector is mention it is referred to one sector of a macro-cell or to a simple small cell. They can be interpreted as the same element, if proper user assignment and resource availability are well programed for each cell. As mention in Section 2.3, small cells must support the same function ability of an eNB. The MapBasic simulator, as explained in [CoLa06] and [Duar08], generates these output files calculating distances between all sectors and all users in range for a connection in which it is possible to guarantee QoS. The C++ simulator then analyses this *data.dat* file and decides in each sector which users are allocated while randomising which users have LoS or not. There are two possible options that are compared: either the user connects to the sector that offers him the strongest received power, calculated with the equations in Annex B and the models explained with a reference frequency, or the user connects to the nearest sector. Keep in mind for this last option that users' possible connections only appear in the *data.dat* if they are in a valid range of coverage. For instance, in Figure 3-4, the user is closer to the small cell than he is to the macro-cell one, but he is not in the coverage range calculated by the MapBasic simulator, so this connection is not be published to the output file. A through extensive examination of simulation parameters was done in order to guarantee proper workflow and avoid bugs or miscalculations.

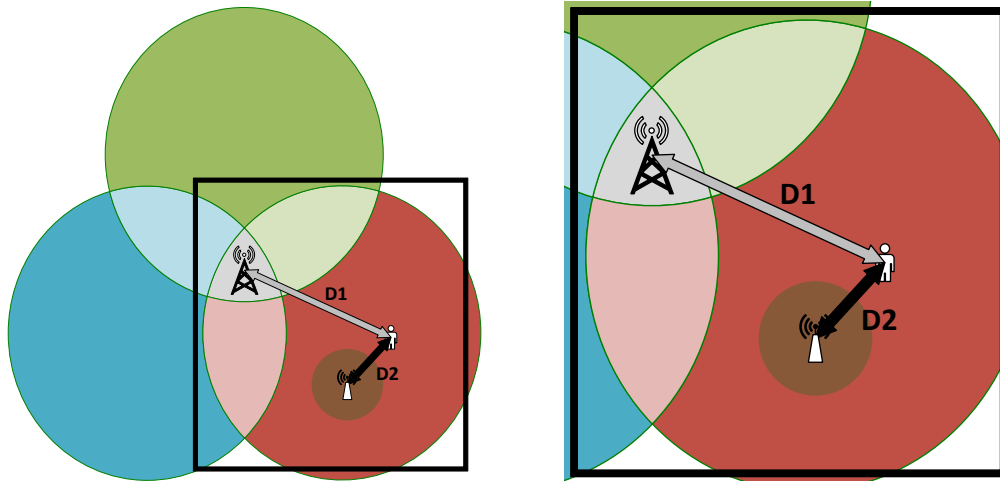


Figure 3-4 User distance to a tri-sector BS and small cell

Also, when connecting by distance, it is also taken into account when a user is in range of two or three different sectors of the same macro-cell. This is possible, e.g., if the user is very close to the antenna site or simply in a frontier region between two sectors, as seen in Figure 3-5. The user connects to the sector that presents the higher antenna gain, obtaining the respective azimuths and orientations, and extracting the antenna gain from the radiation pattern. This radiation pattern corresponds to the Kathrein antennas obtained in files used by [Duar08] and [Jaci09], similar to the antennas actually used on the network. Although the original idea was to connect mainly users by distance, so that small cells were highly promoted over macro-cells, simulations show that results prove to be rather unrealistic and users are assigned the same sectors through all simulations. LoS calculation must have a role on how users connect to sectors, but that only is possible over a received power comparison. This option was only applied in Section 4.3.4.

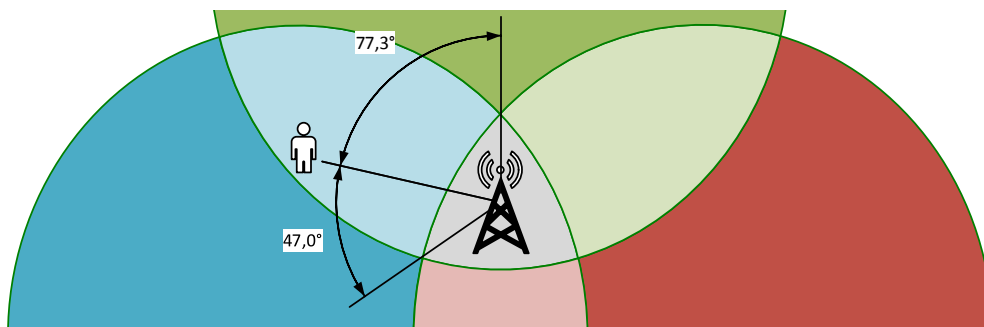


Figure 3-5 Sector antennas orientations and azimuths to user

The step described in the last paragraph, where the radiation pattern is taken into account, is not needed if users are connected by the received power. In other words, when different sectors of the same macro-cell try to connect to a user, the one with the higher antenna gain is the one that presents the higher power received, which is implemented already in the power functions. This is due to all other factors that are taken into account when calculating power (LoS, user scenario, distance, etc.). A proper LoS random values calculation and proper storage was needed to avoid that a user has different LoS to different sectors of the same cell. It was important to guarantee this, otherwise there would be no way to obtain a good connection between this simulator and a realistic scenario. When

different sectors are compared for a single user, the user will always store one as the current connection and the other in a list of interfering sectors.

The frequency band is taken as 2650 MHz for the 2600 MHz band and 1840 MHz for the 1800 MHz one. According to the European Telecommunications Standards Institute (ETSI), [3GPP11], and to the Frequency Attribution National Board (QNAF, in Portuguese), [ANAC11], the LTE bands for DL corresponding to the 2600 MHz band are between 2620 MHz and 2690 MHz and for the 1800 MHz between 1805 MHz and 1880 MHz. For this thesis, taking 20 MHz for each band, one considered between 2640 MHz and 2660 MHz, and between 1830 MHz and 1850 MHz.

Before distributing resources, it is important to assign RBs to the sectors according to the FRS used. All sectors have their RBs assigned and initialised to be ready to be used, which is done by the help of simple vectors and integer storing indexes, the allocation being made more directly and taking less time. The possible FRSs will have different definitions for RBs distribution, so for each simulation this is defined at start. The resource availability in each FRS is described in Sub-section 3.1.6.

After all users are connected to a sector, and sectors know which RBs to use, the resources start being distributed. The first step is to consider service prioritisation. In a realistic system, users must have priority to be served based on the service they are requesting and on their channel condition. Service priority and channel condition are the main factors considered in this thesis that determinate which users receive RBs first. These QoS priorities are presented later, relating them with the respective application QCI.

Firstly, using the reference frequency, the SNR is calculated for each user, then, the list storing the users is organised from the highest to the lowest SNR. The main cycle will go through every service: in the first time, it will serve only users with the first QoS priority service, in the second time the second QoS priority service, and so on. The rest of the algorithm for each cycle is summarised in Figure 3-6. One starts by allocating resources in the user with best channel condition, and then the next one, and so on. On the MapBasic output file *definitions.dat*, there are options made by the user in the MapBasic simulator as described in Annex F, one of them being the desired throughput for each service and the minimum throughput. User's throughput is calculated based on SNR, so, it will be the sum of the throughput of each resource block assigned to the user. The algorithm works by using one RB at a time to add throughput to the user, and verifying if the total throughput already reached the desired value. If the sector runs out of RBs before the desired value is reached, the algorithm starts over the same process but trying to serve the minimum value. If the user still is not served, this user has no condition to make a connection, joining the not connected users. If any of the previous allocation works, the user is connected. In Figure 3-6, a flow chart summarising the algorithm is presented.

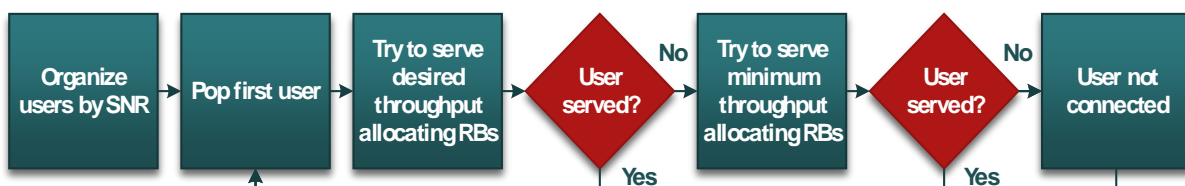


Figure 3-6 Assignment of RBs to users based on SNR repeated one time for each service

To keep a fair resource distribution, as the PFS algorithm applies, this service priority algorithm only serves users that have an SNR over 5 dB. Also, this algorithm only allows for user to have a maximum of 20 RBs (20% of all sector resources), meaning that, if a user needs 21 RBs as the minimum value of his service, he is blocked. This is a useful technique to avoid a single high priority user to starve alone a large number of RBs due to a low channel condition. The user must always have reference SNR higher than 5 dB, but still, if he requests a throughput that needs 60 RBs to guarantee QoS, it makes no sense to allow that a single user gets 60% of all sector resources. So, only users with SNR over 5 dB and a maximum of 20 RBs have been considered for the simulator.

All high priority users and the users with the highest channel condition are served. Most RBs from sectors are distributed at a starting point, and only zones less populated have some RBs left. What follows is the exactly the same algorithm presented in Figure 3-6 for the so far non-connected users. The only difference from the previous situation is that there is no service prioritisation, and there is no limit to the number of RBs to be allocated, meaning that only channel condition is taken into account. This less limiting situation promotes sectors usage and loading of users, as one expects in a realistic network. From this point on, only poor channel condition users and low priority users are not served, either due to starvation of sectors or due to being impossible to guarantee QoS for these users.

Resource allocation is done sequentially, meaning that, for the 100 RBs, the first one to be allocated is the one of index 1, and the last one is of index 100. This is based on 3GPP's specification of Type 2 in resource allocation types, [3GPP13]. This type is the only one that allows the usage of all RB allowed by the 20 MHz bandwidth, and sustains from this logic of resources allocation.

For the desired study, it makes more sense to analyse a fully loaded network in some scenarios. There is an option in the simulator to assign all sectors' RBs using the total system's capacity. After all previous allocations, this option works by going through all connected users in which the corresponding sectors still have non used RBs and adding one RB to each one; the same process is repeated until all resources are utilised. This results in a fair distribution of all remaining RBs. This distribution does not make sense for services like streaming or voice, but it does for FTP, Web Browsing and Pear-to-Pear. Although this option successfully loads every RB in the system, it contributes to increase the already calculated throughput and the further calculated final throughput with interference. So this option contributes to obtain a little more optimistic results, but that is not the desired goal for this thesis. This option was only applied in Sub-section 4.3.4, where high data services are tested and the small cell deployment is analysed.

Once all users have RBs assigned, the simulator calculates the throughput based on SINR, by going through all users' RBs, and calculating interference for each one. When users are connected to sectors at the beginning of the program, each time a user compares two sectors, the one that "looses" is stored in a user list with its interfering sectors, as previously referred. This way, every user is connected to its best cell, but he also has a list of all other interfering sectors. This optimises computation time when the SINR calculation algorithm is executed, automatically knowing which sectors interfere with that user connection. The sectors' RB allocation vector is consulted each time interference from a sector is calculated, because if a sector is not using the specific RB, it will not

contribute with interference. The user will have assigned its specific RB, so the way this algorithm works is by going through the list of all users in a big cycle: first, it calculates for every RB (in a vector with 100 positions) which is the received interference power for that user, using the list of interfering sectors, and consulting the RBs that are being used; then, the RBs the user is using are analysed, and the interference of each one is taken into account on new SINR calculations. Then, with SINR, the final throughput is obtained in the same way it was for SNR. A variety of studies were conducted in order to assess this function, and the calculated values of interference make much sense. One should remember that by connecting users with power received, every single interfering cell generates less received power compared with the connected cell. One later concludes that the used network has only a few areas where overlapping occurs. The most common is the overlapping of two sectors, followed by some rare zones where three sectors overlap, and finally two very specific zones where 4 sectors overlap. LoS could also have an impact over interference calculation, if interfering cells could have LoS as the directly connected ones.

3.3 Model and Simulator Assessment

In this section, the simulator validation is shown by analysing different factors in the system and comparing them to the values expected theoretically. The propagation models and frequency algorithms were confirmed, firstly using different calculations in excel sheets and generated input files for a proper analysis. A reference scenario was chosen with specific simulation inputs, and various simulations were performed in order to draw conclusions about results assessment; also, single simulations were performed to test data peak values.

The previous explained steps to calculate final user throughput were programmed into different functions, and each of these functions generates an output txt file proper for debugging. For each simulation, it is possible to consult, e.g.: the list of users organised by SNR; which RBs are available in each sector and which are their throughputs, with and without interference; which RBs each user has assigned and which is the user throughput; and all other used variables and calculated values relevant to output calculation. These values were constantly monitored, during the programming phase.

Expected theoretical peak rates are presented in Table 3.1, equal to the ones presented by 3GPP. These values have been confirmed by a variety of studies, [CuiDo09], being also confirmed for this simulator. A peak rate is calculated for an ideal situation where the user is the only one in the cell, exhausting all resources, considering also all environment aspects and attenuating factors as the most optimistic ones. This means the user has LoS, has no attenuation due to any kind of obstruction, his scenario will be pedestrian with the lowest fast and slow fading margins, and he will be located near to a cell with approximately zero angle to the antenna orientation. This process is done for a small cell and macro-cell, and can be compared with the theoretical value in Table 3.1. The obtained values are very similar to the expected ones, and keep the proportionality between 1x1 and 2x2 streams. The small difference between the values is justified by the possibility of the user not having exactly null

angle with the antenna orientation or the distance not being relatively small enough.

Table 3.1 LTE DL Peak Rates for the band 2600 and 20 MHz Bandwidth

Extracted from [CuiDo09]	Result from the Simulator
1x1 parallel data stream	1x1 SISO small cell
75 376 Mbps	74 948 Mbps
2x2 parallel data stream	2x2 MIMO macro-cell or small cell
150 752 Mbps	149 894 Mbps

Comparing simulation times, when MapInfo output files need to be generated, it takes about 10 to 20 minutes to conclude the whole process of choosing parameters, inserting users and network deployment. The C++ simulator takes about 0.2 s to conclude all necessary calculations. The simulations were performed on a laptop with an Intel® Core™ i7-2670QM CPU @ 2.2 GHz processing unit.

A larger amount of simulations need to be performed for the reference scenario in order to draw overall system conclusions. This is only possible by simulating for the same defined scenario various numbers of simulations. The programmed simulator only has a few random generated values for each simulation, which are the values for LoS and a few attenuating factors. For this simulator assessment, user requested throughput is the same for each service (8 Mbit/s) as well as the minimum throughput (2 Mbit/s), and the program feature to increase RB usage is disabled, to simplify the analysis. So, the obtained results allowed us to observe that all obtained values made sense with what one would expect from the system and the explained theoretical models, other than peak rates.

In order to proper analyse results from simulations, one can only draw conclusions in multiple values by calculating the average and standard deviation statistical values, [Mora10]. The calculated values address the multiple throughputs by users and cells, so one must ensure that many simulations are done so that the calculate values have more statistical relevance. The average value and the standard deviation are respectively calculated by the following equations:

$$\mu = \frac{\sum_{i=1}^{N_z} z_i}{N_z}$$

where:

- z_i is the value of sample i ;
- N_z is the number of samples.

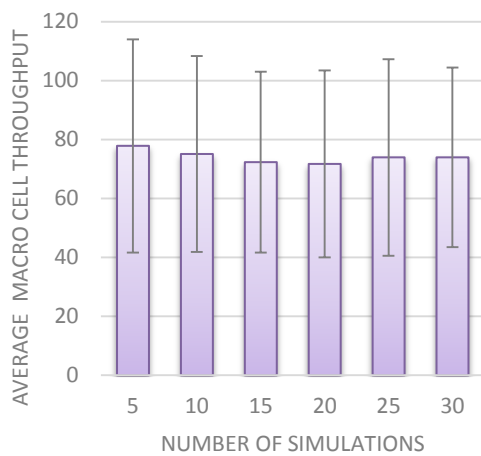
$$\sigma = \sqrt{\frac{1}{N_z} \sum_{i=1}^{N_z} (z_i - \bar{z})^2}$$

where:

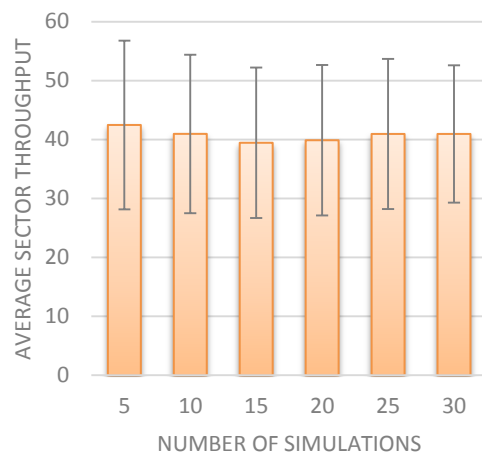
- \bar{z} is the average value of the population Z.

In the simulator, the last function runs all the stored values in a cycle, calculating all average values. These values alone are not enough to draw conclusions, so a second cycle is performed to calculate the standard deviations with the respective averages. In the first cycle, maximum and minimum values are also stored to simplify assessment, and to ensure the all values are reasonable.

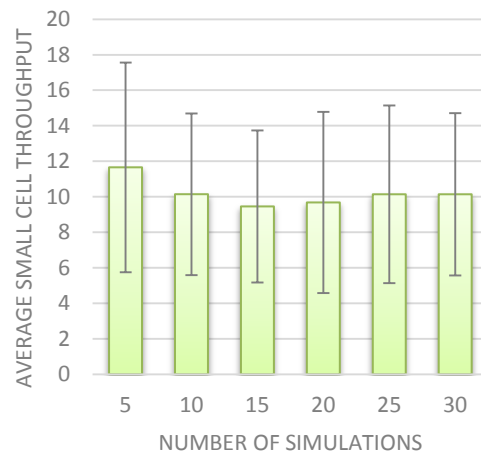
Considering a controlled scenario using one specific *users.txt* input file, this is simulated 5 times to assure statistical relevance for the random values explained. This process is then repeated for 5 different input files allowing the geographic distribution of users to vary, added by the requested service and user scenario, making a total of 25 simulations. The results along each 5 simulations are displayed in Figure 3-7 for different performance parameters. The overall variation of these values justifies that 25 simulations are more than enough to assure results worthiness, using this mechanism throughout this thesis.



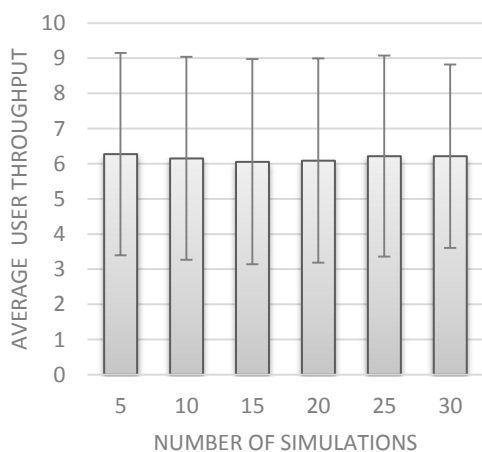
(a) Average Macro-cell Throughput (Mbit/s)



(b) Average Sector Throughput (Mbit/s)



(c) Average Small Cell Throughput (Mbit/s)



(d) Average User Throughput (Mbit/s)

Figure 3-7 Average Values of Instantaneous Throughput and the respective Standard Deviation

In Figure 3-7 (d), the user throughput slightly varies from over 6 Mbit/s, which makes sense for the requested throughput of 8 Mbit/s and minimum 2 Mbit/s, placing most users around the requested value and fewer in the minimum value. The high standard deviation for all charts is easily justified by

the characteristics of the cluster, which is presented in the next section. It is a small cluster in which each sector varies in overlapping and number of users. The number of users deployed to perform these simulations is approximately 250 users.

In Figure 3-8, the evolution of satisfied users (users above minimum service throughput) with the respective covered users is presented. Remember that many users deployed in the network, due to their positioning, scenario and LoS, will never have channel conditions that guarantee the minimum throughput for a specific service using a reasonable number of RBs. One can observe that the number of satisfied users continues to increase with the number of covered users, but it makes no sense to consider more than approximately 350 users covered for the reference scenario, corresponding to approximately 100 satisfied users. Keep in mind that this chart is also obtained for the requested throughput of 8 Mbit/s and minimum 2 Mbit/s, so, results in the next sections may vary when all users request different service throughputs and also, much lesser minimum throughputs. In other words, a higher number of served users is expected in the real analysis of results.

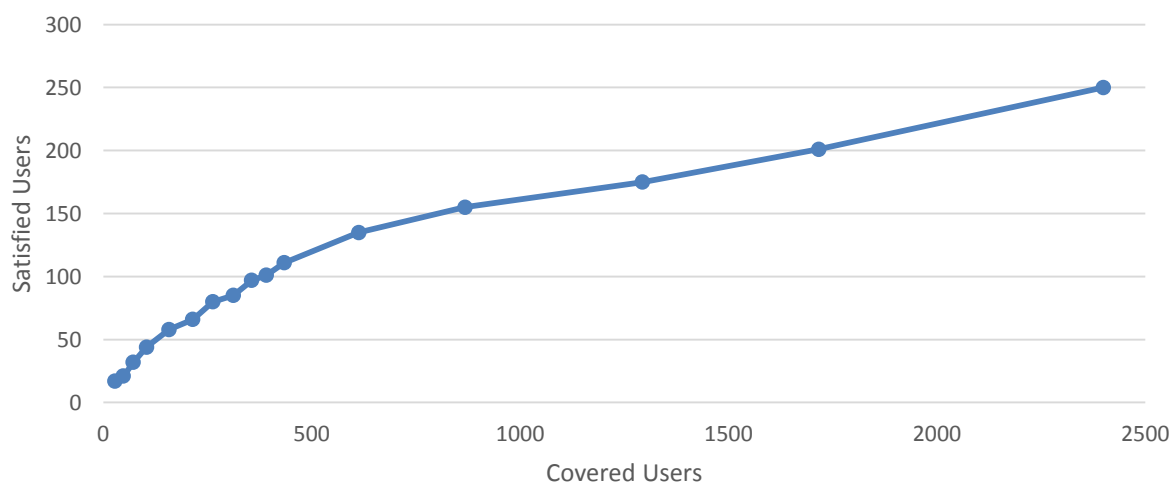


Figure 3-8 Evolution of Satisfied Users with the respective Covered Users

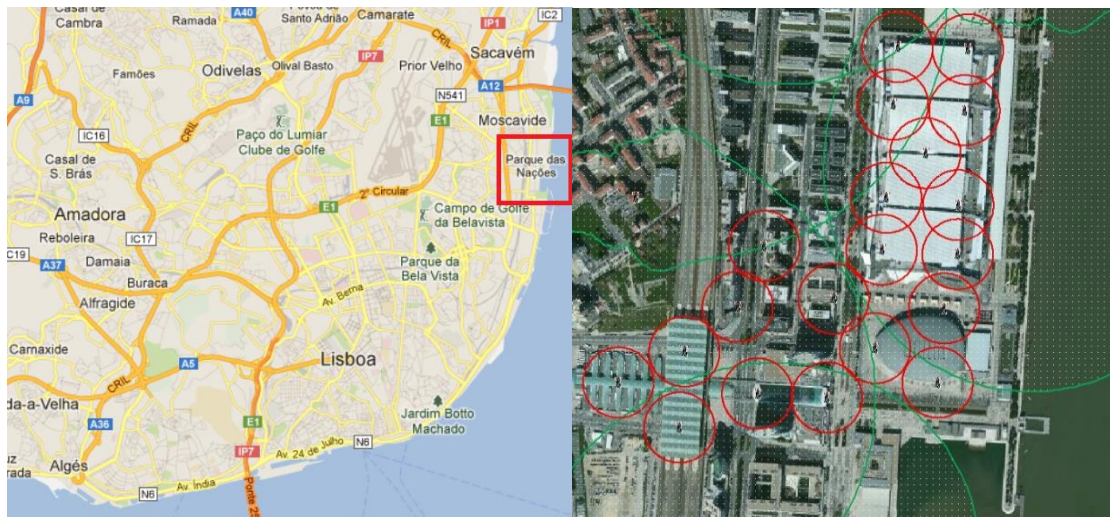
Chapter 4

Results Analysis

This chapter contains the simulated scenarios and the corresponding simulation results plus their analysis. First, the scenarios' overall description is made, where the more general concepts are presented and the parameters taken into consideration for all scenarios are presented. The second section addresses the average normal day scenario, where a uniform distribution of users is considered, similar to what would happen in a normal business day. The last and final section presents the event day scenario, where users tend to be more concentrated in a specific region in the network where an event takes place.

4.1 Scenarios Description

One has chosen a typical urban scenario of offices location, composed of heavy traffic users during the day, and occasional heavy affluence of users in case of a special event, i.e., a specific region in the city of Lisbon, Parque das Nações; this location is quite interesting, since it illustrates a scenario with various data traffic profiles. It is also the headquarters location of many major corporations based in Lisbon, and also entertainment facilities as Meo Arena and Casino of Lisbon, with night-shows of heavy network traffic load; another facility of interest is the International Fair of Lisbon (FIL, in Portuguese) which promotes a variety of different events that can last for a week, also attracting a large number of users. All cluster information was provided in order to obtain the most accurate results. In Figure 4-1 (a), a map of the city is presented, where it is highlighted in red the Parque das Nações region; in Figure 4-1 (b), the Optimus cluster is detailed, where small cells were inserted, with all the locations of the small cells and the coverage of a few macro-cells.



a) Lisbon Map

b) Small cell deployment in Parque das Nações

Figure 4-1 Target scenario location.

A total of 20 small cells were deployed over the critical event areas, visible in Figure 4-1 (b); the results try to show what one would obtain by adding first 10 small cells, and then the other 10. The deployment was made manually with the help of the MapInfo geographic tool in specific locations where it would be possible to install a small cell. The region of analysis can be consulted in Annex G, where the deployment can be analysed in detail.

The described location has a propagation environment similar to a dense urban scenario: most of the coverage is obtained by multipath and it is likely that users have LoS. Also, users can experience a low interference, due to cell overlapping that occurs in some regions. Azimuths are adequately optimised, which contributes to interference avoidance.

The values of the COST231-Walfish-Ikegami model are described in Annex A. For this simulation, the fixed values that reflect the most realistic approximation for the target scenario are shown in Table 4.1, based on [Pires12]; these values are considered for all scenarios. A value is added to the propagation model to take building penetration loss into consideration, based on user indoor scenario.

Table 4.1 COST231-Walfisch-Ikegami model parameters.

Parameter	Value Considered
BS Height (h_B) [m]	26
MT Height (h_m) [m]	1.7
Buildings Height (H_B) [m]	24
Street Width (w_s) [m]	24
Inter Buildings Distance (w_B) [m]	48
Incidence Angle (ϕ) [°]	90
Penetration Loss (L_i) [dB]	10 or 20

The values used for the small cells propagation model are presented in Table 4.2. The wall attenuations in the table are based on [3GPP12g], where the study case for dense urban scenario resembles with the one presented in this thesis. The number of penetrated floors is always 0, since this is a two dimensional simulation not taking users located on buildings' floors into account. All users are deployed at ground level, either indoor or outdoor. The number of indoor walls is a randomly generated integer between 0 and 3, based on user indoor scenario. The number of outdoor walls is random generated integer between 0 and 2, also based on user indoor scenario.

Table 4.2 Small cell propagation model parameters

Parameter	Value Considered
Penetration Loss of Indoor Wall (L_{iw}) [dB]	5
Penetration Loss of Outdoor Wall (L_{ow}) [dB]	20
Number of Penetrated Floors (n)	0
Number of indoor walls (q)	0, 1, 2 or 3
Number of outdoor walls (i)	0, 1 or 2

Two mobility patterns are considered: pedestrian and vehicular. The pedestrian refers to a static user (or at max, 3 km/h according to ITU Pedestrian A channel, as described in Annex C) at ground level with low loss margins, being used for outdoor and indoor users. The vehicular refers to a fast moving user, typically at 50 km/h, also at ground level with higher attenuation margins. These mobility patterns were taken into consideration with the respective user scenarios and are also explained in more detailed in Annex C, including how they influence throughput calculation in the SINR mapping.

Four different types of users are considered, as explained in Section 3.2.1. Their impact is based on the amount of attenuation their scenario has been assigned, their influence on the fading margins, and the channel conditions. All these factors are presented in Table 4.3.

Table 4.3 User scenario available and the respective parameters

Parameter	User Scenario			
	Pedestrian	Vehicular	Indoor Low Loss	Indoor High Loss
Fast Fading Margin (M_{FF}) [dB]	0.3	1	0	0
Slow Fading Margin (M_{SF}) [dB]	4.5	7.5	7	7
Number of indoor walls (q)	0	0	0, 1 or 2	1, 2 or 3
Number of outdoor walls (i)	0	0	1	1 or 2
Penetration Loss (L_i) [dB]	0	0	10	20
Probability of having LoS [%]	50	10	1	1

The default simulation values are presented in Table 4.4. Normally, small cells have a lower transmission power, these values being based on Alcatel-Lucent Metro Cells, [Alca11] and [Alca12]. As explained previously, macro-cells have a 2x2 MIMO configuration, and the same is done for small cells. Also, as explained in Section 3.2.1, the macro-cell antenna radiation pattern is obtained from [Duar08] and [Jaci09], in which the antenna gain varies with the angle of the user, being the maximum the value in the table. For small cells, the antenna has a gain of 5 dBi in every direction, while for the mobile terminal it is assumed to be 1 dBi. The study made in this thesis includes only the two reference bands with 20 MHz bandwidth, i.e., the 1800 MHz and the 2600 MHz bands. The modulations are the ones available in LTE, the selection being done by AMC. The human body naturally absorbs energy, so a 1 dB user loss was considered [Carrei11]. A margin due to losses for cables and connectors was considered as well; although the equipment has a variety of types and manufactures, a 2 dB loss was assumed, [Carrei11].

The available services and the corresponding requested and minimum throughput are presented in Table 4.5. A cross-reference was made with Table 2.3, associating the services with the QCI of the corresponding applications and then assigning QoS Priority based on the desired penetration percentages with the QCI.

All results are obtained from the described simulator. Until the present day, Portuguese mobile communications operators still have not made any investments in small cell deployment, making impossible to compare the theoretical results with others acquired from measurements.

Two types of scenarios are considered, where the Normal Day Load refers to a normal and uniform distribution of users throughout the network, while the Event Day Load refers to 82% of users being concentrated in the most critical event areas, Meo Arena, FIL, Estação Oriente and Vasco da Gama, corresponding to what would happen in these events days, Figure 4-1 (b).

Table 4.4 Default simulation values

Parameter	LTE DL	
	Small Cell	Macro-cell
Transmission Power [dBm]	24	46
Maximum BS Antenna Gain [dBi]	5 (omnidirectional)	17
Antenna Configurations	2x2 MIMO	
MT Antenna Gain [dBi]	1	
Frequency Band [MHz]	1800 or 2600	
Bandwidth [MHz]	20	
Available Modulations	QPSK, 16QAM and 64QAM	
User Losses [dB]	1	
Cable losses between emitter and antenna [dB]	2	
Noise Figure [dB]	7	

Table 4.5 Requested and minimum throughput considered for each service.

Service	Throughput [Mbps]		QCI	QoS Priority	Penetration
	Requested	Minimum			
Voice	0.064	0.032	1	1	20%
Streaming	6.000	1.024	3	2	20%
Chat	0.384	0.064	7	3	10%
Web Browsing	20.00	1.024	8	4	30%
FTP	21.50	1.024	8	5	10%
E-mail	8.000	1.024	9	6	5%
P2P	5.000	1.024	9	7	5%

As already said, all values were obtained from 25 simulations repeated for each series (only macro-cells, 10 small cells and 20 small cells), making a total of 75 simulations. This methodology was applied for every single result, except for the covered users for each case and the requested throughputs, which are fixed values that are the same for all simulations.

4.2 Normal Day Load Scenario

In this section, the performance of the system is analysed in the number of small cells used to proper access the impact of small cell deployment. First, the reference scenario is analysed, with all performance parameters presented. Then, this reference scenario is analysed with different variation settings to determine the impact of each indicator in system performance, such as the carrier frequency used or the FRS applied.

4.2.1 Reference Scenario

The reference scenario considered for this section consists of all the options assumed in the previous section, plus a deployment of approximately 350 users and no FRS applied, meaning the simple Reuse-1 of spectrum, or frequency. First, the cells throughput and performance is evaluated, and then the user performance is analysed. The mobility patterns distribution is that 20% of users are pedestrian, 10% are vehicular, 35% indoor low loss and another 35% indoor high loss. These options aim at a more realistic analysis, along with the option chosen for the code rates in Annex D.

First, the total system throughput is presented in Figure 4-2; one can observe that small cells produce higher network traffic as expected. This is consequence of higher number of resources available and more radio access points available to connect users. These results make sense with what one would expect in a real network with deployment of small cells.

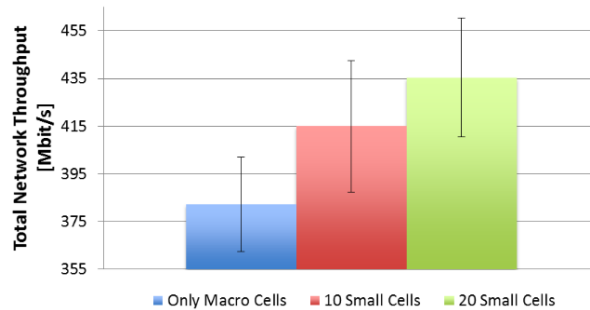


Figure 4-2 Average Total System Throughput

In Figure 4-3, average macro-cell, sector and micro-cell total throughput and respective deviations are presented. Only values for 20 small cells deployment are presented, because there are almost no differences for 0 or 10 small cells. Anyway, the respective values for all deployments are presented in Annex E, Section E.1. There is a residual difference between having small cells deployed or not, naturally for the cases of sector and macro-cell. This difference is lower than 1%, being due to a slight offload that small cells provide to a network. But since there are many users deployed that are not served due to the lack of resources, these users start being served with small cell deployment, as one may observe later. The offload is not bigger due to the way the algorithm has been structured: almost none of the resources are unused, allocating always new users if possible. The high standard deviations are due to the nature of the cluster, where BS positioning and sectors are variable, depending on the number of users deployed, and where some sectors suffer more interference than

others. The results for the small cells total average throughput are also presented, and one can observe a big difference between these values and the ones from macro-cells. These values are easily justified by the number of users connected to a small cell, compared with the number that connect to a sector from a macro-cell.

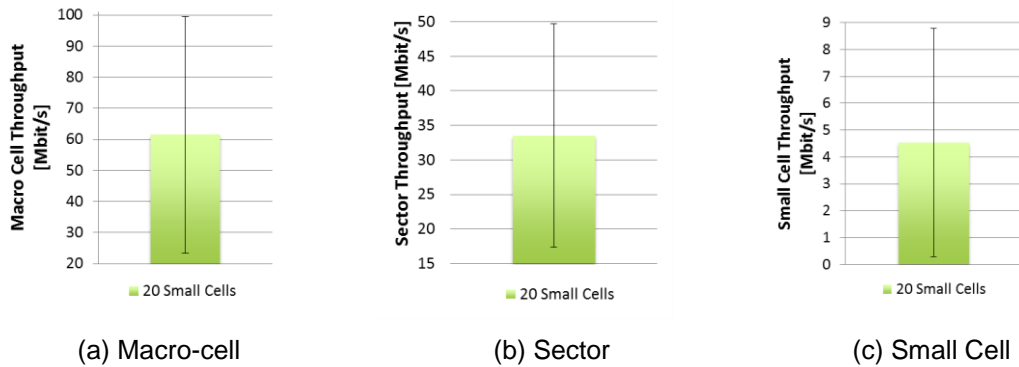


Figure 4-3 Average throughput and respective deviations for different elements

In Figure 4-4, the average users served per macro-cell sector is presented as well as for small cells. The small number of users that connect to a small cell compared to the ones that connect to a macro-cell is mostly the cause for this difference in values. This makes sense, reasoning that small cells mostly do not exhaust their resources for this scenario. The low range of small cells highly restricts the available users to connect in an evenly distribution positioning of users throughout the region under analysis. Users request different values of throughput depending on the service and if their channel condition is poor, they are only served by the minimum service throughput. Comparing the different deployments, one can observe a slight offload of a number of users by adding small cells but still it is quite residual. These values make sense for a realistic scenario, where the difference in areas of coverage between a macro-cell sector and a small cell is very significant; naturally, it is expected that macro-cell cover and connect more users. Also, this indicates that the positioning of users is a key factor to determine small cell deployment usefulness.

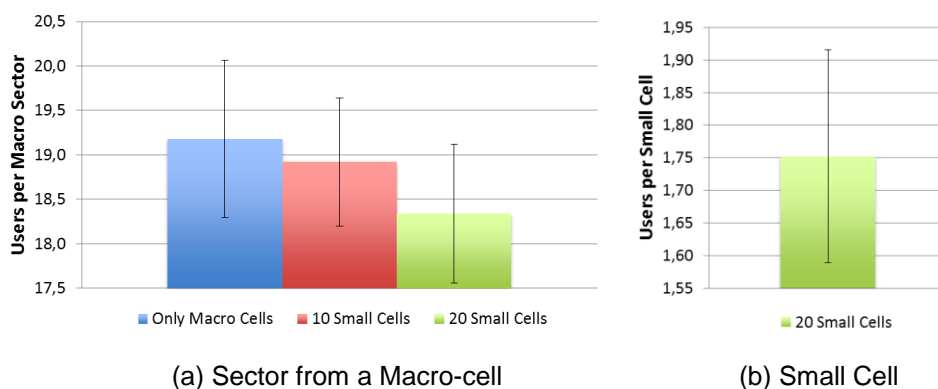


Figure 4-4 Average number of users per different elements of the network

After analysing the impact on the system, the next step is to analyse the impact on the end user. In Figure 4-5, the average user throughput is presented for all users and for only small cell users. Again, more values can be consulted in Annex E. One can observe that the higher average of (b) compared to (a) is a reflection that small cell users are in general best served then macro-cell ones. The way the

resource distribution is taken in the algorithm prevails fairness among users, not letting a single user to consume too much resources of a cell by his own, regardless of his service priority. This justifies why the average values are so close to the minimum values of services, the majority of the users being connected with the minimum service throughput rather than the requested one. Again, since there are many served users, the variation of the throughput values continues to be residual with the small cell insertion. Also, the smaller amount of users connected per small cell also contributes to this residual difference between the two values. These values are quite realistic compared to what one would expect in a very populated network such as this one, also proving fairness of the resource distribution algorithm, as one expects from a real network.

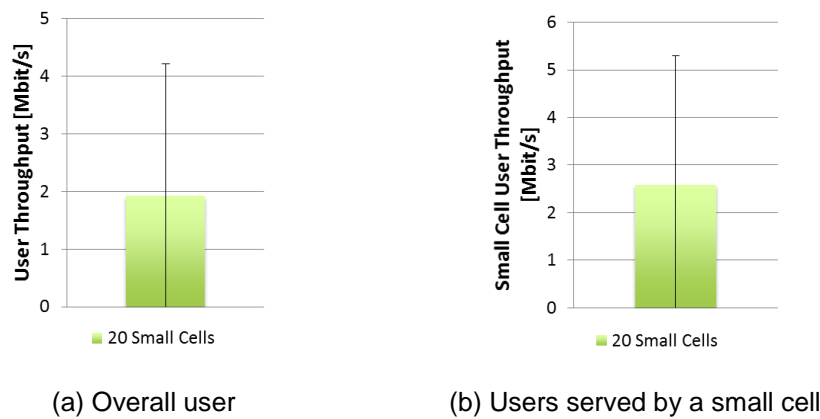


Figure 4-5 Single user average throughput for different elements

User satisfaction characterisation is presented in Figure 4-6. The simulator allocates RBs to a user based on SNR, trying to serve the requested or the minimum throughputs, calculating the real throughput based on SINR after that. A satisfied user is a user that after interference has been accounted for in SINR, still has a throughput that is higher than the minimum value for the service. Remember that throughput is based on SINR, taking interference into consideration. Naturally, with the deployment of small cells, the number of satisfied users increases heavily, but the satisfaction ratio starts to decay residually. This is due to a small interference effect created by the insertion of small cells but, as it can be observed, this effect is not very relevant. In a realistic network, with a proper planning of BS location and azimuth orientations, one should expect this lower effect from interference compared with a network with many overlapping sectors; this matter is addressed later.

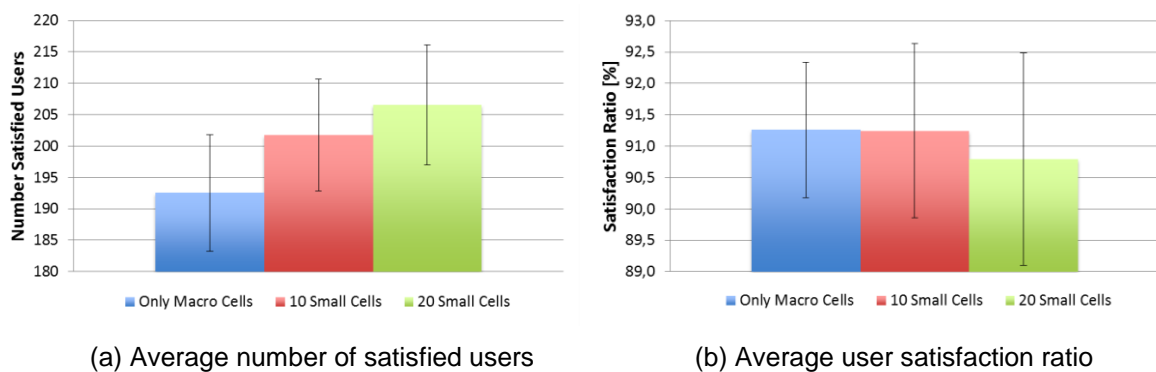


Figure 4-6 Different average user characterisation values

In Figure 4-7, the relation between covered and served users is presented. This is a very subjective part to analyse, as explained in Section 3.1.4, since the number of served users depends highly on which services and throughputs are requested. For the presented values, these results are quite satisfactory. In a real scenario, there will not be 30% of all users requesting 20 Mbit/s of throughput, proving that these results are acceptable for a pessimist analysis. The nearly 150 users non-connected correspond to the users that actually present the worse channel conditions. Naturally, the number of served users increases with the deployment of small cells, as one observes in Figure 4-7, small cells will in almost every case boosting network capacity.

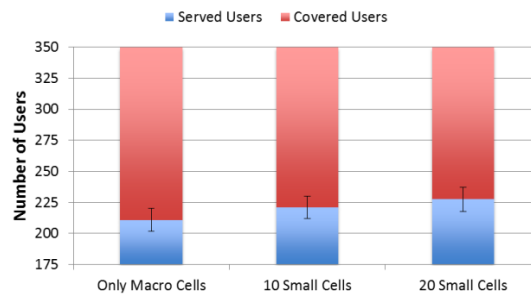


Figure 4-7 Relation between the average of served users and the number of covered users

To support the results from Figure 4-5, Figure 4-6 and Figure 4-7, an analysis is made in terms of services in Figure 4-8, only for the 20 small cells. There are no relevant differences for the other two types of deployments in terms of throughput results, and this deployment proves to be more worth of a detailed analysis. The same is repeated for all the following scenarios. The average number of served users is compared with the number of covered users (or deployed users) for each service in Figure 4-8 (a), and the average and requested throughput for each service is compared in Figure 4-8 (b). One can observe and confirm in Figure 4-8 (a) the penetration margins assumed for each service presented in

Table 4.5. As explained, the percentage of served users for each service depends on service priority in a first level. The next limiting factor is the channel condition the user presents to make the connection, the ones that present a better SNR being serving. The visible non served users in Figure 4-8 (a) that are from priority services, like voice or streaming, must all present very poor channel condition. To connect these users, cells would have to use many RBs in a single user to provide the requested or minimum throughputs, which would prove to be an extremely unfair distribution of resources. To avoid this, the service priority is only applied in a first stage in users with SNR higher than 0 dB; when the second phase starts, it is possible for cells with already starved RBs to leave these priority service users not served. The effectiveness of the PFS algorithm explained in Sections 3.1.4 and 3.2.2 is more visible in the respective average values of provided versus requested throughput in Figure 4-8 (b); this effectiveness is proved by the most visible factor in this chart: the average throughput in Web Browsing and FTP. Requesting a throughput of 20 and 21.5 Mbit/s in 4th and 5th priority services forces cells to allow these users to use only the minimum throughput to maintain the service. A further service analysis is presented later, in proving high data capabilities, but for the presented analysis, the focus is on average normal day scenario, where a single user cannot

exhaust all cell resources. Since the requested values from services like Streaming, E-mail and P2P are more reasonable, it is possible to observe that most users have the requested throughput rather than the minimum one; the contrary applies to Web Browsing and FTP. A note for the two lower priority services, E-mail and P2P: one should keep in mind that the actual number of served users in these two services is very low compared with all other services, with a penetration of 5%. It is natural that only a very low number of users served present optimal channel conditions, thus the high average user throughput values. To reinforce this idea, the E-mail throughput request is 3 Mbit/s more than P2P, and presents a lower average value compared with the requested throughput for each.

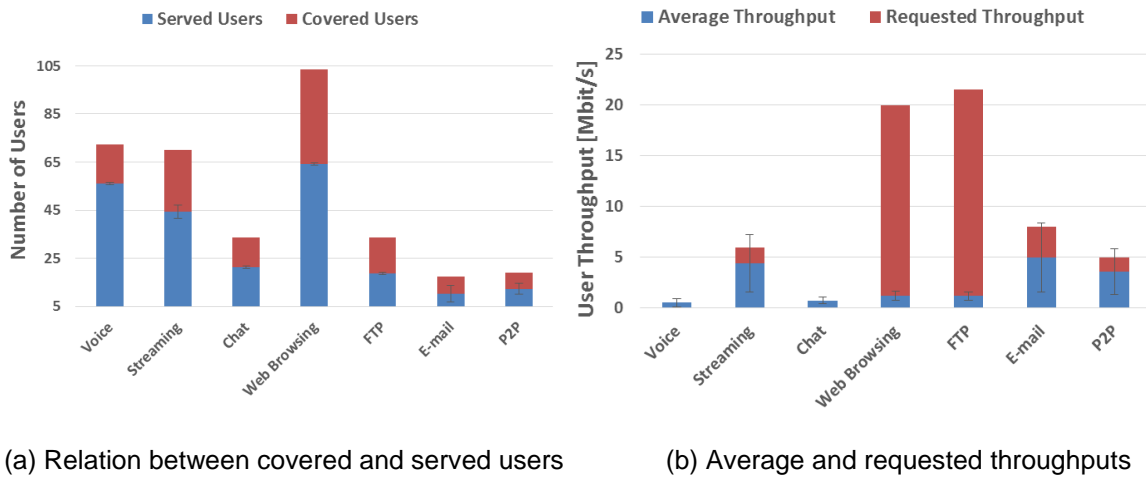


Figure 4-8 Average values of served users and throughput for each service

As repeatedly referred, the throughput values shown are calculated based on SINR, taking interference into account from the beginning. But for one to study the interference effect, the values of SNR and SINR must be compared, since these values can be used to determine throughput. During simulation, throughput for SNR were calculated with an interference margin, not leaving many differences from the expected throughput in SINR, but still in some specific cases users are unsatisfied, as seen in Figure 4-6 (b). To further analyse the interference effect, the values of SNR and SINR are shown in Figure 4-9, and also compared in terms of averages in Figure 4-10

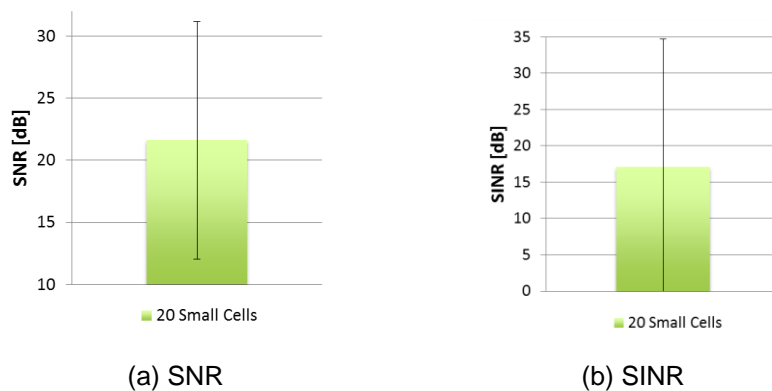


Figure 4-9 Average user SNR and the average user SINR

The two average values presented are only approximately 5 dB apart, from which one could conclude that the interference effect is not visible. But the much higher value of standard deviation in Figure 4-9

proves the contrary. By having a much more chaotic distribution of values in SINR proves that for only a small portion of elements in the network the actual degrading effect of interference is felt. This is supported by the percentages presented in Figure 4-6 (b), with most users satisfied. Also, the averages values presented in Figure 4-8 (b) are always lower than the requested ones. A proper distributed and planed macro-cells network, such as the one used in this thesis, does not have much degrading effects from interference with the applied load.

To finalise this analysis, one can observe that in a small cell deployment for this specific scenario, user distribution and network deployment do not contribute to add more interference, as seen in Figure 4-10. In a realistic scenario, the comparison between interference effects would highly depend on area characteristics and small cell placement.

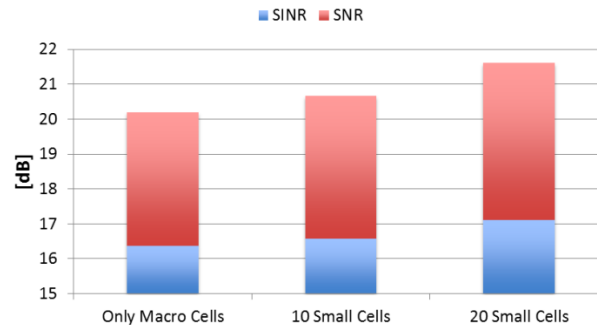


Figure 4-10 Comparison between the average values of SNR and SINR

4.2.2 Carrier Analysis

In this section, all previous settings are taken into consideration but the carrier frequency is changed to the 1800 MHz band. The results are all compared with the 2600 MHz band used in the reference scenario. Only relevant different values are presented, the remaining ones being in Annex E.

The total system throughput is analysed for the different deployments in Figure 4-11.

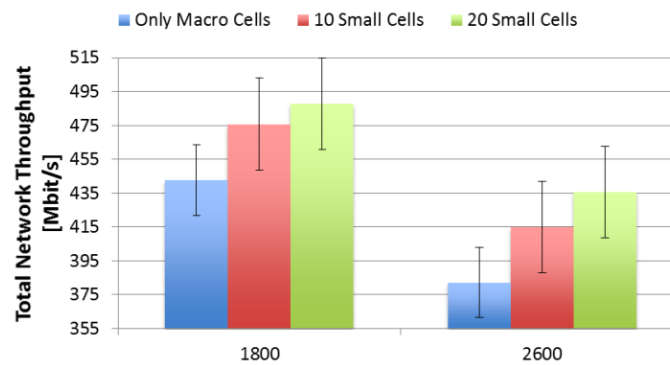


Figure 4-11 Average Total System Throughput

One can observe the main difference between these two frequencies: observing the equations used in Annex A for the macro-cells, one can notice that lower frequencies present a lower propagation attenuation. This is observed by this increment of approximately 12.6% of total throughput produced

by the network. The used propagation model for the small cells does not show the effect of different frequency attenuation, since users are connected with an average distance that is in order of 1/10 of the macro-cell users, leading this attenuation to very residual levels. Nevertheless, the overall results imply that one needs less RBs to serve the same users as previously, and an increase of capacity in terms of throughput. The consequences of this growth are analysed later. Comparing with a realistic scenario, one should also expect better results from 1800 MHz compared with 2600 MHz.

In Figure 4-12, one can continue to observe and confirm the capacity growth shown in Figure 4-11, where the number of users increases approximately 21% for the macro-cell. The contrast described in the previous paragraph between the 2 propagation models, for macro- and small cells, is confirmed with the differences visible in (a) and the almost same value of users per small cell presented in (b). The better condition of macro-cells with this frequency allows for this capacity increase, while in small cells the residual change visible is in the opposite direction, a minor consequence of increasing the number of users connected to macro-cells.

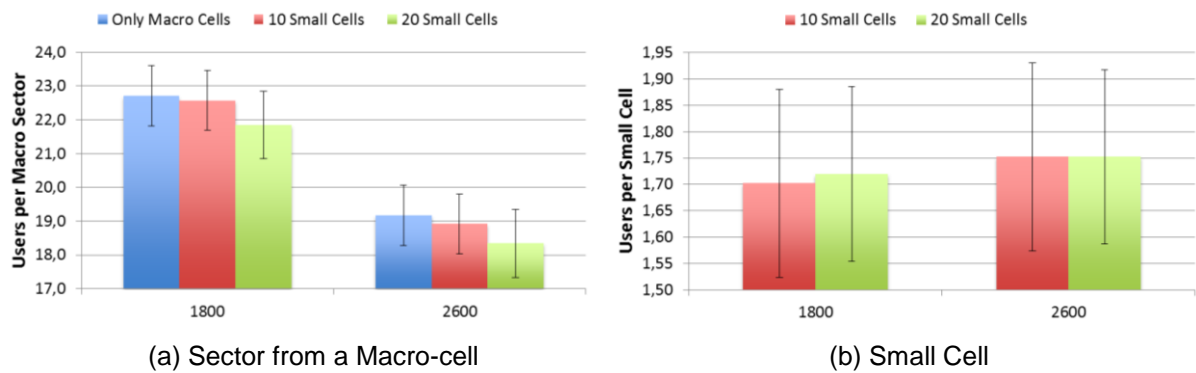


Figure 4-12 Average number of users per different elements of the network

In Figure 4-13, the average number of satisfied users evolution is presented in (a) as well as the satisfaction ratios for each case presented in (b).

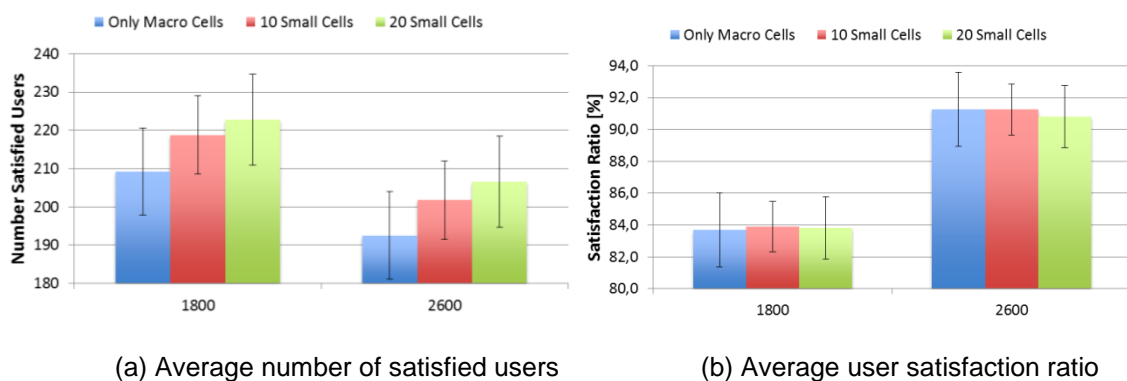


Figure 4-13 Different average user characterisation values

The values that are presented for the two different bands are very different in (a), proving once again the already shown evidences of capacity up growth done by this carrier under study. Also, the effect of small cells is exactly the same for both carriers, supporting pass statements. All other values, such as user throughputs or small cells throughput are all presented in Annex E, E.3. In Figure 4-13 (b), a substantial difference in satisfaction is observed, and the first disadvantage in using the 1800 MHz is

shown. The same way users experience less propagation attenuation, they will also feel the interference effect in a more relevant scale. The same increment in received power due to the lower frequency, also affects in the same way the received power of interference by other cells, thus, having lower satisfaction ratios. As observed in 2600 MHz, small cells do not make sufficient destructive contribution with interference by being deployed.

SNR and SINR are compared in Figure 4-14. These results confirm almost the same conclusions from the 2600 MHz: in this scenario, interference is not a very restricting factor, and small cells do not contribute significantly to interference. The only interference aspect relevant between 1800 MHz and 2600 MHz is the one presented in the difference in satisfaction ratios.

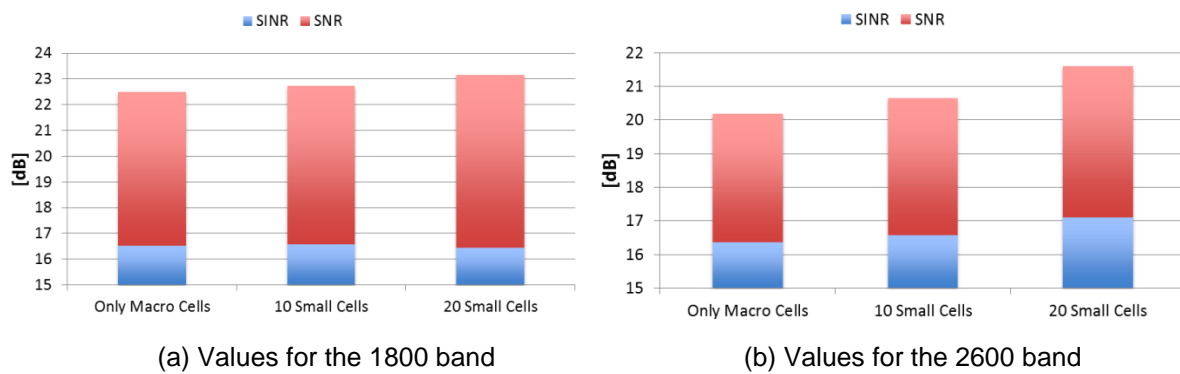


Figure 4-14 Comparison between the average values of SNR and SINR

As already said, all remaining values are presented in Annex E, E.3.

4.2.3 Frequency Reuse Schemes

In this section, FRS is analysed. As explained previously, these schemes are essential for interference cancelation, but also have some downsides that need to be evaluated through simulation. All previous settings considered for the reference scenario are taken into consideration, and the results are presented as Reuse of 1. Then, FRS is changed to the Reuse of 3 and for the proposed scheme. All results are presented for each scheme. Like in the others sections, only the relevant results are presented, leaving all other results in Annex E, 0.

The first analysis is also about the total network throughput, presented in Figure 4-15. At a first glance, one can see the major downside of using a FRS: the capacity reduction due to restricting the usable spectrum, thus restricting resources. This is clearly more visible comparing Reuse of 1 and of 3, where in the latter only a third part of the spectrum is used in total, for both small and macro-cells. Note that even using only a third of the spectrum, the Reuse of 3 produces a throughput way over half of the one produced by Reuse of 1, proving quite some spectrum efficiency over the opposing schemes. The Proposed Scheme does not limit the spectrum to a third, but also it has a usage of approximately 60% of the whole spectrum, 40% being in the inner region and 20% in the outer one of the sector. This being for macro-cells, small cells also have their spectrum limited to 2 intervals of 20% making the 40% total usage. One can observe by the differences presented in Figure 4-15 that the Proposed Scheme allows for a half way solution between the other two tested schemes. As it has been

repeatedly observed, small cells contribute to capacity improvement, and this case is no exception.

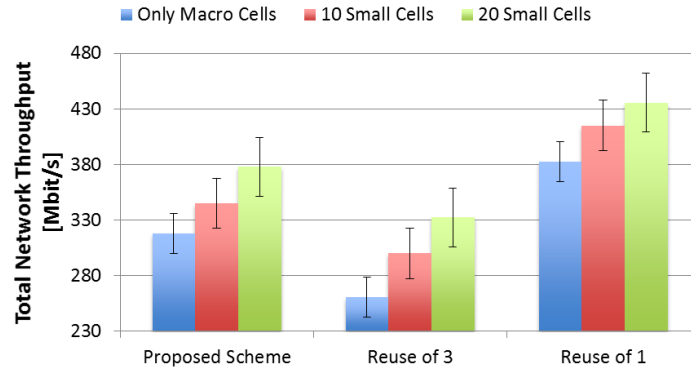


Figure 4-15 Average Total System Throughput

In Figure 4-16, one can observe the average number of users per macro-cell sector and per small cell. This figure supports the same overall conclusions that were drawn in the last paragraph. The same perspective continues to be visible here, by the lower number of users that the 2 schemes offer compared with Reuse of 1, in (a). Again, also as expected, the proposed scheme obtains values that are a half way solution between the two other possibilities. Notice that for small cell insertion in the Reuse of 3, where they do not contribute at all for an offload of users from the macro-cell layer. This can be related to the capacity allowed by the Reuse of 3, being very low compared with the other two schemes. There are relevant differences between the schemes presented in (b) for this scenario, since they reduce the interference experienced by the user.

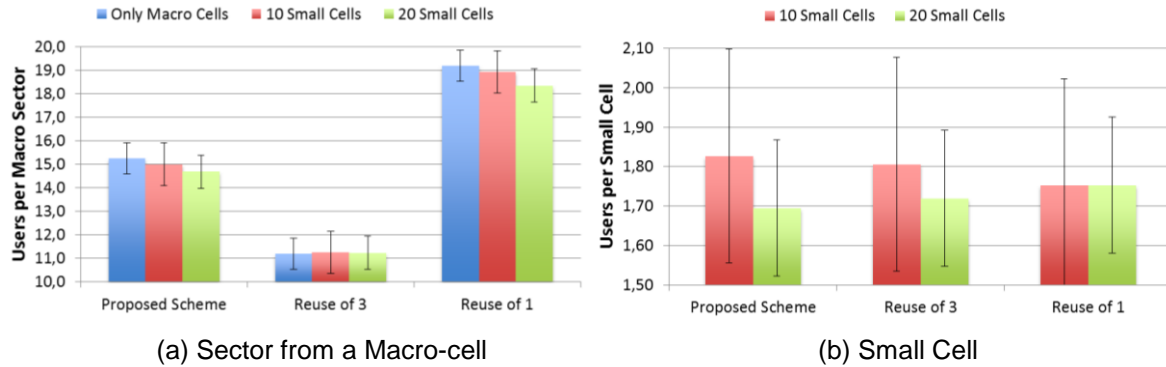


Figure 4-16 Average number of users per different elements of the network

In Figure 4-17, the average number of satisfied users and the average satisfaction ratio is presented. In (a), one can confirm the tendency for the 3 schemes: Reuse 3 presents a worse performance and the proposed scheme again shows a possible half way solution compared with the other two. In (b), one can observe the main advantage of using FRS, interference cancelation, achieving satisfaction ratios much higher than what one would ever achieve in Reuse of 1. This is valid for small cells, where in the Proposed Scheme, the satisfaction slightly increases with the deployment of small cells.

To confirm the advantage of using FRS, the average user SNR and SINR are presented in Figure 4-18. The differences in SNR for the different schemes are justified by the algorithm that allocates RBs based on SNR. SNR is an average value obtained from every user in the network that is served. A user has different RBs allocated to him, and a value of SNR is calculated for each (varying RB

frequency). The user final SNR is the average SNR of all the RBs he has assigned to him.

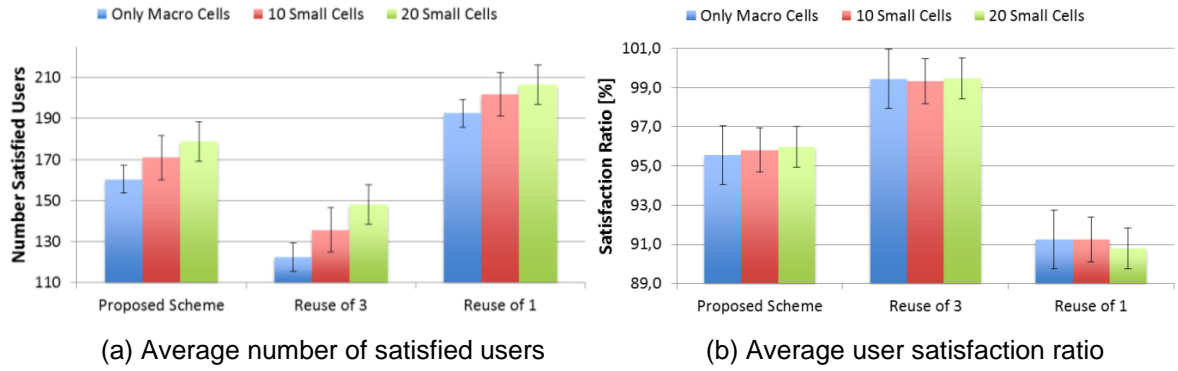


Figure 4-17 Different average user characterisation values

Since the algorithm allocates resources through the channel condition order, and seen in Figure 4-17, the number of served users is much less for the schemes with higher SNR. Hence, since fewer users are served compared with the first scheme, the users that are first server are the ones with better channel conditions. In (b), the difference between the schemes is still aggravated, but one can notice that the values of SINR almost do not differ from the ones in SNR for the two schemes that limit the spectrum, while Reuse 1 suffers degradation. For this scenario in particular, the difference is not very aggravated by interference, and one can conclude that the usefulness of this schemes compared with their disadvantages are not very promising. When comparing the SNR and SINR for the Reuse of 3, one can observe that actually the average value of SNR is lower than SINR in approximately 1 dB for all deployments. This is due to the SNR calculation for all these schemes that uses interference margin of 3 dB to avoid resources bad distribution and lower satisfaction ratios. Small cell deployment has a similar effect in the overall interference for all schemes, where it does not contributed very strongly to interference degradation.

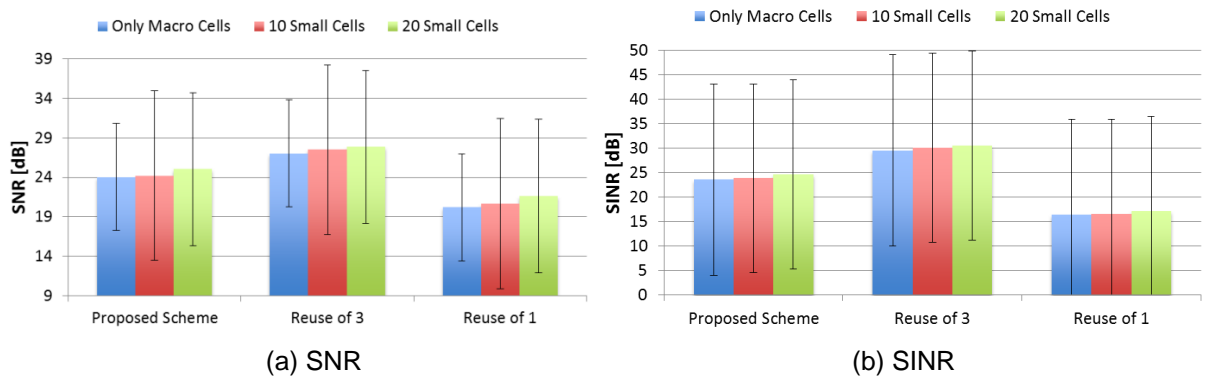


Figure 4-18 Average user SNR and the average user SINR

4.3 Event Day Load Scenario

In this section, performance is analysed for the previously used number of small cells. First, the reference scenario is analysed, with all performance parameters, then this reference scenario is

compared with different parameters such as the carrier frequency used or the FRS applied.

4.3.1 Reference Scenario

The reference scenario considered for this section consists of all the options assumed in Section 4.1 but with a different user distribution. This scenario is focused on an event day, such as a concert or a normal event in the specified area in Figure 4-1. So, the majority of users is concentrated in this area. As previously explained, 83% corresponds to a total of 350 users deployed over this area and the rest 17% corresponds to 75 users deployed over the rest of the network. For this analysis, no FRS is applied, meaning that the simple Reuse-1 of frequency is used. As in Section 4.2.1, the analysis starts on cells throughput and performance to finish on end user performance. The user scenarios considered for the 350 users is that they are either pedestrian, indoor low loss or indoor high loss, with 20%, 40% and 40% respectively. The remaining 75 users are distributed similarly to Section 4.2.1. These options aim also at a more pessimist analysis for these users. Also, in the case of the 350 users, the considered service penetration is different, where only 4 services are considered: Voice and Chat, with a penetration of 40% each, and Streaming and Web Browsing, with a penetration of 10% each. This is because most users at a concert are either trying to connect to friends with voice calls or messaging at the beginning or ending of the show; or are trying to access applications such as Facebook (considered in Web Browsing) to upload images, or even trying to stream something.

The total system throughput is presented in Figure 4-19. As in Figure 4-2, small cells produce higher network traffic as expected. But the biggest difference is the increment in throughput that small cells deployment actually contributes for this scenario in comparison with the previous one. The impact of 10 small cells deployment is an average of 25 Mbit/s for the previous scenario, while for this scenario it is over 75 Mbit/s, even serving many low requested throughput services.

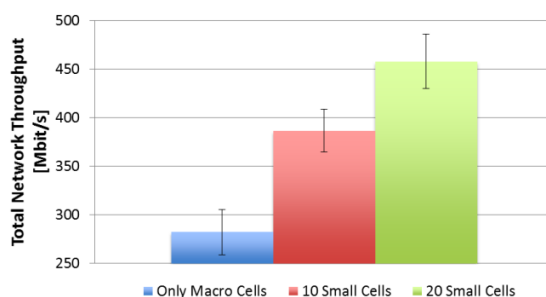


Figure 4-19 Average Total System Throughput

In Figure 4-20, on presents the average macro-cell total throughput and respective deviations along with average sector total throughput plus average small cell throughput. Again, only values for 20 small cells deployment are presented and the respective rest of the values are presented in Annex E, E.2. There are a few differences between the charts obtained for Figure 4-3, in the previous scenario. The small cells average throughput is much more boosted as expected. The same effect visible in Figure 4-19 of lower throughput transmitted in an overall scale is reflected in this chart, but, at least, small cells, while maintaining the same user average throughput, provide a capacity increasing effect.

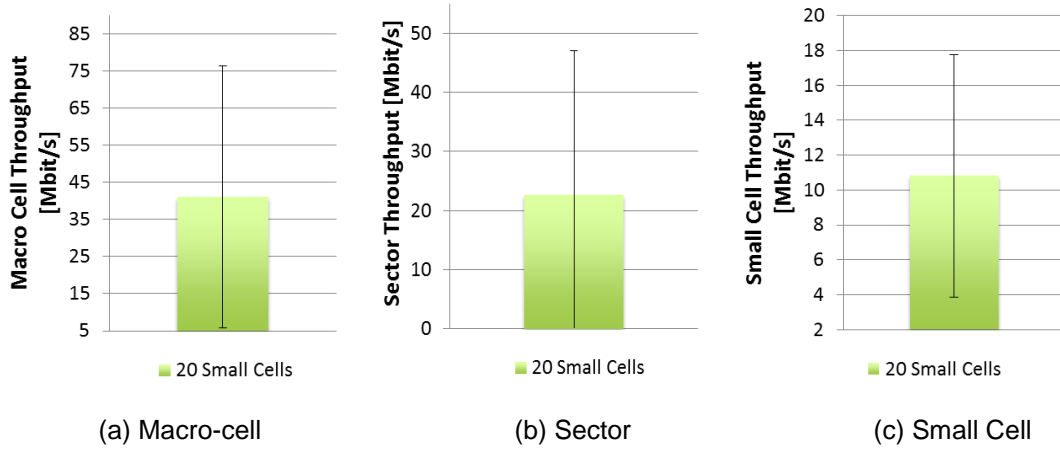


Figure 4-20 Average throughput and respective deviations for different elements

In Figure 4-21, the average served user per macro-cell sector is presented and the same for small cells. As in Figure 4-4, small cells continue to perform a scalable off load of users from the macro-cell layer. In contrast with Figure 4-4, the low range of small cells is not so restrictive and more users effectively connect to them, due to their distribution throughout the specified region.

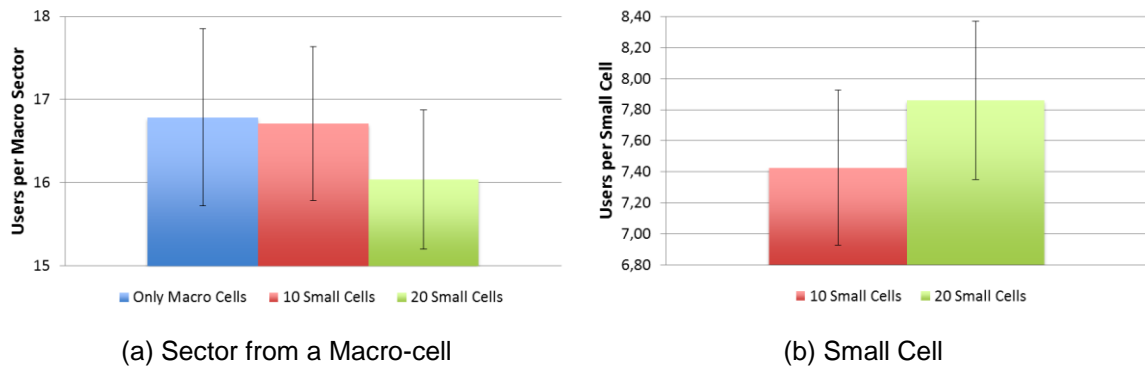


Figure 4-21 Average number of users per different elements of the network

In Figure 4-22, the average user throughput is presented for all users in (a) and for only small cell users in (b). Again, more values can be consulted in Annex E, E.2. Once more, the algorithm for resource distribution leads to quite some fairness among users exactly the same way as observed in Figure 4-5.

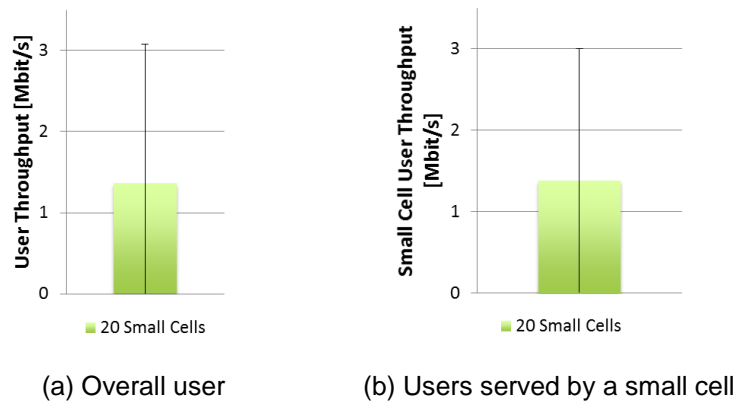
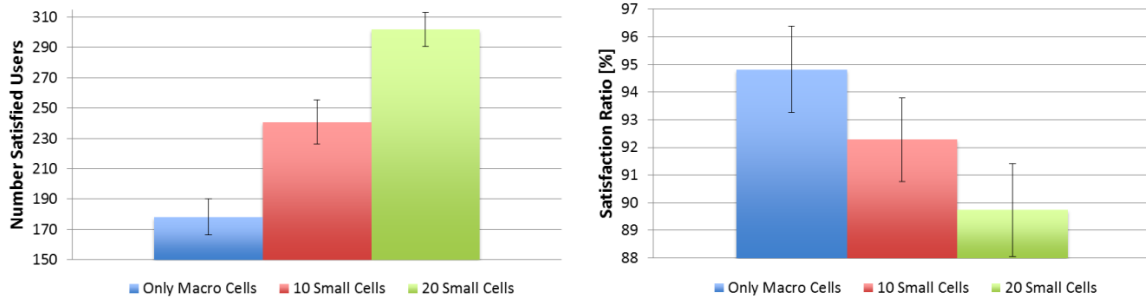


Figure 4-22 Single user average throughput for different elements

User satisfaction characterisation is presented in Figure 4-23. Again, with the deployment of small cells, the number of satisfied users increases heavily but the satisfaction ratio starts to decay also significantly. Contrary to Figure 4-6, the small cell interference attenuation created in the network by the insertion of small cells starts to gain relevant values. In a realistic network, one should expect this effect of interference given the more overloading of small cells usage in comparison with the previous scenario. But still, 6% difference is not a very important value.



(a) Average number of satisfied users

(b) Average user satisfaction ratio

Figure 4-23 Different average user characterisation values

In Figure 4-24, the relation between covered and served users is presented. In a real scenario, these results would be expected. In comparison with the observed values in Figure 4-7, small cells will in almost every case boost even more network capacity. So, while maintaining the user throughput as observed, there are a lot more new users served only due to small cells. This is naturally due to the location of the users in the areas of small cell deployment.

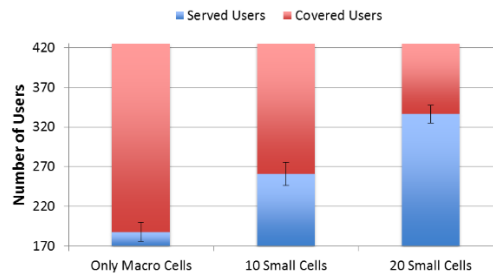


Figure 4-24 Relation between the average of served users and the number of covered users

As in Section 4.2.1, an analysis of the services is made in Figure 4-25, where the 20 small cells deployment is presented, as in Figure 4-8. The average number of served values is compared with the number of covered users (or deployed users) for each service in (a) and the average values and requested values of throughput also for each service is compared in (b). One can confirm the specified penetration assumed for each service in this scenario. Also, the same exact consequences of user throughput and number of served users described for Figure 4-8 are seen here, for either service prioritisation, or average throughput of the very low number of served users in low priority services.

Like the values of SNR and SINR in Figure 4-9 and Figure 4-10, the interference effect is not all that noticeable in Figure 4-26 and Figure 4-27. The most noticeable effect of interference is only visible for the 20 small cells in Figure 4-27, and for the user satisfaction degradation over Figure 4-23. Even

thought, these effects are smaller than a 9 dB difference between SNR and SINR. So, one can observe that small cells deployment for this specific scenario, contrary to the scenarios presented previously, contributes to add more interference into the network. In a realistic scenario, this interference effect is obviously expected. Probably in a more aggressive deployment network, one would obtain a much higher effect of the interference, but for the present network and scenario, it does not seem a high priority matter.

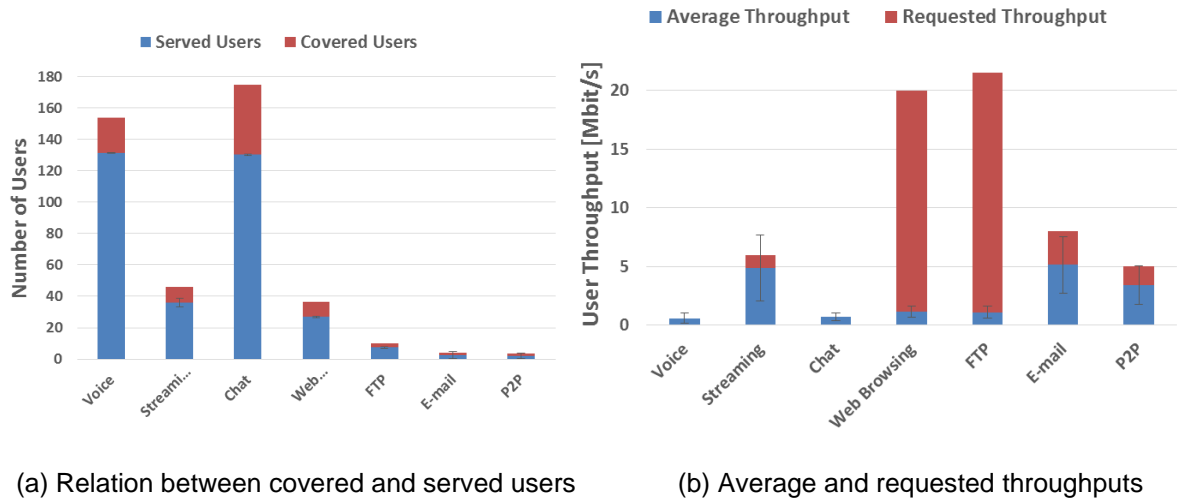


Figure 4-25 Average values of served users and throughput for each service

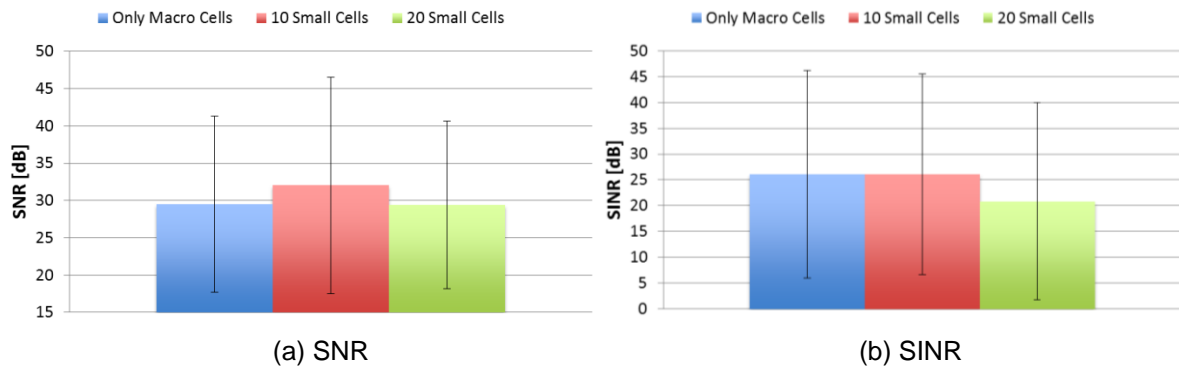


Figure 4-26 Average user SNR and the average user SINR

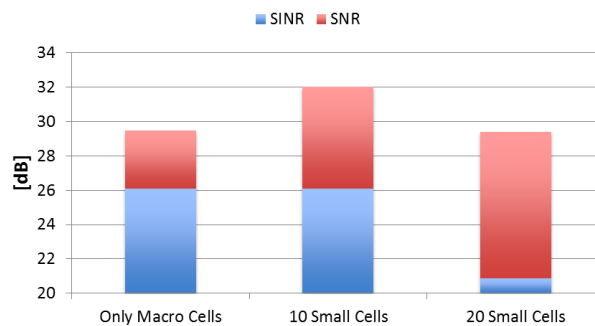


Figure 4-27 Comparison between the average values of SNR and SINR

4.3.2 Frequency Band

For this section, all previous settings are taken into consideration but the carrier frequency is altered to the 1800 MHz band, in resemblance to what was done in Section 4.2.2. The results are all compared with the 2600 MHz band used in the reference scenario but again, only relevant different values are presented and the remaining non relevant values are presented in Annex E, E.4.

At first, the total system throughput is analysed for the different deployments in Figure 4-28. On a contrary of the analysis made in Figure 4-11 for the normal day scenario, one can assume that the difference of carrier is not very relevant for this scenario. This scenario in study, highly promotes the usage of small cells compared with the other one, thus having almost no difference in changing carrier frequency. As already explained, the distance users that connect to small cells is much smaller in average then the users that connect to macro-cells, leaving the attenuation to levels that are misprised. One can immediately support the conclusions taken in the analysis of Figure 4-11 with the Figure 4-28. Naturally, as repeated previously, these results are as expected to what one would see in a realistic network.

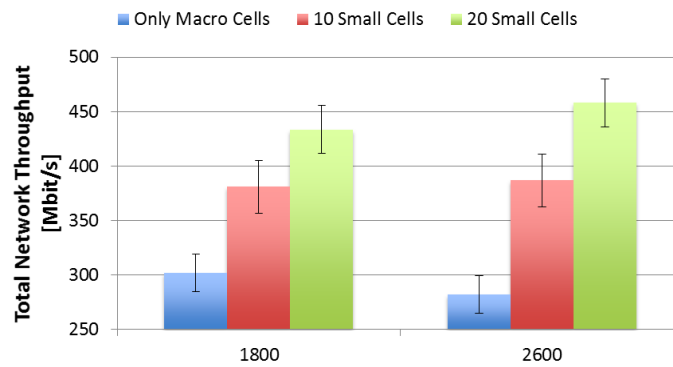


Figure 4-28 Average Total System Throughput

In Figure 4-29, one can observe a small contrast also observed in Figure 4-12 between the number of users connected to a macro-cell sector observed in (a). The reasons for this contrast were the same already explained previously. in a more general matter, this parameters are not different from what one should expect after analysed both reference scenarios and the carrier analysis for the other scenario.

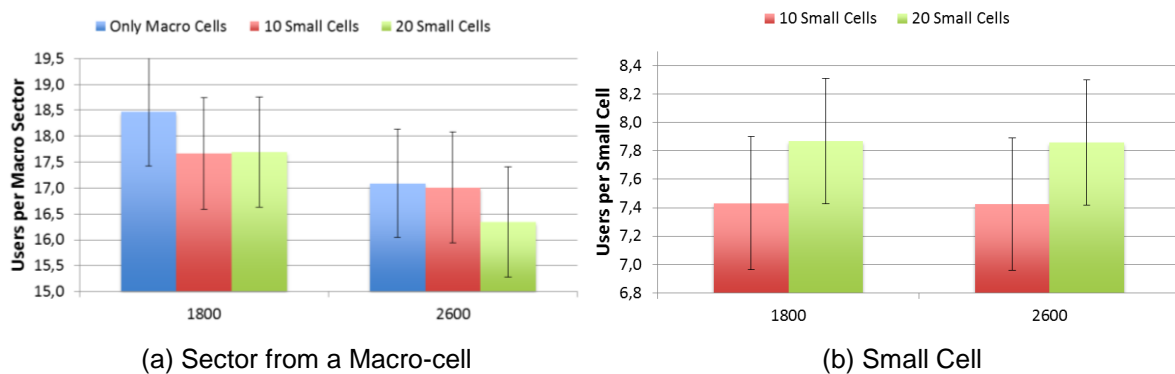


Figure 4-29 Average number of users per different elements of the network

After analysing all system differences, it is left to analyse the effect in the end user and the interference aspect. in Figure 4-30, the average number of satisfied users evolution is presented in (a) as well as the satisfaction ratios for each case presented in (b). The values that are presented for the two different bands are very similar in (a), a big contrast with what one observed in Figure 4-13. This comes to also support the high usage of small cells in this scenario, thus making again the carrier irrelevant. in (b), a substantial difference in satisfaction is observed, and the first real disadvantage in using the 1800 is shown. Remember that until now, 1800 for this scenario have not presented any great disadvantages or advantages in comparison with 2600. As already stated in 4.2.2, the same way users experience less propagation attenuation, they will also feel the interference effect in a more relevant scale. Meaning the same increment in power received thanks to the lower frequency, also affects in the same way the receiving power of interference by other cells, thus having lower satisfaction ratios. As expect, this scenario presents a much more visible effect in interference due to the small cell deployment.

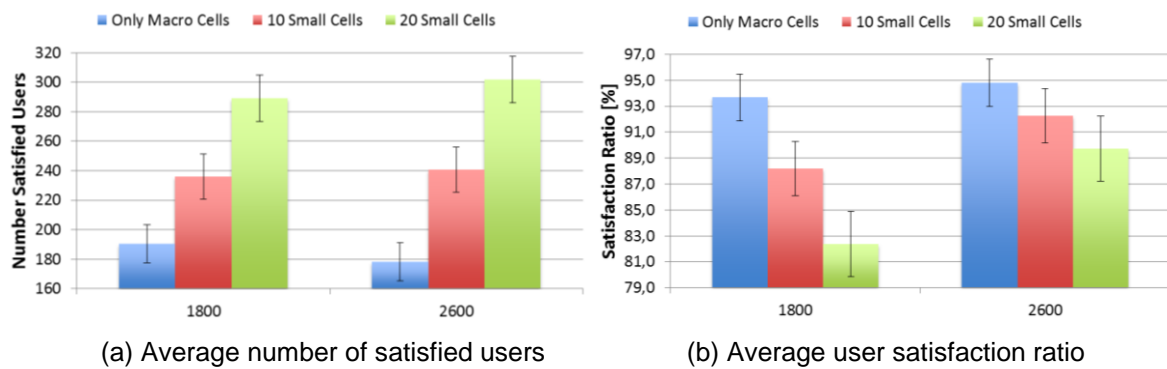


Figure 4-30 Different average user characterisation values

To conclude the carrier analysis, the SNR and SINR are compared and observed in Figure 4-31. in primary analysis, the values from (a) and (b) confirm what already been stated in the past. On a more specific analysis, comparing with Figure 4-14, one can immediately confirm that in this scenario the interference aspect is more relevant. All the justifications presented are in line to what would expect in a realistic scenario.

As already said, remember that the remaining values are presented in Annex E, E.4 but, again, lacked relevance to be analysed.

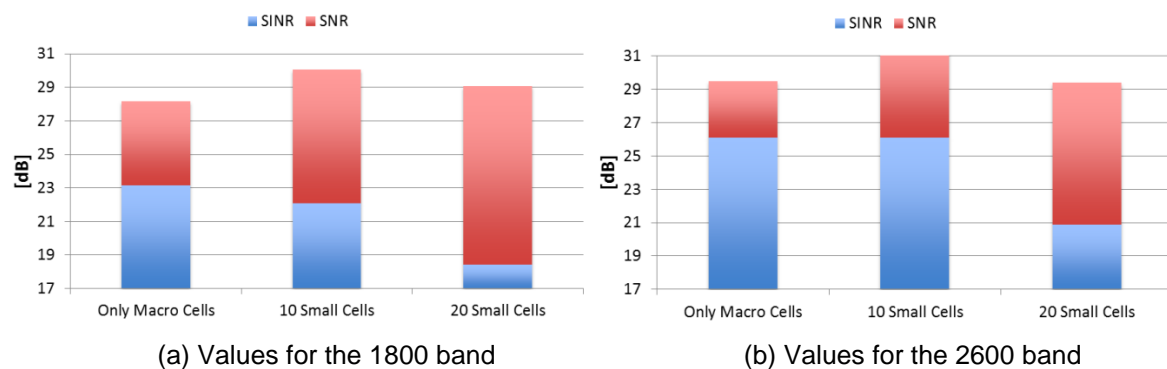


Figure 4-31 Comparison between the average values of SNR and SINR

4.3.3 Frequency Reuse Schemes

In this section, FRS is applied to the specific scenario. All previous settings from the reference scenario are considered and the results are presented as Reuse of 1. The rest of the schemes are the same as for the previous scenario in Section 4.2.3. More results are shown on in Annex E.

The total network throughput is analysed as previously, being presented in Figure 4-32. The same differences observed between the two scenarios in the reference cases are also reflected on the various schemes. The only exception is for the actual growth in total throughput, small cell deployment allowing for the Reuse of 3, in which 20 small cells are enough to produce a significant value of throughput, highly comparable to the ones obtained for the Reuse of 1. Remember again that this scenario prevails the usage of small cells in comparison with the first one. In Figure 4-15, the Reuse of 3 represents very different results in high usage of small cells, the same capacity decrease is more visible for the Proposed Scheme in comparison with Reuse of 1. The same considerations done in Section 4.2.3 for the percentages of spectrum usage for the different schemes are exactly the same as the ones considered in this section.

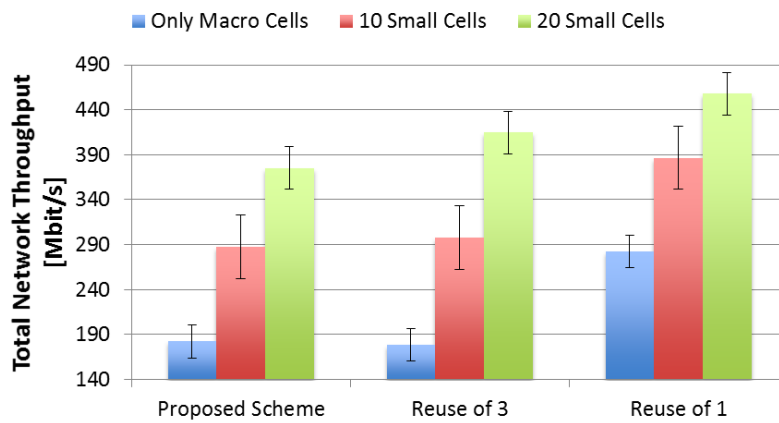


Figure 4-32 Average Total System Throughput

In Figure 4-33, the average number of satisfied users and the average satisfaction ratio are presented. In (a), one can confirm the augmented throughput in Figure 4-32 for the scheme of Reuse of 3, the scheme being the one that best profits in small cell deployment, achieving a very high number of satisfied users. Remember that a served user can be either satisfied or unsatisfied, meaning that the Reuse of 1 values for user satisfaction presented in (b) for the 20 small cells represent that for the total served users only under 90% users are actually satisfied with their service; this number is visible in (a). Still, it is a better value to serve approximately 300 users then the approximately served 255 of Reuse of 3 in (a). In terms of a real scenario, a high user satisfaction is a very good characteristic any network should aim at. Nevertheless, Reuse of 1 still proves that can deliver better capacity, at the cost of user satisfaction ratio with small cell insertion. The results obtain reflect what one should expect with the previous observed trends in reference scenarios, being in line with previous results.

The interference aspect is represented in terms of SNR and SINR in Figure 4-34. With all the analysis made so far, and with the values obtained and presented in Figure 4-18, these results are as expected as well. The FRS effect is visible, and contrary to what happens in the previous scenario, Reuse of 3

comes out on top of the Proposed Scheme. These results reflect the differences between the references scenarios and, again, the interference effect is not dominant enough to actually degrade significantly system performance, proving ineffectiveness of FRS for the analysis in question. These are the same conclusions drawn in the FRS section in the last scenario, although it provides a more useful vision of the aggressive Reuse of 3 limitations.

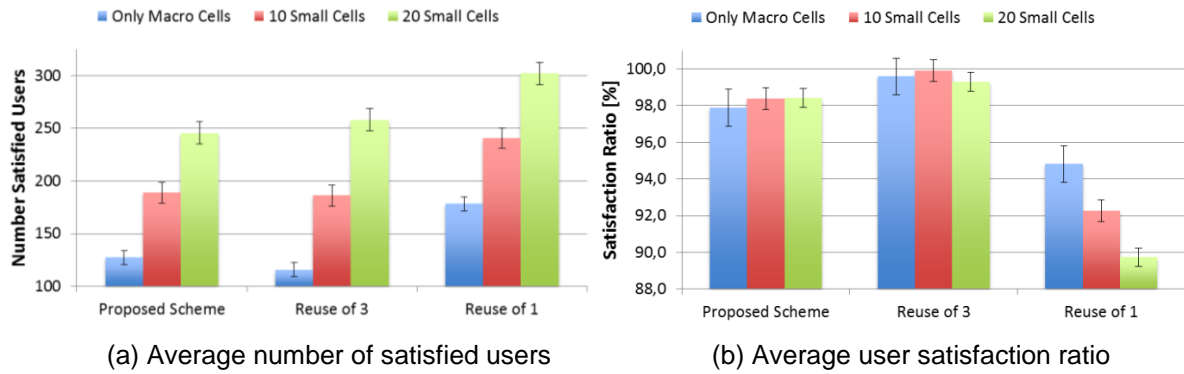


Figure 4-33 Different average user characterisation values

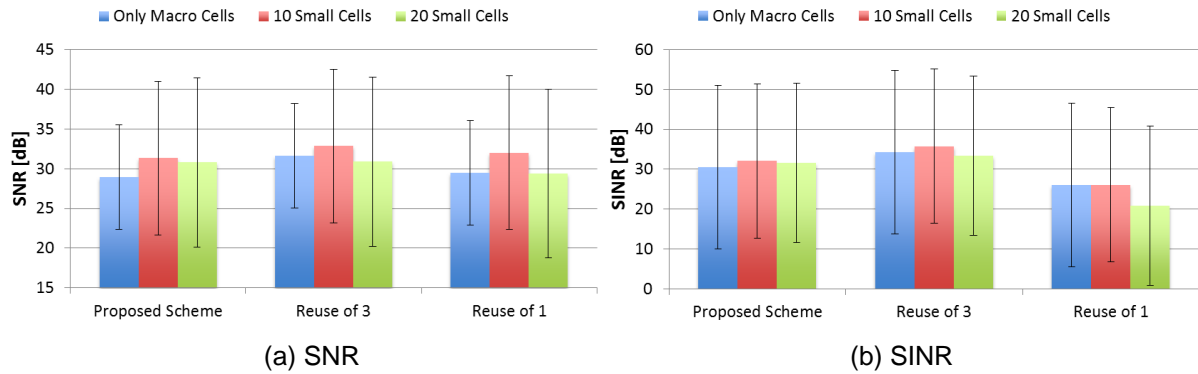


Figure 4-34 Average user SNR and the average user SINR

4.3.4 Data Services Performance

In this section, the heavy traffic data services are analysed. The same scenario as the reference is considered, but less users are deployed in order to achieve less connected users, but much higher users overall throughputs. In total, 10 users are deployed randomly throughout the network and 30 users are deployed over the areas of small cells coverage. Since the user generator deploys users by squares and small cells have an omnidirectional coverage, as presented in Figure 3-4, it is not possible to guarantee that all 30 users are connected to small cells.

In

Table 4.5, the considered throughputs for the data services “Web Browsing” and “FTP” are compared with the rest of the services. This results that users using this service only achieve the minimum throughput, since the PFS algorithm limits the number of RBs a single user can obtain. Keeping the fairness of resource distribution, the algorithm avoids that a single user can starve a cell resources by his own. The overall values obtained for user average throughput are far from the ones expected in an

ideal scenario of data peaks. This section aims at analysing how many heavy users that consume a lot of throughput can be sustained.

Table 4.6 presents the specific services used and respective characterisation. For a high data user analysis, there are only 3 services and the QoS Priority is changed to prioritise the higher data requesting users, focusing on users that use high data capabilities as live streaming, the heavy web browsing multiplayer applications such as Java or Flash games, and the high speed download of files over the file transfer protocol. The requested and minimum throughputs are presented for each of these applications as well as the penetrations. In order to take a uniform perspective, one considers the same penetration for all services. The objective is to analyse different requests of high throughputs in the range from 10 Mbit/s to 100 Mbit/s. Nevertheless, the real aim is towards proving the very high data capabilities of LTE in serving various strong heavy users, but most importantly, how small cells affect these capabilities and if they prove to be a useful tool in network optimisation. Until now, small cells proved to be a good improvement in capacity, but in this section, the most important factor is to keep a high data rate.

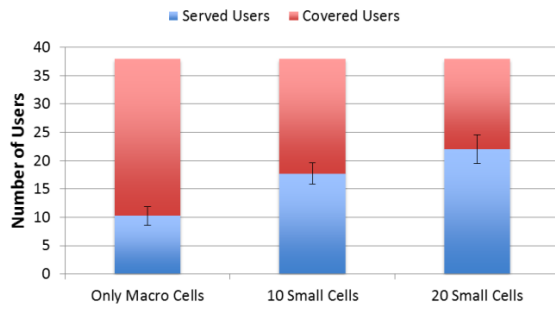
Table 4.6 Requested and minimum throughput considered for the used services

Service	Throughput [Mbps]		QCI	QoS Priority	Penetration
	Requested	Minimum			
Streaming	100	60	3	1	33%
Web Browsing	75	30	8	2	33%
FTP	50	10	8	3	33%

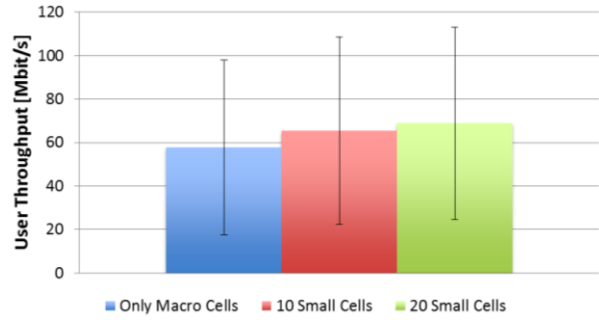
For the presented results, a few changes were made into the simulator workflow different from all the previous presented results:

- first, the implemented function explained in Section 3.2.2 that exhausts all cells resources is applied maximising throughput obtained and maximise the resource usage of the network;
- second, users are connected by distance and not by the offered power, a function also explained in Section 3.2.2;
- third and last, there is no limit to the number of RBs a single user can have assigned to him, also maximising single user throughput.

In Figure 4-35, the average number of served and covered users is presented along with the average user throughput for all users and respective deviations. One can observe that even with a few users in the network, it is possible to obtain very high average throughputs in LTE. Naturally, small cells increase network capacity, but the most important thing small cells achieve is that while they are increasing capacity they also maintain and even slightly increase average user throughput. Non-served users are the ones that presented poor channel conditions, not ideal for this study. Contrasting with every value presented in this thesis for user throughput, note that this section achieves an optimal value of average user throughput, approximately of 60 Mbit/s, much higher than previous value. Small cells prove to improve network capacity maintaining this value.



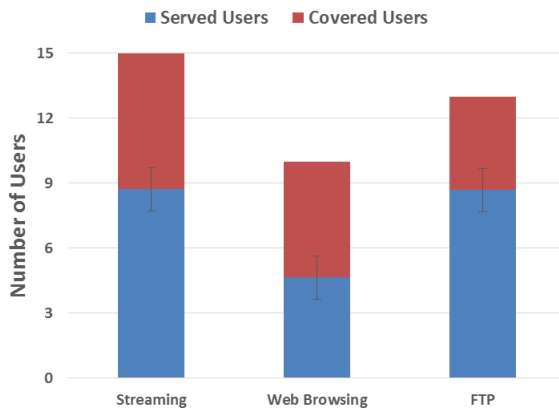
(a) Number of served versus covered users



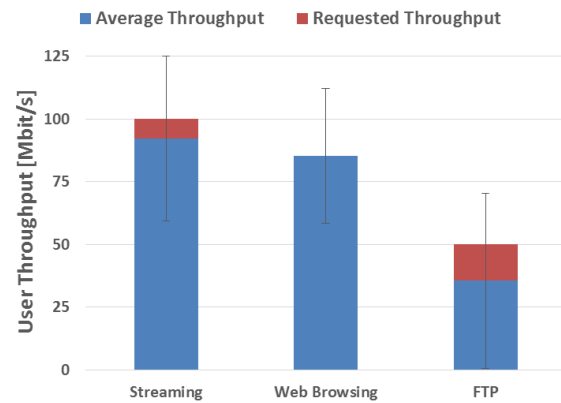
(b) User throughput

Figure 4-35 Different average user values varying with small cells

In Figure 4-36, the user service values discrimination is presented in detail for the 20 small cells deployment. The average number of served users for each service is presented in (a) versus the total covered users for the specific service. It proves to be a satisfactory average number of users connected for each service, but the penetration margins are harder to keep fair, since the amount of users is very lower than in the previous scenarios. The average user throughput for each service is presented in (b), which can prove that the majority the users are allocated with their request throughput rather than the minimum value. LTE high capabilities are very good as proved and small cells only contribute positively in that aspect.



(a) Number of served versus covered users



(b) User throughput

Figure 4-36 Different average user values varying with services

Chapter 5

Conclusions

This chapter finalises this work and presents all overall conclusions drawn. All work is summarised and approached, and the major outline of the thesis is drawn alongside with the major aspects concluded on global matter. To finalise the thesis, some regards are made for possible future work.

The main objective of this thesis was to analyse various aspects around small cells deployment, in terms of performance improvement in a typical urban scenario. The analysed network was provided by a Portuguese operator and the region under study was a specific zone of the cluster where heavy users try to use the network. The deployment of the small cells was analysed, and its impact on LTE usefulness in data capabilities was observed in large scale, the overall results being satisfactory compared with what one would expect in a real scenario.

In Chapter 2, all fundamental concepts of LTE are presented and a theoretical analysis of known concepts is addressed along with the state of the art. The small cells concept and the integration with LTE are analysed. Some references are made to important topics such as interference and services. The first section is about the network architecture in LTE, where overall functioning and structure of the network is displayed and element detail is explained. The next section is the radio interface aspect where all details about how LTE works in terms of frame structures or applied frequencies by operators are analysed. The third section is where small cells are addressed, backed up by the 3GPP considerations in the matter. Small cells are a relative simple concept to approach and this thesis also tries to keep the analysis simple. The next section is where a competitor technology to small cells is addressed: the relays alternative. Since operators in Portugal have not made any advancement in this matter, the analysis is only theoretical and the various types of relays considered by 3GPP are presented along with the details on how they operate. A comparative analysis to small cells would be a possible future work in this matter. The fifth section is where the interference subject is approached. At an initial level, interference is a major aspect operators try to solve. Simulations have shown that by applying a real operator network, the proper network planning of this proves to be extremely useful in interference cancelation. The sixth section approaches services and applications, where the concepts of QoS are addressed. The seventh section has the state of the art, where studies from the current literature related to small cells and the topics under study in LTE are analysed and described.

The model description and the implementation into a simulator are explained in Chapter 3. All aspects regarding the models are first described. Then, a simulator description is made and the models from the previous section are described on how they were implemented. This chapter ends with the assessment of the programmed simulator. The model development is the first section, and it addresses how the propagation models are applied and how they are taken into consideration. A bridge between the theoretical information presented in the previous chapter and the implementation into the simulator described after is done. The first sub-section explains the two propagation models used, one for the small cells and the other one for the macro-cells. The explanation on how they work is done. The second sub-section explains how SNR and SINR are calculated and how they are used. The third sub-section explains precisely how one can obtain throughput in LTE and how it was done in this work. The fourth sub-section explains the capacity aspect and a reflection is made on the subjective way on how to analyse it. The fifth sub-section explains the coverage matter and how it is taken into consideration. The sixth and last sub-section explains all concepts behind the applied and studied FRS, the theoretical aspect about spectrum limitation. The next section presents the development of the simulator and all details related to the implementation. The first sub-section makes an overview of the simulator structure. A segmentation of modules is made and the explanation is

detailed, describing the developed work and challenges discovered, explicitly describing what is reused work by colleagues and original work developed for this thesis. Each module is described except for the major one related to the C++ simulator that is described in the next sub-section. All work history is presented and all original work is described. The major challenges are explained while the algorithm explanation is done for all modules. Small cells characterisation is described and how it is taken into simulation. To finalise this chapter, the last and third section has the assessment of the modules. Various simulations and results are obtained to analyse how the network is behaving. Data peak values are tested in ideal conditions, proving simulator truthfulness when it comes to data capabilities. Various simulations were repeated to understand the best number of simulation to assure statistical relevance of the results. Also, the reference number of users is determinate in order to choose a number of users that uses network full capabilities, bringing realism into the simulations.

Chapter 4 contains the results obtained from simulation. It has 3 sections where the first one is about scenario description, the second about the analysis of the first scenario relative to a normal day, and the third on the analysis of the second scenario relative to an event day load. The first section is the overall description of the used settings and the local where simulations take place. This description is essentially focused on the scenarios, all the settings described are in general taken into account in every case. The second section is about the average day load, focusing on a realistic approach of an even distribution of the users throughout the network. The load in the network is sufficient to use full capacity. The first sub-section concerns the reference scenario. The decisions taken are explained and the results are shown for the different performance aspects, analysing the way the small cells deployment affects the network. The second sub-section is about the carrier analysis and a functional comparison between the different bands is presented. The third and last sub-section is the analysis and results obtained by applying the studied and explained FRS plus the small cell impact on performance. The third section focus on the event day load, trying to emulate what would happen in a realistic event day, attracting a lot of users to a specific location where the small cells are deliberately deployed. The results are conclusive in small cells positive effect in all the tested scenarios. The last and fourth sub-section is where data services performance is fully analysed and high data capabilities of LTE are addressed.

The analysis done in this thesis is a result of the different processes described in the previous paragraphs. The random factors of the simulator are varied through a total of 5 simulations obtaining final averages results. This process is repeated for 5 different files of users varying user positioning and services requested; a total of 25 simulations were done. To proper analyse the deployment of small cells, these were analysed into 3 groups, or series, where the groups are only the macro-cell layer in usage, 10 small cells plus macro-cell and 20 small cells also plus macro. For each scenario, this 3 series were repeated and in the case of the comparison between the FRS, this 3 series were done for each applied scheme. Every series represents the described 25 simulations resulting as already described in a total of 75 simulations, whenever a different option is taken into consideration.

The results are in a global scale satisfactory. Remember that the programmed simulator was initially designed for other purposes in the past, and much work was made over this to change the focus of

analysis and even more original development was made to emulate the LTE desired techniques. Also, one of the most important factors to take into consideration when analysing results is that the simulator uses a snap shot basis methodology. No time basis analysis is implemented, so the results do not have necessarily to reflect an exact copy of what happens in a full complex LTE network. The programmed PFS algorithm emulates what would happen in reality. Still, in reality, a time based study of user average instantaneous throughput is made in order to determinate the fair amount of RBs the user will receive. This depends on previous information that BSs already have about the users and is continuously updated in desired time frames changing continuously user throughput. This is naturally impossible to execute in snap shot analysis in the exact realistic terms, but still, a good approximation is possible to obtain and that was the major goal of this thesis: to obtain the better approximation to reality as possible. Again, all analysis results are only based on instantaneous data, meaning that RBs distribution is done for each simulation and instantaneous throughputs calculated. So, there were many considerations taken that support the reality of analysis, bringing the framework of simulation to a more pessimist state. Examples of these considerations are: not considering the higher code rates for the 3 modulations, Annex D; the distribution of users for the 4 user scenarios, considering most users indoor in a more attenuator conditions; and the low probabilities of LoS considered for all users throughout the distribution of users. Still, the results are conclusive and satisfactory.

The major outline conclusion drawn by all results is that small cell deployment has a great impact on overall network capacity, as one already expected as a starting point. The capacity improvement capability of small cells is proven in all simulations results, comparing the different small cells system deployment. One can argue on the quantity of this improvement and less subjective approaches need to be done to conclude on that. Nevertheless, the possible discussion of this capacity being worth of a scalable investment was never the focus of this thesis, and it is a reasonable direction of future work for this thesis. Comparing both scenarios, small cells without a doubt, and without any surprise, prove to be much more useful when a large group of users concentrate in a specific region. Various examples represent this situations like concerts or conferences, and that is exactly what is done for the second scenario. While in the first scenario, 20 small cells only allows for an average augment of 20 users, the second scenario 20 small cells allows for an improvement of 125 in averaged satisfied users. Operators normally use movables macro-cell BSs to give extra capacity over large area events, but still, this macro-cell station contribute with less resources then using various number of small cells and more interference thanks to the overlapping with the previous installed macro-cell layer. That is the second major outline drawn by all results, meaning that small cells are not destructive as one would think in terms of interference. Mostly due to their lower power and range, a user that is actually in a destructive interference range of a small cell, will mostly be served by it. The only results that actually show some degrading effects thanks to small cells are the ones of the second reference scenario, event day load, when the average satisfaction ratio obtained, degrades approximately 3% with each insertion of 10 small cells. Considering the case where small cells are mostly overloaded and the most interference vulnerable scheme, a 3% satisfaction drop compared with an approximately over 50 satisfied users increment is negligible and does not imply as actual degrading effect of small cells, indicating precisely the opposite. Still concerning interference, the considered part of the network

already described did not actually show many disadvantages caused by interference, when only macro-cell simulations were performed. This is due to the network being based on a realistic network of the Optimus Portuguese operator which was properly planned, and was configured into the simulator with rigor, defining each BS sectors and azimuths extensively. One can immediately conclude that proper planning is the best interference cancelation tool.

Some FRS were also studied and. The already discuss lack of interference in this specific network proved that FRS are not at all desired for macro-cell networks that were very well planned. The cancelation of interference effects is very well visible for both scenarios, with or without small cells, and for the applied schemes, but again, the gain over this cancelation is very low, due to the weak effect of interference for this network. Another interesting note for future work, would be to use the FRS to properly implement a much more aggressive deployment of small cells. If one can nullify properly the interference degradation due to the overlaying of regions of coverage, in theory, there is exponential grow of the limit to the capacity the deployment of small cells can achieve.

The two different carriers possible to use in small cells by Portuguese operators are compared, corresponding to the bands of 1800 MHz and the 2600 MHz. As explained, due to the low coverage range of small cells, there is no difference in the designed models between the different carriers. Their effect is mostly visible in the first scenario, where the macro-cells are ultimately used. There is no natural conclusion over the deployment of small cells.

The last results obtained for this thesis were focused on the high data capabilities of LTE. This was well demonstrated, proving that small cells can, once again, have a vital role in improving capacity in regions where this heavy users are located. The user throughput obtained is very high compared with all previous simulation, but the most incredible factor was that small cells allow for a capacity increase while improving a bit the already high average throughput for the users.

After presenting the limitations of the simulator and the all results have been analyse, the developed simulator proved to be a very reasonable approach in this matter in study in this thesis. Results are not incoherent, and the same conclusions drawn by the first evaluated values are later confirmed throughout the results, proving the usefulness and worth of the developed tool. Remember that every conclusion drawn in this thesis by this simulator results are in scalable matter, referent to the specific small area of the network in analysis. When scaling the problem addressed to a much bigger size network, as for example, the city of Lisbon, the very small improvements at cost of capacity proposed by the FRS can provide a different vision in how optimisation is possible. Again, small cells are by name a small area problem and require much local morphology knowledge so that analysis is allowed to grasp a realistic approach.

Regarding future work, a small note was already made in comparing small cells and relays and some other aspects. If the development of relays starts to take place in the near future, the comparison study would gain very realistic connotations. Nevertheless, the most interesting aspect to actually compare to small cells is its most rival technology: WiFi. While this is already wildly used throughout particular houses, many public places also already have Wifi available for use, after the payment of a voucher or a monthly subscription. Small cells using its support over mobile communication

technology, are a more viable investment in the future, where the paradigm will be even more related in data capabilities, and more services will work over the mobile communications network. Still, a functional comparison between the 2 technologies would be and prove to be very useful in the actual paradigm.

Annex A

COST 231 Walfisch-Ikegami

This annex presents the COST 231 Walfisch-Ikegami propagation model used to calculate the path loss in an urban environment.

This annex describes the COST 231 Walfisch-Ikegami Model. All the following equations and explanations presented in this annex are based on [Corr09] and [Pires12].

The following image illustrates the propagation model parameters which can be used to calculate the path loss for urban scenarios:

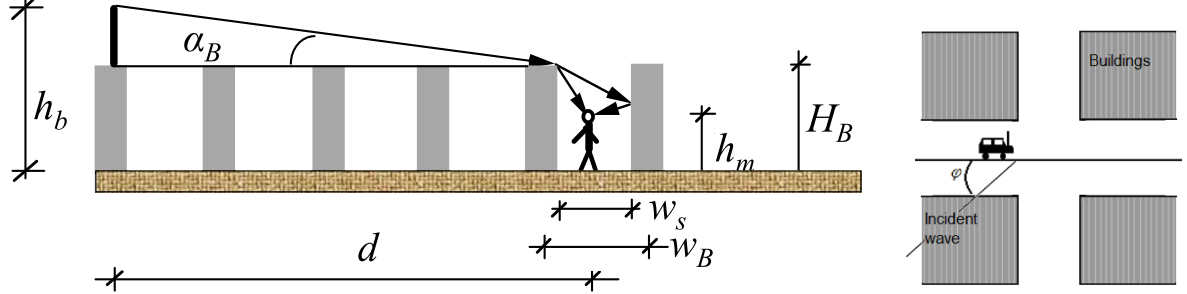


Figure A.1 COST 231 Walfisch-Ikegami Model diagram and parameters (adapted from [Corr09]).

For LoS propagation, path loss is given by:

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

where:

- d is the horizontal distance between the BS and the MT;
- f is the frequency carrier of the signal.

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

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

where:

- L_0 is the free space propagation path loss;
- L_{rt} is the loss between the last rooftop and the MT;
- L_{rm} is the loss between the BS and the last rooftop.

The free space propagation path loss is given by:

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

The loss between the last rooftop and the MT is given by:

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

where:

- L_{bsh} is the loss due to the height difference between the rooftop and the antennas;
- k_a is the increase of path loss for the BS antennas below the roof tops 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 is the buildings separation distance.

The loss due to the height difference between the rooftop and the antennas is given by:

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

where:

- h_b is the BS height;
- H_B is the buildings height.

The other parameters are given by:

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

$$k_d = \begin{cases} 18 , & \text{for } h_b > H_B \\ 18 - 15 \frac{h_b - H_B}{H_B} , & \text{for } h_b \leq H_B \end{cases} \quad (\text{A.7})$$

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

The loss between the BS and the last rooftop is given by:

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

where:

- w_s is the width of the street;
- h_m is the height of the MT;
- L_{ori} is the street orientation loss.

The street orientation loss is given by:

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

where:

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

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

- $f \in [800, 2000]$ MHz;
- $d \in [0.02, 5]$ km;
- $h_b \in [4, 50]$ m;
- $h_m \in [1, 3]$ m.

Finally, the model standard deviation takes values from 4 dB to 7 dB.

Annex B

Link Budget

In this annex, the link budget between the transmitter and receiver is presented. With these equations it is possible to calculate propagation losses in the link.

When considering a link between a transmitter and a receiver, this tool is used to calculate an estimation of the signal power at receiving antenna with the purpose of coverage estimation and to define the proper modulation for each MT. All the following equations presented in this annex are based on [Corr09] and [Pires12].

The signal power at the receiving antenna can be calculated by:

$$P_{r[\text{dBm}]} = P_{t[\text{dBm}]} + G_{t[\text{dBi}]} + G_{r[\text{dBi}]} - L_{p[\text{dB}]} \quad (\text{B.1})$$

where:

- P_r : power available at the receiving antenna;
- P_t : power fed to the antenna;
- G_t : gain of the transmitting antenna;
- G_r : gain of the receiving antenna;
- L_p : path loss.

The power fed to the antenna in the DL is given by:

$$P_{t[\text{dBm}]}^{DL} = P_{Tx[\text{dBm}]} - L_{c[\text{dB}]} \quad (\text{B.2})$$

where:

- P_{Tx} : transmitter output power;
- L_c : losses in the cable between the transmitter and the antenna.

The power fed to the antenna in the UL is given by:

$$P_{t[\text{dBm}]}^{UL} = P_{Tx[\text{dBm}]} - L_{u[\text{dB}]} \quad (\text{B.3})$$

where:

- L_u : losses due to the user's body.

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

$$P_{Rx[\text{dBm}]}^{DL} = P_{r[\text{dBm}]} - L_{u[\text{dB}]} \quad (\text{B.4})$$

where:

- P_{Rx} : receiver input power.

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

$$P_{Rx[\text{dBm}]}^{UL} = P_{r[\text{dBm}]} - L_{c[\text{dB}]} \quad (\text{B.5})$$

The path loss can be calculated as:

$$L_p [\text{dB}] = L_{p, \text{ COST 231 WI }} [\text{dB}] + L_{p, \text{ environment }} [\text{dB}] + M_{SF} [\text{dB}] \quad (\text{B.6})$$

where:

- $L_{p, \text{ COST 231 WI }}$: path loss from the COST 231 Walfisch-Ikegami Model;
- $L_{p, \text{ environment }}$: path loss from the user environment;

- M_{SF} : slow fading margin.

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

$$\rho_N \text{ [dB]} = P_r \text{ [dBm]} - N \text{ [dBm]} \quad (\text{B.7})$$

where:

- ρ_N : SNR;
- P_r : average signal power at the receiver;
- N : average noise power at the receiver.

The noise power at the receiver can be calculated by:

$$N_{\text{[dBm]}} = -174 + 10 \log_{10} \Delta f_{\text{[Hz]}} + F_N \text{ [dB]} \quad (\text{B.8})$$

where:

- Δf : bandwidth of the radio channel being used;
- F_N : noise figure at the receiver.

SINR can be calculated by the following expression:

$$\rho_{IN} \text{ [dB]} = 10 \log_{10} \left(\frac{P_r \text{ [mW]}}{N \text{ [mW]} + I \text{ [mW]}} \right) \quad (\text{B.9})$$

where:

- ρ_{IN} : SINR;
- I : interference power at the receiver.

Annex C

LTE Data Rate Models and related SINR

In this annex, the LTE latest Data Rate Models are presented based on SNR and SINR. One can consult the used equations to determine SINR and throughput for several system configurations. These equations are valid performance parameters for throughput over the physical layer of each system. Other performance parameters like block error rate and overhead load are not considered, [Carrei11].

This annex has been developed in a continuous study from [Duar08], [Jaci09], [Carrei11] and [Pires12] and it has been used by these theses when addressing LTE throughput calculations. All the following explanations and data was extracted and combined by these four theses.[Duar08]

Trial measurements documented by the 3GPP were taken as reference for deriving the expressions for throughput in the physical layer and SNR. The chosen channel models, Extended Pedestrian A (EPA), Extended Vehicular A (EVA) and Extended Typical Urban (ETU), are characterised in terms of the maximum Doppler frequency considered and maximum delay spread, as shows Table C.1. In addition, (C1) shows throughput as a function of the SNR for the EPA 5Hz channel, for some selected modulation schemes and MIMO configurations, regarding DL.

Table C.1. Channels mode characterisation in terms of Doppler frequency spread and delay spread (extracted from [Jaci09]).

Channel Mode	Doppler Frequency [Hz]	Delay Spread [ns]
EPA 5Hz	5 (low)	43 (low)
EVA 5Hz	5 (low)	357 (medium)
ETU 70Hz	70 (medium)	991 (high)

DL interpolations presented are based on the results in [Duar08], [Jaci09], [Carr11] and in simulation results from 3GPP. SIMO, MISO and MIMO configurations are considered for 10 MHz-bandwidth, using normal CP and considering the EPA5Hz channel mode, for low delay spreads. When results for the considered channel mode were not available, an extrapolation was made, base on the results for the EVA5Hz channel, as shown in Table C.2. This was the case of MIMO 4x2 with QPSK and 16QAM modulations and MIMO 2x2 using 16QAM. Furthermore, saturation of the curves for higher values of SINR was done to assure coherence between different MIMO and modulation configurations.

Because of the different radio channel models, the extrapolation factors used to derive results for the EPA5Hz can also be easily used to obtain results for the EVA5Hz channel mode. Thus, the interpolations obtained present mean errors lower or approximately equal to 5%.

Table C.2. Extrapolation EVA5Hz to EPA5Hz (extracted from [Duar08]).

M	$\frac{\text{EPA 5Hz}}{\text{EVA 5Hz}}$	$\bar{\epsilon}_T [\%]$
QPSK	1.027	5.3
16QAM	1.061	4.6
64QAM	1.04	15.2

Also, results from higher order MISO and MIMO configurations in DL, namely 4x2 and 4x4 and 2x2 using QPSK, were obtained recurring to Relative MIMO Gain Model [KuCo08], together with the model for the receive diversity gain, via selection combining, explained in [OeCl08].

In order to easily obtain results for different bandwidths, throughput for a single RB is considered for

the following expressions. An estimate of the channel throughput is obtained by multiplying the average throughput per RB by the number of RBs used for the required channel bandwidth, according to Table C.3.

Table C.3. Transmission band (extracted from [Carr11]).

Channel bandwidth [MHz]	Number of RBs	Transmission bandwidth [MHz]	Spectral efficiency [%]
1.4	6	1.08	77
3	15	2.7	90
5	25	4.5	90
10	50	9	90
15	75	13.5	90
20	100	18.0	90

For SIMO 1×2, coding rate of 1/3 and QPSK modulation, SNR in the DL is given by, based on [Duar08]:

- EPA5Hz

$$\rho_{N[\text{dB}]} = \begin{cases} 2.55 \times 10^7 R_b^5 - 6.303 \times 10^6 R_b^4 + 5.803 \times 10^5 R_b^3 - 2.502 \times 10^4 R_b^2 + \\ + 609.1 R_b - 12.93, & 0.02037304 \leq R_b [\text{Mbps}] < 0.09338800 \\ 7.457 \times 10^9 R_b^3 - 2.126 \times 10^9 R_b^2 + 2.02 \times 10^8 R_b - \\ - 6.397 \times 10^6, & 0.09338800 \leq R_b [\text{Mbps}] \leq 0.096261 \end{cases} \quad (\text{C.1})$$

ETU70Hz

$$\rho_{N[\text{dB}]} = \begin{cases} -61.62 R_b^2 + 104.2 R_b - 8.231, & 0.04145 \leq R_b [\text{Mbps}] < 0.08313 \\ 4.465 \times 10^4 R_b^2 - 7476 R_b + 313, & 0.08313 \leq R_b [\text{Mbps}] \leq 0.0916893 \end{cases} \quad (\text{C.2})$$

For SIMO 1×2, coding rate of 1/2 and using 16QAM, SNR in DL is obtained, according to the results in [Duar08], by:

- EPA5Hz

$$\rho_{N[\text{dB}]} = \begin{cases} -70.91 R_b^2 + 61.37 R_b - 5.045, & 0.09042 \leq R_b [\text{Mbps}] < 0.2200675 \\ (820.7 R_b^5 + 1151 R_b^4 - 644.9 R_b^3 + 180.6 R_b^2 - 25.26 R_b + 1.412) \times 10^8, \\ 0.2200675 \leq R_b [\text{Mbps}] \leq 0.29382 \end{cases} \quad (\text{C.3})$$

ETU70Hz

$$\rho_{N[\text{dB}]} = \begin{cases} 2968 R_b^4 - 1233 R_b^3 - 12.73 R_b^2 + \\ + 93.33 R_b - 6.971, & 0.08175 \leq R_b [\text{Mbps}] < 0.27310179 \\ (1664 R_b^4 - 1824 R_b^3 + 749.5 R_b^2 - \\ - 136.9 R_b + 9.374) \times 10^9, & 0.27310179 \leq R_b [\text{Mbps}] \leq 0.27500964 \end{cases} \quad (\text{C.4})$$

In SIMO 1×2, coding rate of 3/4 and 64QAM modulation, one gets for DL, [Duar08]:

- EPA5Hz

$$\rho_{N[\text{dB}]} = \begin{cases} -3.891 \times 10^4 R_b^4 + 1.418 \times 10^4 R_b^3 - \\ -1756 R_b^2 + 110 R_b - 0.1967, & 0.003036 \leq R_b [\text{Mbps}] < 0.152616 \\ -7931 R_b^3 + 4946 R_b^2 - 946.6 R_b + 62.48, & 0.152616 \leq R_b [\text{Mbps}] < 0.25014 \\ 455.2 R_b^4 - 599.4 R_b^3 + 246.2 R_b^2 - \\ -11.18 R_b + 6.022, & 0.25014 \leq R_b [\text{Mbps}] < 0.637095 \\ 1.547 \times 10^4 R_b^2 - 1.972 \times 10^4 R_b + 6300, & 0.637095 \leq R_b [\text{Mbps}] < 0.648575 \end{cases} \quad (\text{C.5})$$

ETU70Hz

$$\rho_{N[\text{dB}]} = \begin{cases} (-9.862 R_b^4 + 3.195 R_b^3) \times 10^4 - \\ -3458 R_b^2 + 165.5 R_b + 0.8493, & 0 \leq R_b [\text{Mbps}] < 0.1428556 \\ 7838 R_b^3 - 3441 R_b^2 + 527 R_b - 21.91, & 0.1428556 \leq R_b [\text{Mbps}] < 0.220953 \\ 198.2 R_b^3 - 267.3 R_b^2 + 135.4 R_b - 7.904, & 0.220953 \leq R_b [\text{Mbps}] < 0.5656632 \\ 2290 R_b^2 - 2617 R_b + 766.5, & 0.5656632 \leq R_b [\text{Mbps}] < 0.6068352 \\ (3.684 R_b^2 - 4.472 R_b + 1.375) \times 10^4, & 0.6068352 \leq R_b [\text{Mbps}] \leq 0.6076992 \end{cases} \quad (\text{C.6})$$

For MIMO 2×2, coding rate of 1/2 and 16QAM, for DL, SNR is obtained based on the results in [3GPP08a], [3GPP08b], [3GPP08c] and [3GPP08d]:

- EPA5Hz

$$\rho_{N[\text{dB}]} = \begin{cases} 683.8 R_b^3 - 399.4 R_b^2 + 115.8 R_b - 7.195, & 0.081909 \leq R_b [\text{Mbps}] < 0.2619 \\ 5.149 \times 10^4 R_b^5 - 1.056 \times 10^5 R_b^4 + 8.561 \times 10^4 R_b^3 - \\ -3.43 \times 10^4 R_b^2 + 6812 R_b - 528, & 0.2619 \leq R_b [\text{Mbps}] < 0.52724 \\ 2740 R_b^2 - 2868 R_b + 766.7, & 0.52724 \leq R_b [\text{Mbps}] < 0.5507425 \\ 2.851 \times 10^4 R_b^2 - 3.105 \times 10^4 R_b + 8472, & 0.5507425 \leq R_b [\text{Mbps}] \leq 0.5531 \end{cases} \quad (\text{C.7})$$

ETU70Hz

$$\rho_{N[\text{dB}]} = \begin{cases} 23.21 R_b^2 + 27.73 R_b - 0.7635, & 0.02782 \leq R_b [\text{Mbps}] < 0.23376343 \\ 1.765 \times 10^4 R_b^3 - 1.391 \times 10^4 R_b^2 + \\ +3675 R_b - 317.4, & 0.23376343 \leq R_b [\text{Mbps}] < 0.3024 \\ 1.019 \times 10^4 R_b^4 - 1.595 \times 10^4 R_b^3 + \\ +9329 R_b^2 - 2396 R_b + 237.4, & 0.3024 \leq R_b [\text{Mbps}] < 0.5155584 \\ 197.8 R_b - 85.95, & 0.5155584 \leq R_b [\text{Mbps}] < 0.5206152 \\ (3.909 R_b^2 - 4.0689 R_b + 1.059) \times 10^5, & 0.5206152 \leq R_b [\text{Mbps}] < 0.5232 \end{cases} \quad (\text{C.8})$$

For MIMO 2×2, coding rate of 3/4 and 64QAM, based on [3GPP08a], DL SNR is given by:

- EPA5Hz

$$\rho_{N[\text{dB}]} = \begin{cases} 1.071 \times 10^5 R_b^3 - 1.023 \times 10^4 R_b^2 + 337.1 R_b + 2.201, \\ 0.000636 \leq R_b [\text{Mbps}] < 0.0510 \\ -1475 R_b^4 + 1090 R_b^3 - 283.9 R_b^2 + \\ +52.07 R_b + 4.943, & 0.0510 \leq R_b [\text{Mbps}] < 0.3522 \\ 97.69 R_b^3 - 179 R_b^2 + 118.4 R_b - 10.72, & 0.3522 \leq R_b [\text{Mbps}] < 0.7042 \\ 158.6 R_b^3 - 418.5 R_b^2 + 380.9 R_b - 98.1, & 0.7042 \leq R_b [\text{Mbps}] < 1.0780 \\ (3.49 R_b^3 - 11.55 R_b^2 + 12.75 R_b - 4.689) \times 10^4, & 1.0780 \leq R_b [\text{Mbps}] < 1.1434 \end{cases} \quad (\text{C.9})$$

- ETU70Hz

$$\rho_{N[\text{dB}]} = \begin{cases} 3.69 \times 10^4 R_b^3 - 5182 R_b^2 + 269 R_b + 0.8425, & 0 \leq R_b [\text{Mbps}] \leq 0.07103922 \\ -10.14 R_b^3 + 5.678 R_b^2 + 24.37 R_b + 5.248, & 0.07103922 \leq R_b [\text{Mbps}] \leq 0.858 \\ 243.1 R_b^3 - 675.3 R_b^2 + 643.7 R_b - 184.8, & 0.858 \leq R_b [\text{Mbps}] \leq 1.1452 \end{cases} \quad (\text{C.10})$$

Considering throughput in the physical layer as a function of the SNR in LTE, interpolated expressions were obtained.

For SIMO 1×2, coding rate of 1/3 and using QPSK, DL throughput is given by, [Duar08] and [3GPP08a]:

- EPA5Hz

$$R_b [\text{bps}] = \begin{cases} (0.0190 \rho_N^3 - 0.1455 \rho_N^2 + 0.3516 \rho_N + 9.3388) \times 10^{-2}, & -2 \leq \rho_{N[\text{dB}]} < 2 \\ (0.0063 \rho_N + 9.6009) \times 10^4, & 2 \leq \rho_{N[\text{dB}]} < 4 \\ 96261, & 4 < \rho_{N[\text{dB}]} \leq 6 \end{cases} \quad (\text{C.11})$$

ETU70Hz

$$R_b [\text{bps}] = \begin{cases} (0.01035 \rho_N + 0.08285) \times 10^6, & -4 \leq \rho_{N[\text{dB}]} < 0 \\ (0.0001279 \rho_N^3 - 0.001638 \rho_N^2 + 0.006616 \rho_N + 0.08313) \times 10^6, & 0 \leq \rho_{N[\text{dB}]} \leq 6 \\ 91484.4, & \rho_{N[\text{dB}]} > 6 \end{cases} \quad (\text{C.12})$$

For SIMO 1×2, coding rate of 1/2 and 16QAM, DL throughput is given by, [Duar08] and [3GPP07]:

- EPA5Hz

$$R_b [\text{bps}] = \begin{cases} -263.5 \rho_N^3 + 303 \rho_N^2 + 26360 \rho_N + 90420, & -4 \leq \rho_{N[\text{dB}]} < 2 \\ (-0.000945 \rho_N^4 + 0.0103 \rho_N^3 - 0.0141 \rho_N^2 + 0.1696 \rho_N + 1.0083) \times 10^5, & 2 \leq \rho_{N[\text{dB}]} < 6 \\ (0.0048 \rho_N^3 - 0.1503 \rho_N^2 + 1.5644 \rho_N - 2.4858) \times 10^5, & 6 \leq \rho_{N[\text{dB}]} < 12 \\ 293820, & 12 \leq \rho_{N[\text{dB}]} \leq 14 \end{cases} \quad (\text{C.13})$$

ETU70Hz

$$R_b [\text{bps}] = \begin{cases} (0.002862 \rho_N^2 + 0.03113 \rho_N + 0.07953) \times 10^6, & -4 \leq \rho_{N[\text{dB}]} \leq 0 \\ (1.204 \rho_N^2 + 12.02 \rho_N + 81.75) \times 10^3, & 0 < \rho_{N[\text{dB}]} \leq 8 \\ 66,41 \rho_N^2 + 1909 \rho_N + 261300, & 8 < \rho_{N[\text{dB}]} \leq 14 \\ 275009.64, & \rho_{N[\text{dB}]} > 14 \end{cases} \quad (\text{C.14})$$

For SIMO 1×2, coding rate of 3/4 and 64QAM, DL throughput is obtained by, [Duar08]:

- EPA5Hz

$$R_b [\text{bps}] = \begin{cases} (-0.1292 \rho_N^3 + 1.3299 \rho_N^2 - 0.4279 \rho_N + 0.3036) \times 10^4, & 0 \leq \rho_{N[\text{dB}]} < 6 \\ (-0.1018 \rho_N^2 + 2.92 \rho_N + 3.8494) \times 10^4, & 6 \leq \rho_{N[\text{dB}]} < 10 \\ (0.0585 \rho_N^2 - 1.0032 \rho_N + 6.4581) \times 10^5, & 10 \leq \rho_{N[\text{dB}]} < 16 \\ (0.4354 \rho_N - 1.6098) \times 10^5, & 16 \leq \rho_{N[\text{dB}]} < 18 \\ (-0.0241 \rho_N^2 + 1.0214 \rho_N - 4.33555) \times 10^5, & 18 \leq \rho_{N[\text{dB}]} < 22 \\ 647085, & 22 \leq \rho_{N[\text{dB}]} \leq 26 \end{cases} \quad (\text{C.15})$$

ETU70Hz

$$R_b \text{ [bps]} = \begin{cases} 727.4\rho_N, & 0 \leq \rho_{N[\text{dB}]} < 2 \\ 127.6\rho_N^4 - 3709\rho_N^3 + 34850\rho_N^2 - 91410\rho_N + 72490, & 2 \leq \rho_{N[\text{dB}]} < 10 \\ 3933\rho_N^2 - 71940\rho_N + 5.364 \times 10^5, & 10 \leq \rho_{N[\text{dB}]} < 18 \\ -100.8\rho_N^4 + 9480\rho_N^3 - 334300\rho_N^2 + 5.239 \times 10^6\rho_N - \\ -30.18 \times 10^6, & 18 \leq \rho_{N[\text{dB}]} \leq 26 \\ 604499.2, & 18\rho_{N[\text{dB}]} > 26 \end{cases} \quad (\text{C.16})$$

For MIMO 2x2, coding rate of 1/2 and 16QAM, DL throughput is given based on the results in [3GPP08a], [3GPP08b], [3GPP08c] and [3GPP08d]:

- EPA5Hz

$$R_b \text{ [bps]} = \begin{cases} (-0.0348\rho_N^3 - 0.0922\rho_N^2 + 2.045\rho_N + 8.1909) \times 10^4, & -4 \leq \rho_{N[\text{dB}]} < 2 \\ (0.0023\rho_N^2 + 2.4658\rho_N + 6.4636) \times 10^4, & 2 \leq \rho_{N[\text{dB}]} < 8 \\ (-0.0049\rho_N^2 + 0.1405\rho_N + 1.8086) \times 10^5, & 8 \leq \rho_{N[\text{dB}]} < 10 \\ (3.8501\rho_N - 9.1235) \times 10^4, & 10 \leq \rho_{N[\text{dB}]} < 16 \\ 412.3468\rho_N^3 - 2.4976 \times 10^4 + 5.0302 \times 10^5 - 2.8162 \times 10^6, & 16 \leq \rho_{N[\text{dB}]} \leq 22 \\ 552524, & \rho_{N[\text{dB}]} > 22 \end{cases} \quad (\text{C.17})$$

ETU70Hz

$$R_b \text{ [bps]} = \begin{cases} 21.63\rho_N^4 - 335.4\rho_N^3 + 1058\rho_N^2 + 31030\rho_N + 27820, & 0 \leq \rho_{N[\text{dB}]} < 10 \\ 330.4\rho_N^3 + 18560\rho_N^2 + 347600\rho_N - 1.648 \times 10^6, & 10 \leq \rho_{N[\text{dB}]} \leq 20 \\ 533200, & \rho_{N[\text{dB}]} > 20 \end{cases} \quad (\text{C.18})$$

Considering MIMO 2x2, coding rate of 3/4 and 64QAM, based on the results in [3GPP08a], throughput in the DL is given by:

- EPA5Hz

$$R_b \text{ [bps]} = \begin{cases} (0.1853\rho_N^2 - 0.8564\rho_N + 1.0352) \times 10^4, & 2 \leq \rho_{N[\text{dB}]} < 6 \\ (0.0005738\rho_N^4 - 0.02762\rho_N^3 \\ + 0.4778\rho_N^2 - 3.088\rho_N + 6.81) \times 10^5, & 6 \leq \rho_{N[\text{dB}]} < 13 \\ (0.0893\rho_N^2 - 2.0808\rho_N + 15.3841) \times 10^5, & 13 \leq \rho_{N[\text{dB}]} < 19 \\ (0.010304\rho_N^2 + 0.16608\rho_N - 1.247) \times 10^5, & 19 \leq \rho_{N[\text{dB}]} < 24 \\ -4424\rho_N^2 + 281800\rho_N - 3344000, & 24 \leq \rho_{N[\text{dB}]} \leq 30 \\ 1143420, & \rho_{N[\text{dB}]} > 30 \end{cases} \quad (\text{C.19})$$

ETU70Hz

$$R_b \text{ [bps]} = \begin{cases} 36.62\rho_N^4 - 387.8\rho_N^3 + 2810\rho_N^2 - 3080\rho_N - 1.011 \times 10^{-11}, & 0 \leq \rho_{N[\text{dB}]} < 8 \\ 80.56\rho_N^3 - 3033\rho_N^2 + 76910\rho_N - 3.55 \times 10^5, & 8 \leq \rho_{N[\text{dB}]} < 24 \\ -2800\rho_N^2 + 192700\rho_N - 2.154 \times 10^6, & 24 \leq \rho_{N[\text{dB}]} \leq 32 \\ 1145200, & \rho_{N[\text{dB}]} > 32 \end{cases} \quad (\text{C.20})$$

Annex D

LTE Used Throughput Equations

This annex presents the used throughput equations in this thesis based on SNR and SINR. The equations were extracted from [Alme13] and all details are explained there.

[Alme13] performed an average of all values sent from manufactures to 3GPP that related SNR and SINR with throughput. There are three possible scenarios: using modulation QPSK with a 1/3 of coding rate, using modulation 16QAM with a 1/2 of coding rate and using modulation 64QAM with a 3/4 of coding rate. The first one was originally defined to EVA5 instead of EPA5, so using the extrapolation in table Table C.2 an approximation was made. The rest of the details are presented in [Alme13]. A final note is made, where the coding rates chosen are not the maximum ones possible for LTE. This promotes a more realistic approach of the calculated values since it is not an optimistic approximation of every connections.

The equations for the three possible modulations are, respectively:

$$tp_1 = \frac{2280441,2727217874}{14,005140037510571 + e^{(-0,5778969006043214 * SNR)}} * 3 * 1.027 * \frac{0,33333}{10^6} \quad (D.1)$$

$$tp_2 = \frac{47613,05094787189}{0,0926274904521111 + e^{(-0,295838412098985 * SNR)}} * 2 * \frac{0,5}{10^6} \quad (D.2)$$

$$tp_3 = \frac{17603,857570084674}{0,022018582206702525 + e^{(-0,2449102441508849 * SNR)}} * 2 * \frac{0,75}{10^6} \quad (D.3)$$

By putting in the term SNR our calculated value, it is possible to obtain throughput. In the implemented code from the simulator, the SNR is substituted in all equations and the values of tp_1 , tp_2 and tp_3 are calculated. By comparing this three values, the one that presents the higher value is the one that represents the modulation used by the user and his designated throughput.

Annex E

Simulation Complementary and Additional Results

This annex presents the complementary and additional results obtain in this thesis. The complementary results consist of results that are already showed in the respective sections but in this section are showed for all the calculated series, rather only for the 20 small cells deployment. The additional results consist of results that were not showed but also lacked interests to analyse in detail. The results are presented for both different scenarios in a different corresponding section.

E.1 Reference Scenario for Normal Day Load

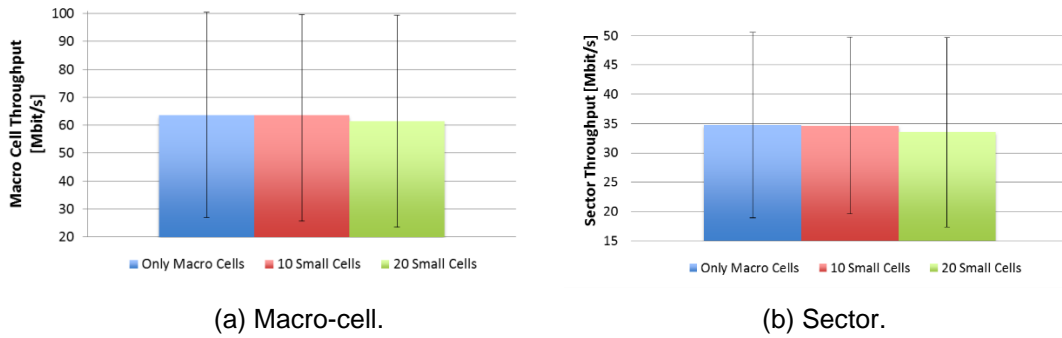


Figure E-1 Average throughput and respective deviations for different elements.

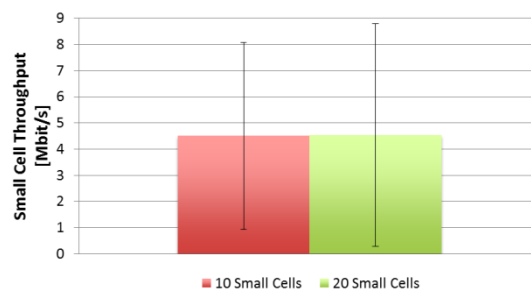


Figure E-2 Average throughput for small cell and respective deviations.

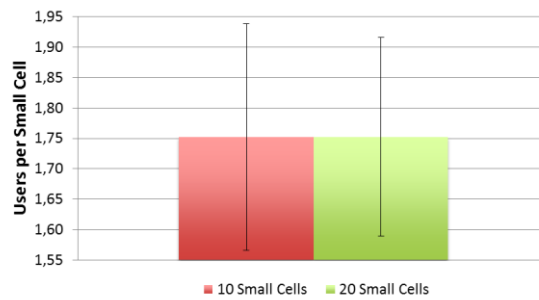


Figure E-3 Average number of users per small cell.

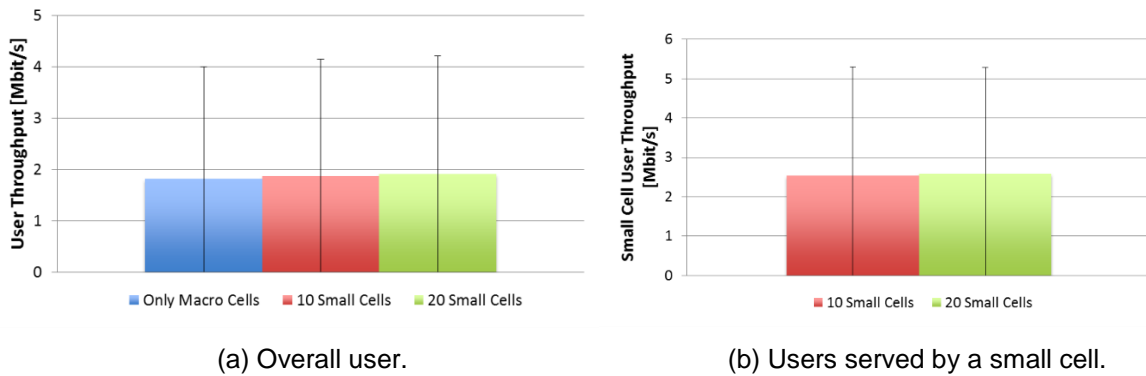


Figure E-4 Single user average throughput for different elements.

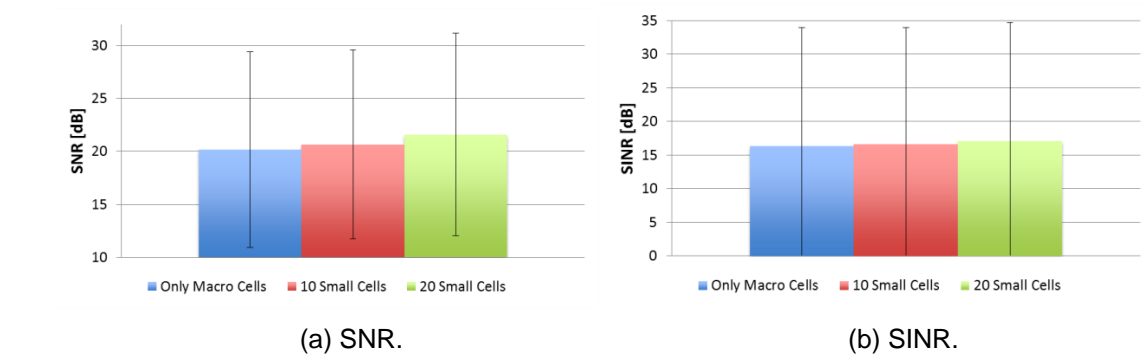


Figure E-5 Average user SNR and the average user SINR.

E.2 Reference Scenario for Event Day Load

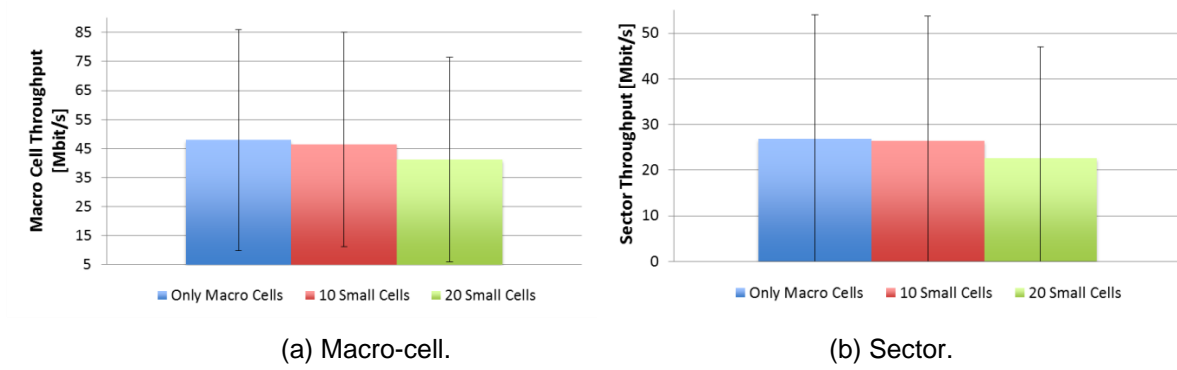


Figure E-6 Average throughput and respective deviations for different elements.

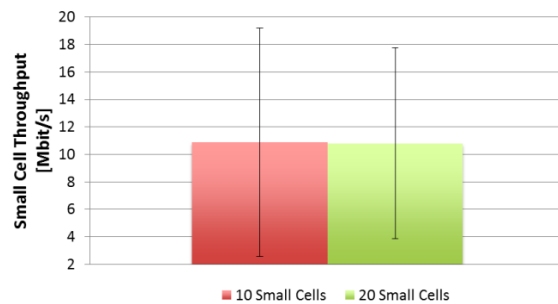


Figure E-7 Average throughput for small cell and respective deviations.

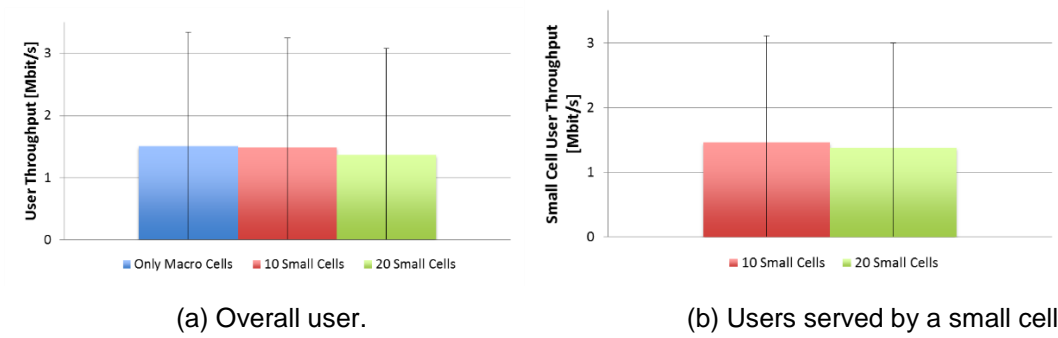


Figure E-8 Single user average throughput for different elements.

E.3 Carrier Analysis for the Normal Day Load

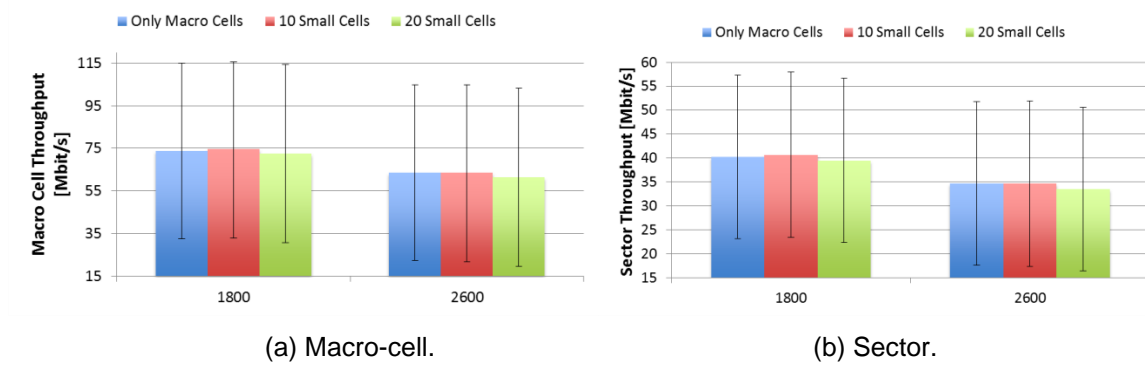


Figure E-9 Average throughput and respective deviations for different elements.

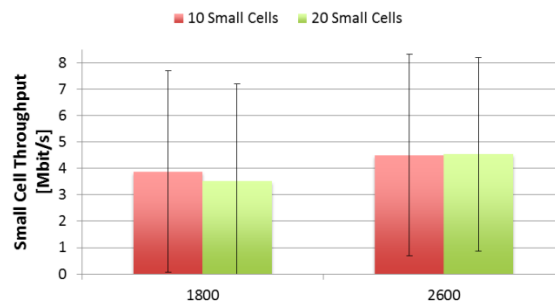
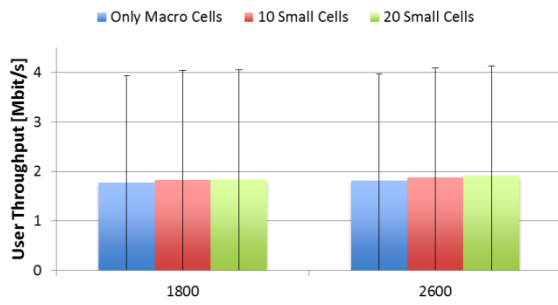
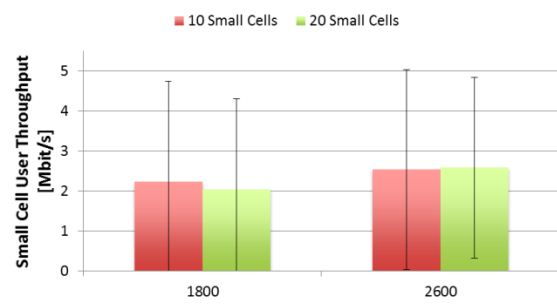


Figure E-10 Average throughput for small cell and respective deviations.

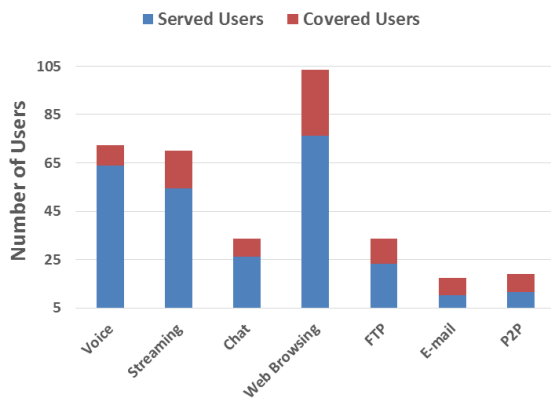


(a) Overall user.

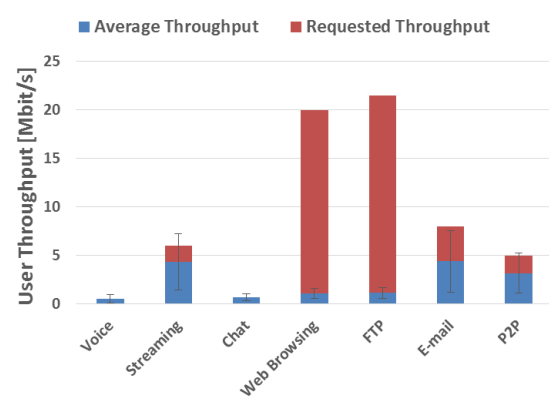


(b) Users served by a small cell.

Figure E-11 Single user average throughput for different elements.



(a) Number of covered users VS served users.



(b) User throughput.

Figure E-12 Average different values by services.

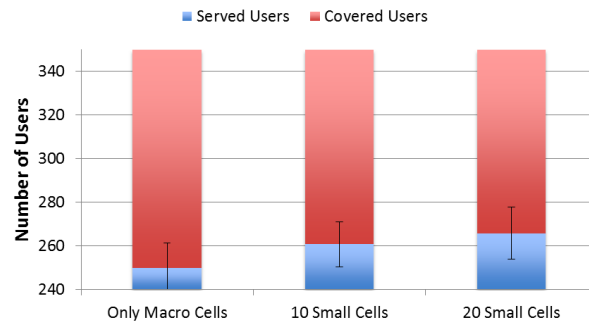
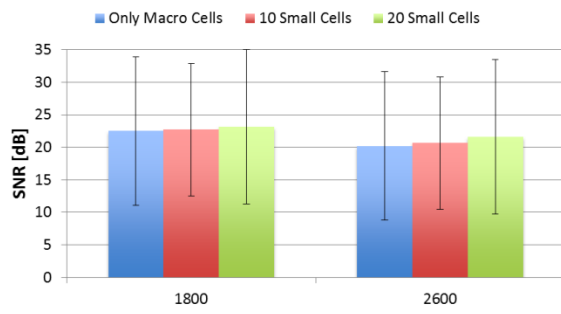
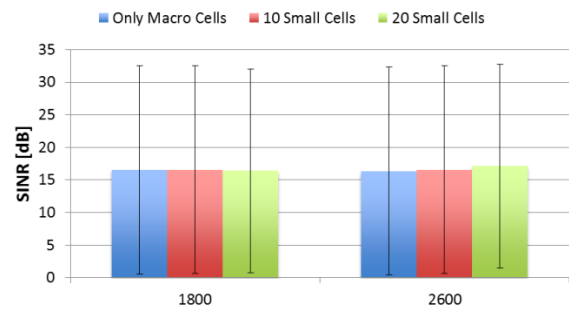


Figure E-13 Average number of covered users VS served users.



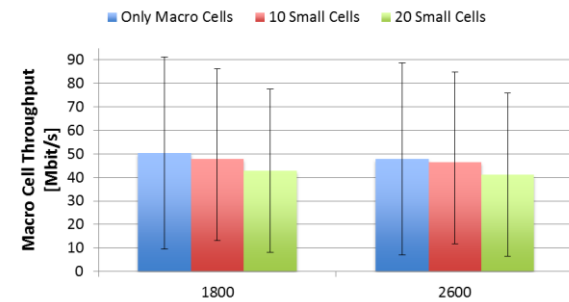
(a) SNR.



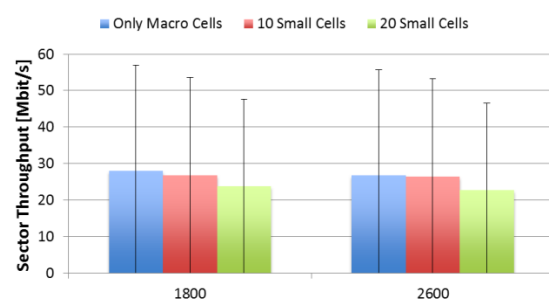
(b) SINR.

Figure E-14 Average user SNR and the average user SINR.

E.4 Carrier Analysis for Event Day Load



(a) Macro-cell.



(b) Sector.

Figure E-15 Average throughput and respective deviations for different elements.

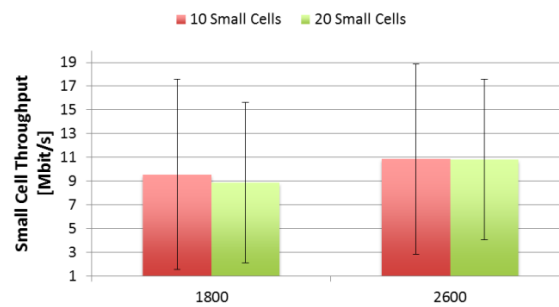


Figure E-16 Average throughput for small cell and respective deviations.

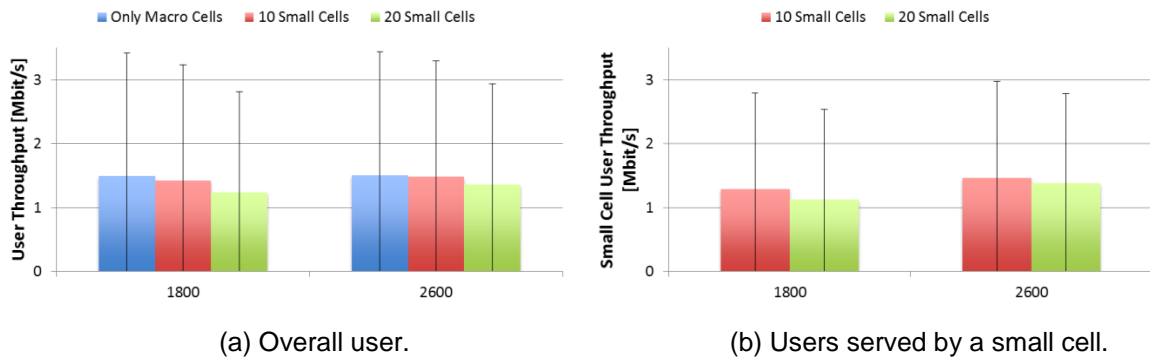


Figure E-17 Single user average throughput for different elements.

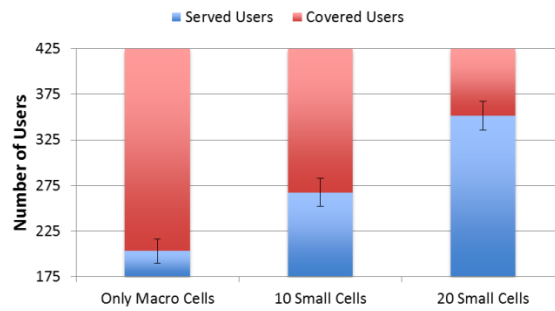


Figure E-18 Average number of covered users VS served users.

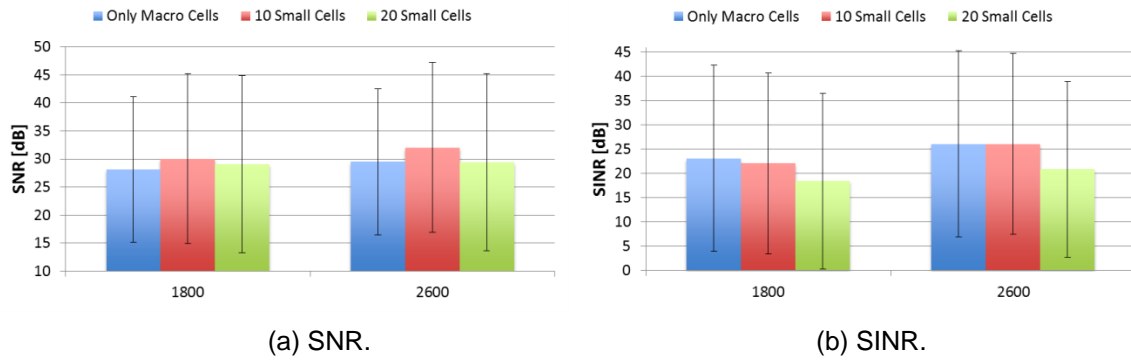


Figure E-19 Average user SNR and the average user SINR.

E.5 Frequency Reuse Schemes for Normal Day Load

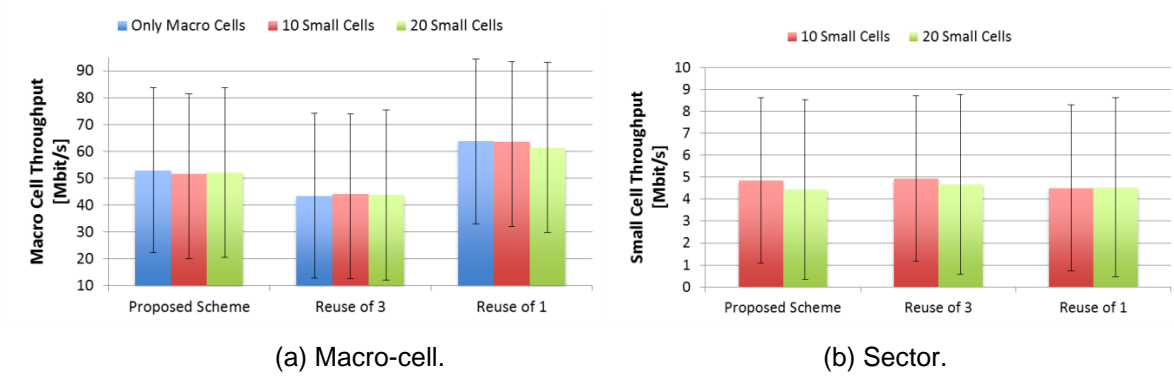


Figure E-20 Average throughput and respective deviations for different elements.

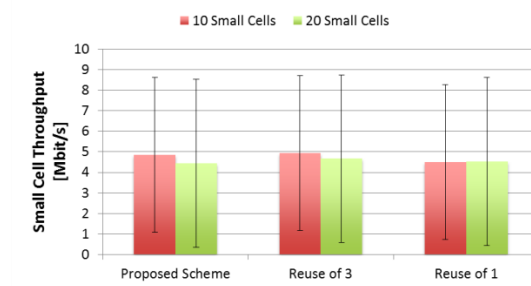


Figure E-21 Average throughput for small cell and respective deviations.

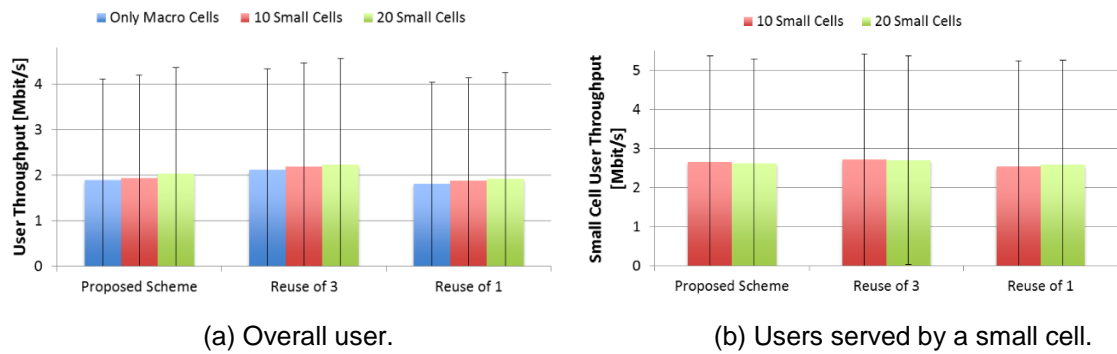


Figure E-22 Single user average throughput for different elements.

E.6 Frequency Reuse Schemes for Event Day Load

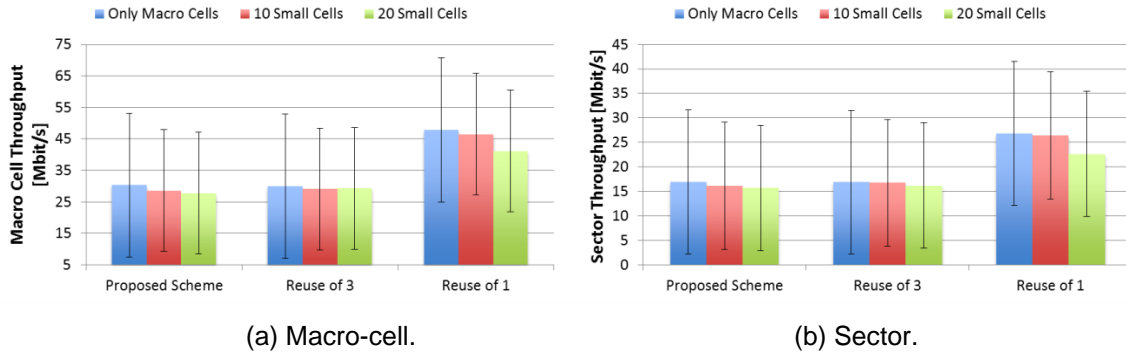


Figure E-23 Average throughput and respective deviations for different elements.

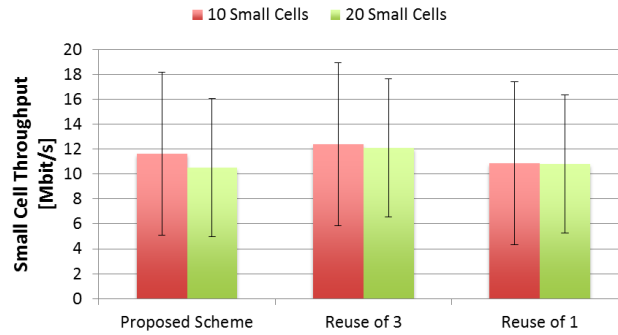


Figure E-24 Average throughput for small cell and respective deviations.

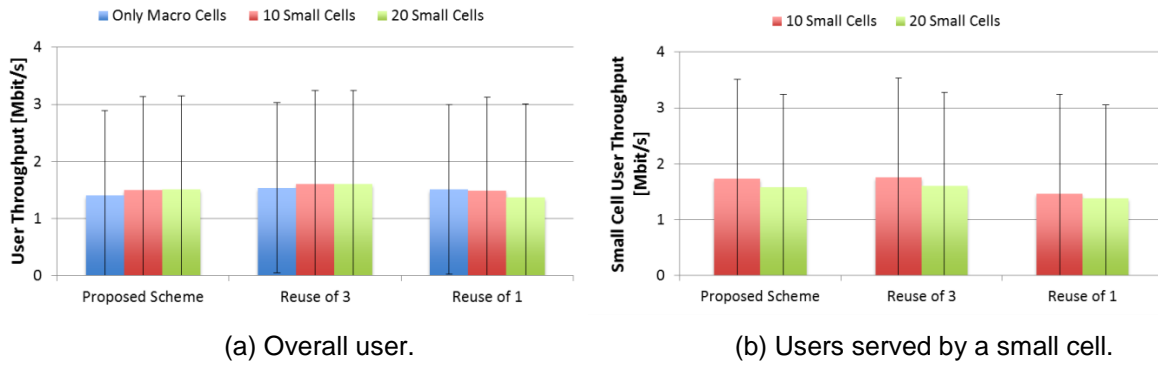


Figure E-25 Single user average throughput for different elements.

Annex F

User Manual

This annex presents the user manual for the design simulator.

To start the applications, one must first run the file UMTS_Simul.MBX and then one must select three input files, as Figure F-1 shows for the radiation pattern:

- “Ant65deg.TAB”, with the BS antennas gain structure;
- “DADOS_Lisboa.TAB” with the information regarding the city of Lisbon and its districts;
- “ZONAS_Lisboa.TAB”, with area characterisation regarding the districts.

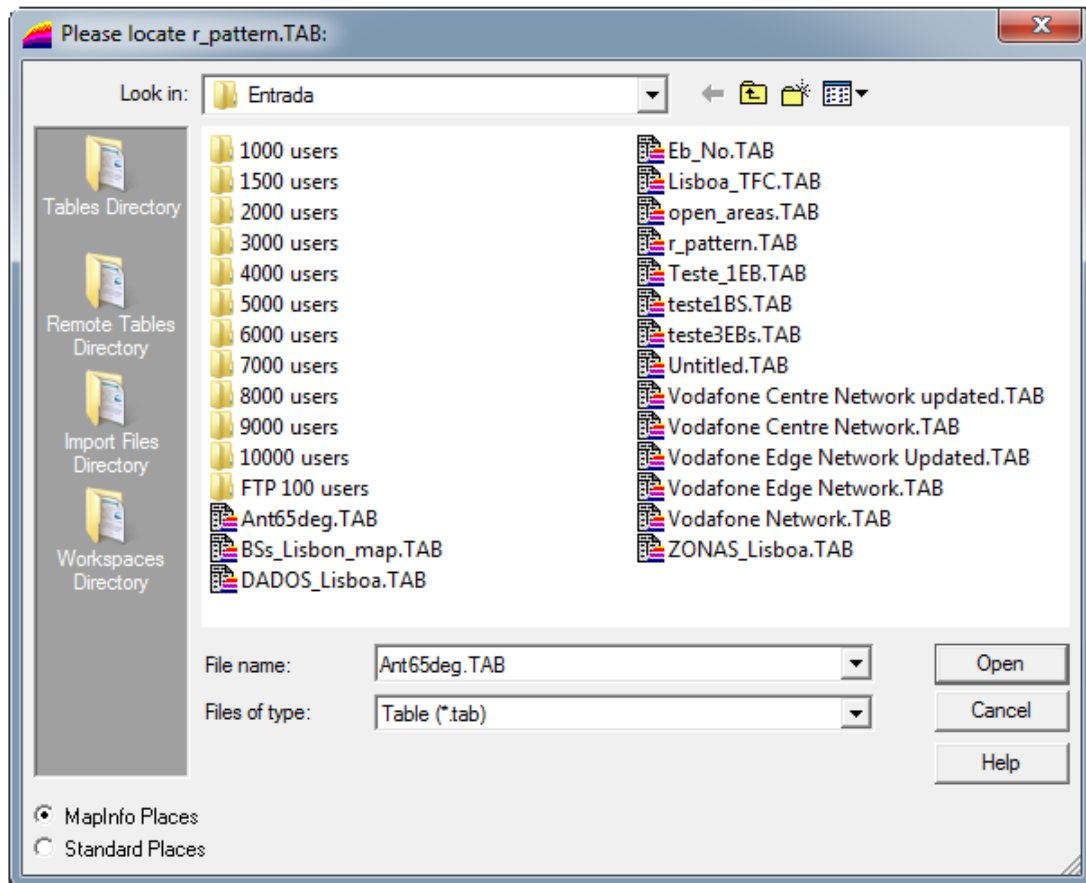


Figure F-1 Window for the selection of the radiation pattern file.

After the introduction of the geographical information, the map of Lisbon appears in the MapInfo program and a net tab called “System” is now available, where one should access to select the “LTE-DL” as shows Figure F-2.

Now one can configure several parameters that are spread in more than one window. The first window that one can open is the propagation model where one can chose the sizes of the urban area characterisation, the departing angle from the closest building and the MT height, as illustrated in Figure F-3.

The “LTE-DL Settings” window is the main panel where the majority of the parameters can be configured, such as the transmission power, FRS and radio interface parameters such as frequency band, as illustrates Figure F-4. After selecting these parameters and choosing “ok” button, the “User Profile” tab gets available, where one can select the minimum and maximum throughput associated with each service, as shows Figure F-5.

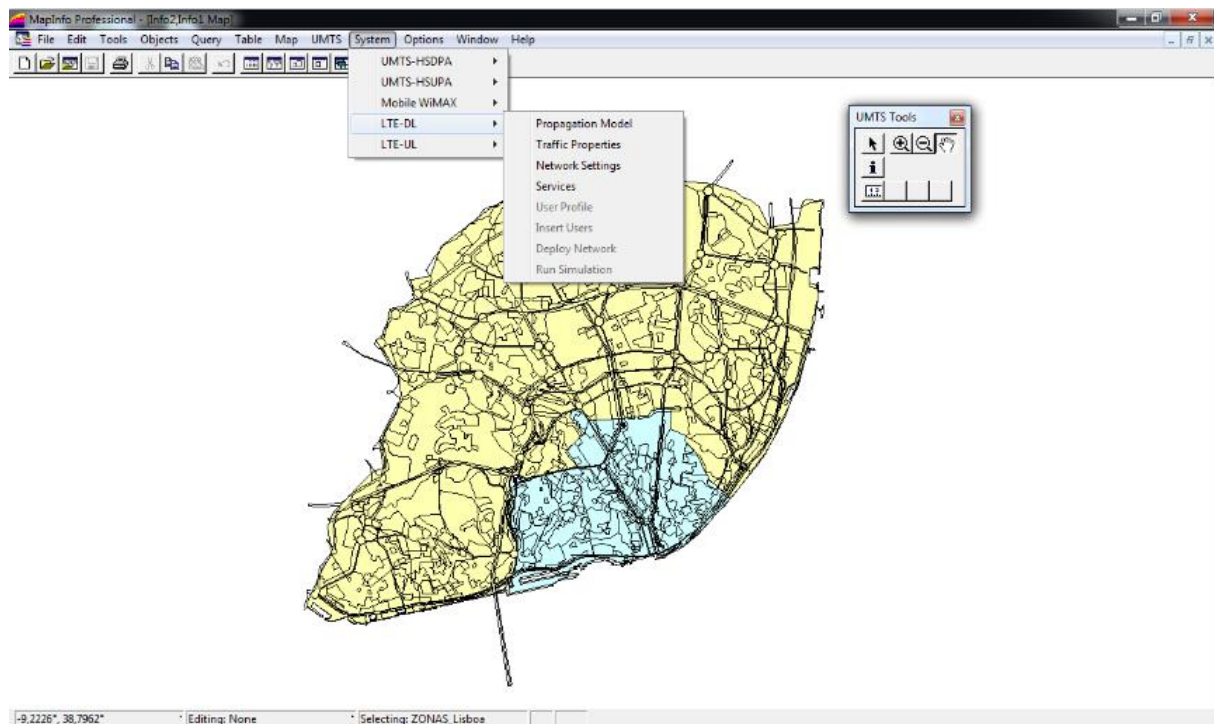


Figure F-2. System tab with the LTE-DL.

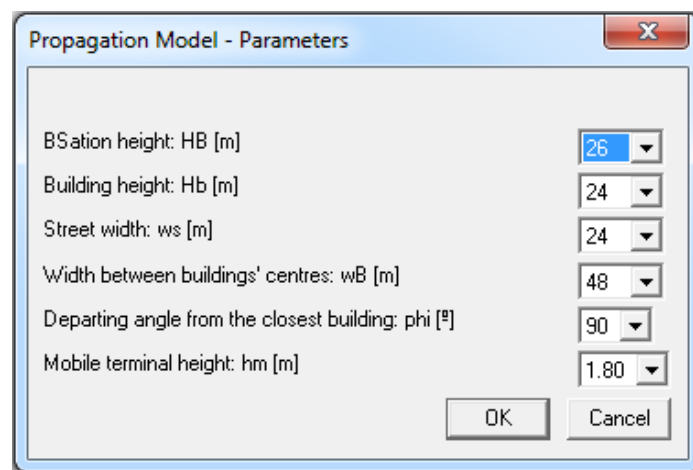
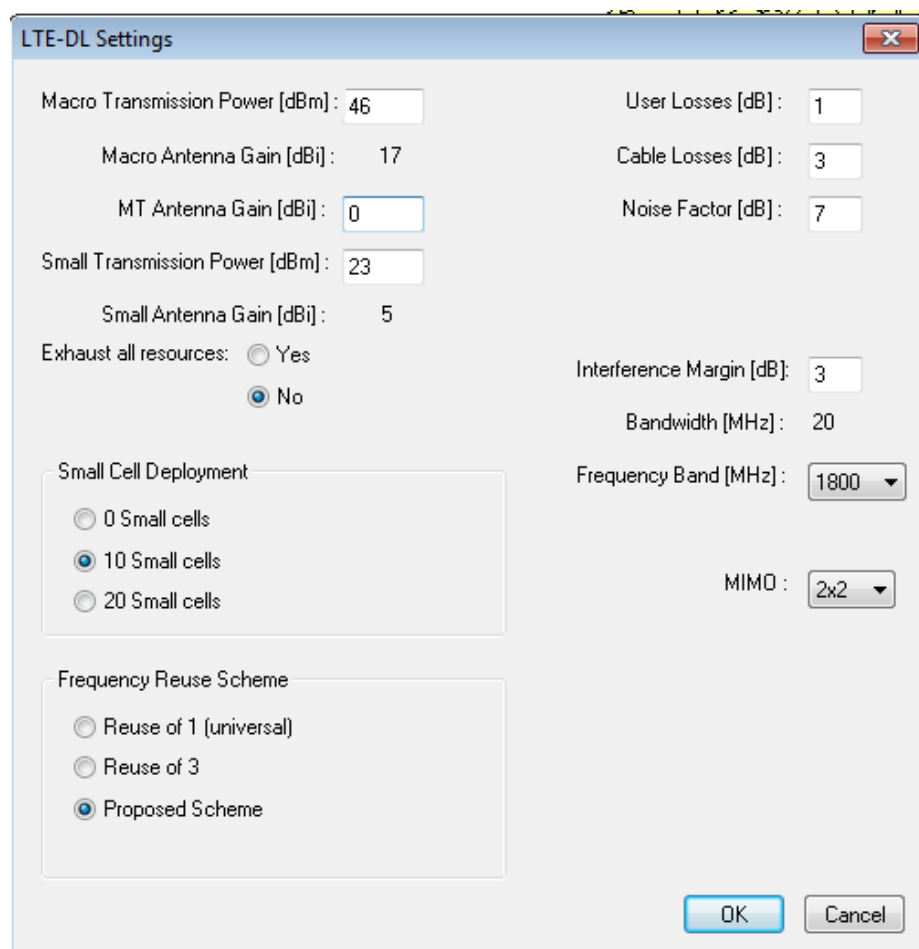


Figure F-3. Propagation model parameters.

After the associated services throughputs are set up, the tab “Insert users” is available and must select this tab and insert the files with the users that will be placed in the city of Lisbon, as in Figure F-6. The users files are created by the user generated program described in this thesis. After the users are loaded, users are represented in the map by flags, each one of a colour that represents the required service. Then one must load the BSs network, by selecting the “Deploy Network” tab and choose the desired network table, which contains in each row the identification and coordinates of each BS, as illustrates Figure F-7. When the network is loaded, it is represented with the users along the map and one can finally select “Run Simulation” in order to run the simulation, as shown in Figure F-8. When the simulation ends, three windows appear, the first presenting some statistical information regarding the simulation performed as shows Figure F-9.



LTE-DL Settings

Macro Transmission Power [dBm]: 46

Macro Antenna Gain [dBi]: 17

MT Antenna Gain [dBi]: 0

Small Transmission Power [dBm]: 23

Small Antenna Gain [dBi]: 5

Exhaust all resources: ☐ Yes ☒ No

Small Cell Deployment

☐ 0 Small cells

☒ 10 Small cells

☐ 20 Small cells

Frequency Reuse Scheme

☐ Reuse of 1 (universal)

☐ Reuse of 3

☒ Proposed Scheme

User Losses [dB]: 1

Cable Losses [dB]: 3

Noise Factor [dB]: 7

Interference Margin [dB]: 3

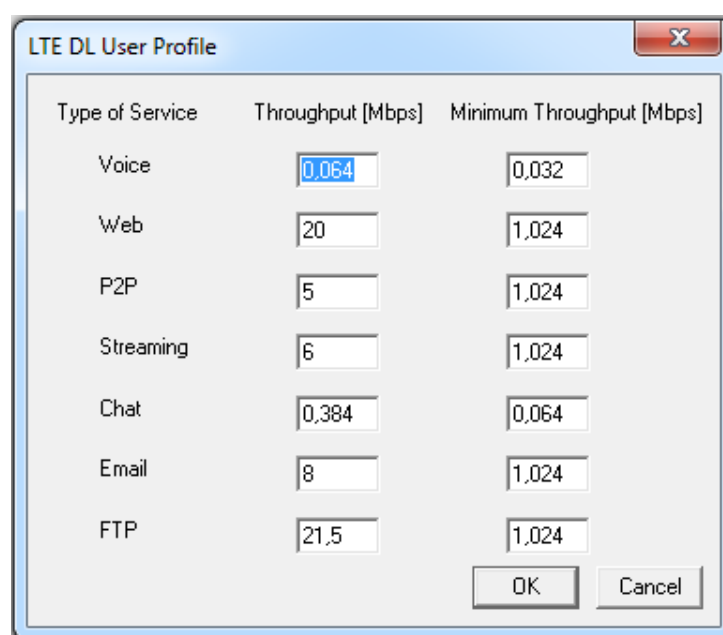
Bandwidth [MHz]: 20

Frequency Band [MHz]: 1800

MIMO: 2x2

OK Cancel

Figure F-4. Radio Interface parameters.



LTE DL User Profile

Type of Service	Throughput [Mbps]	Minimum Throughput [Mbps]
Voice	0,064	0,032
Web	20	1,024
P2P	5	1,024
Streaming	6	1,024
Chat	0,384	0,064
Email	8	1,024
FTP	21,5	1,024

OK Cancel

Figure F-5. User Profile parameters.

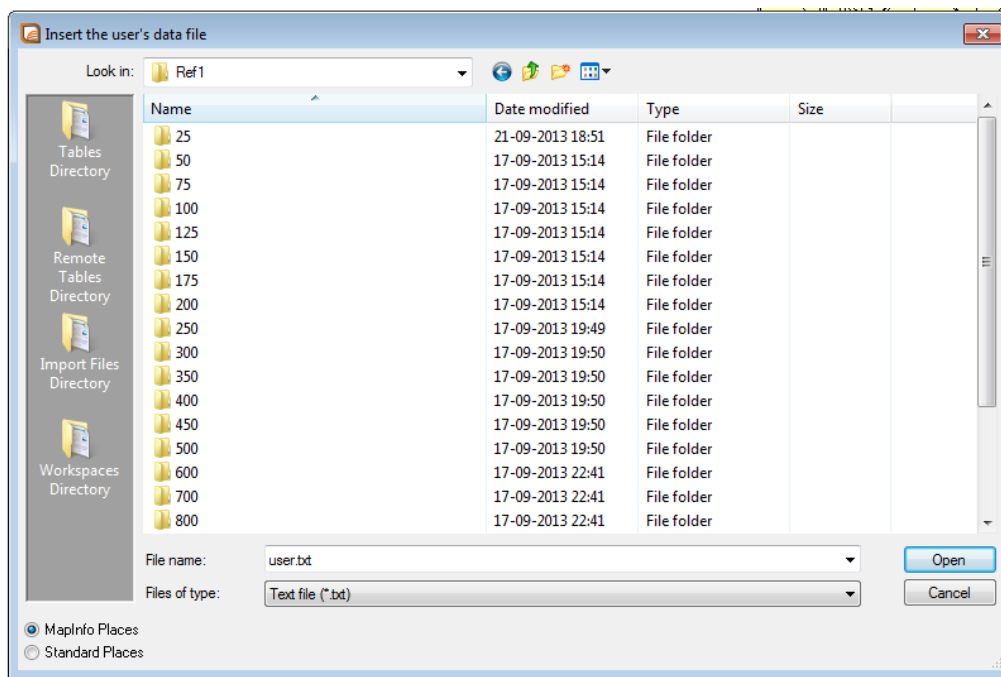


Figure F-6. Users data file.

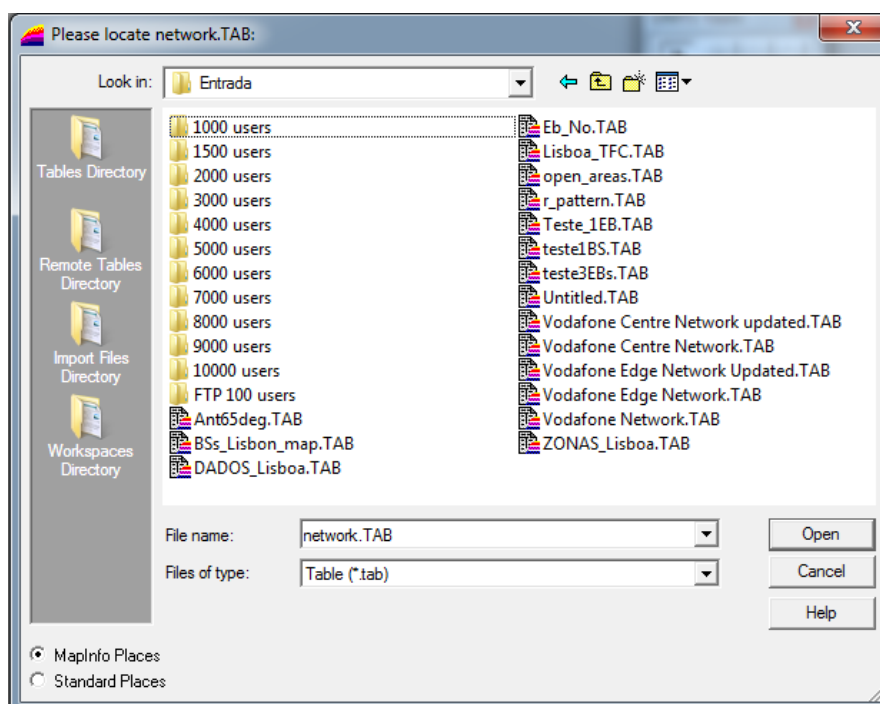


Figure F-7. Deploy Network window.

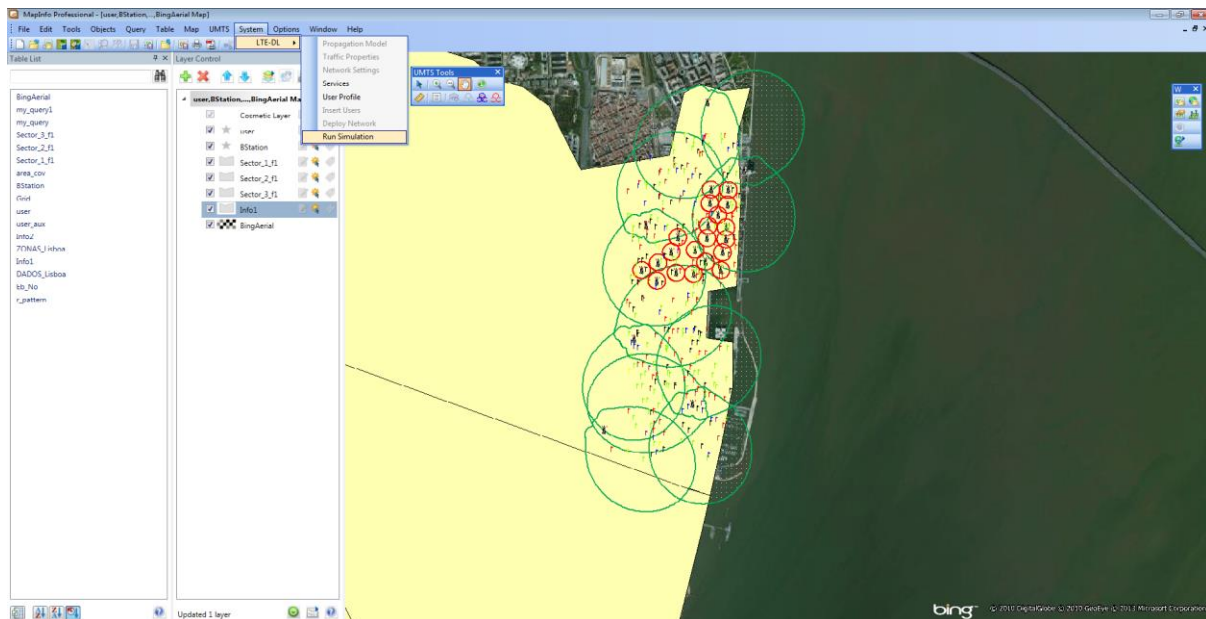


Figure F-8. Run Simulation command.

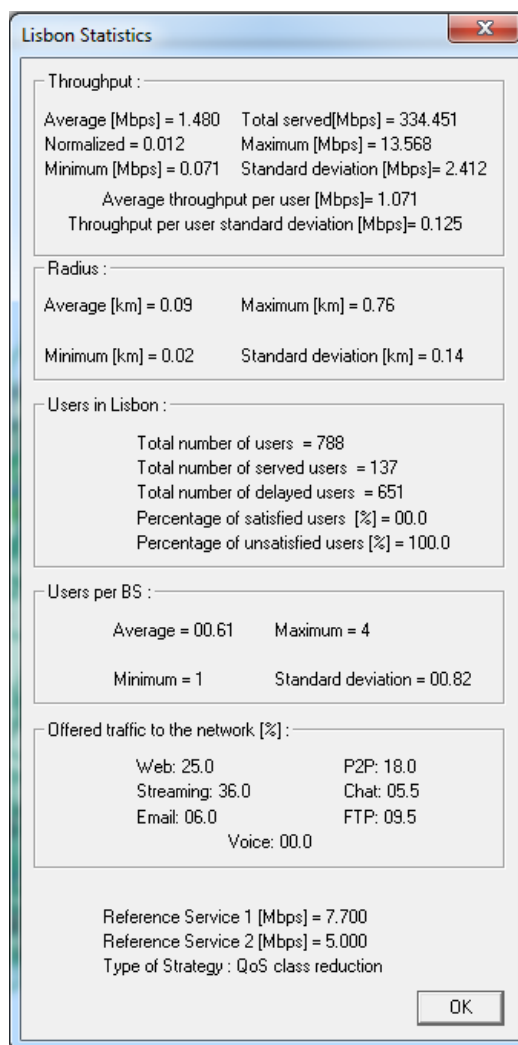


Figure F-9. Final simulation window.

Annex G

BSs, small cells and users distribution on the network

This annex presents the used network from the Optimus operator. The region of analysis is shown and the distribution of the macro-cells alongside with the distribution of the small cells is presented. The distribution of users is also performed.

The simulations performed in this thesis address a very specific network provided by the Portuguese Operator Optimus.

Figure G-1 shows the specific region in analysis for this thesis highlighted in red. One can immediately notice the small size of the network, but only by analysing this small scale problem, one can obtain proper conclusions about small cell deployment. Even by deploying 20 small cells, they only cover less than 40% of all region in analysis. There a total of 6 macro-cell base stations and 11 sectors enter the region of analysis. It was considered a maximum of 20 small cells deployment.

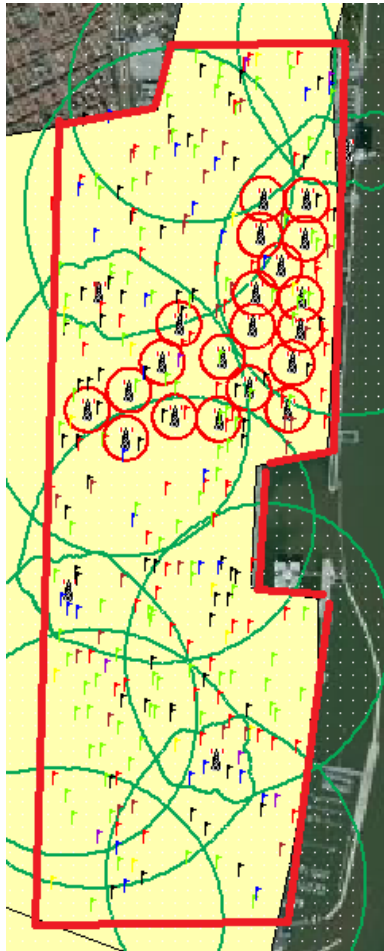
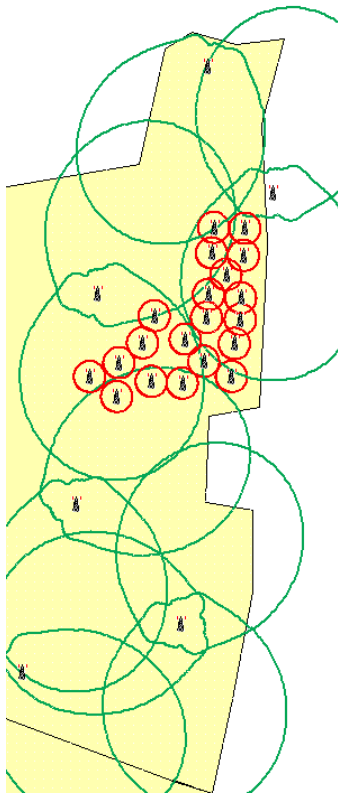
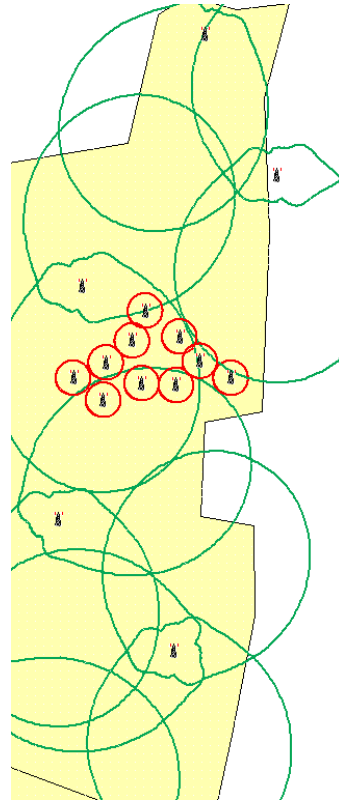


Figure G-1 Area of analysis for this thesis simulation

From Figure G-2, one can see the difference between the two possible deployments of small cells analysed in this thesis. Naturally the third not represented, is the same but without any small cells. In Figure G-3, the described user distribution done by the programmed module to randomisation user location are presented. One is referenced to the 350 users uniformly throughout the network and the other one corresponds of other example of 75 users uniformly and 350 users concentrated over the critical areas.

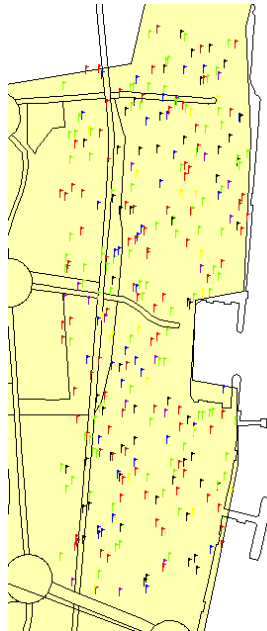


(a) 20 small cells deployment.

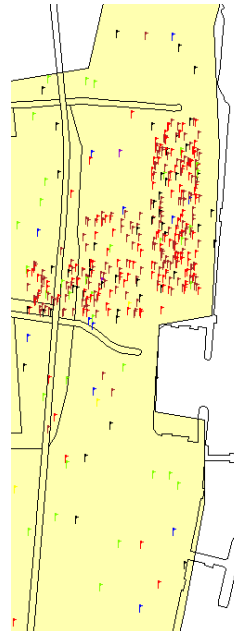


(b) 10 small cells deployment.

Figure G-2 The two studied deployments of small cells.



(a) Normal day load.



(b) Event day load.

Figure G-3 The two implemented user distribution.

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