LTE radio network deployment design in urban environments under different traffic scenarios

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To my family

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Abstract

The focus of this thesis was on the dimensioning of LTE radio access networks and the development of tools for dimensioning purposes. The main purpose is to compute the number of cells needed to cover a given area, taking a specific traffic profile into account. A model taking coverage and capacity planning into account was developed, regarding the 800,1800 and 2600 MHz frequency bands, in three different environments (urban, suburban and rural). The effect of varying parameters regarding user density, geographical area, frequency band and bandwidth, cell edge target throughput, traffic profile, among others, was studied in order to understand the impact of these parameters on the number of cells. For this purpose, a model was implemented, which takes a certain area and user density into consideration and makes the allocation of resources depending on system coverage and available capacity, replicating as close as possible the behaviour of a real network. A significant increase in the total number of cells is verified when the density of users increases. With more users, more resources are needed to fulfil the coverage and capacity requirements. Results show that, for all scenarios, most of the obtained cells are limited by capacity. Thus, the variation of service mix and services throughputs has a particular impact on the required number of cells. The number of urban cells for the voice centric scenario decreases about 12% over the ROM scenario, whereas, for the scenario with lower throughputs, the number of urban cells decreases about 41% over the ROM scenario.

Keywords

LTE, Dimensioning, Coverage, Capacity, Number of Cells, Lisbon.

Resumo

O foco desta tese foi o dimensionamento das redes de acesso de rádio LTE e o desenvolvimento de ferramentas de dimensionamento. O objetivo principal é calcular o número de células necessárias para cobrir uma determinada área, tendo em conta um perfil de tráfego específico. Foi desenvolvido um modelo tendo em conta o planeamento da cobertura e da capacidade, considerando as bandas de frequências de 800, 1800 e 2600 MHz, em três ambientes diferentes (urbano, suburbano e rural). Estudou-se o efeito da variação de alguns parâmetros relativos à densidade de utilizadores, área geográfica, banda de frequência e largura de banda, débito binário requerido no bordo da célula, perfil de tráfego, entre outros, de forma a compreender o impacto destes parâmetros no número de células. Para isso, foi implementado um modelo que tem em consideração uma determinada área e uma determinada densidade de utilizadores e realiza a atribuição de recursos dependendo da cobertura do sistema e da capacidade disponível, tentando replicar tanto quanto possível, o comportamento de uma rede real. Verifica-se um aumento no número de células quando a densidade de utilizadores aumenta. Com mais utilizadores, mais recursos são necessários para cumprir os requisitos de cobertura e capacidade. Os resultados mostram que, para todos os cenários, a maioria das células obtidas encontra-se limitada pela capacidade. Assim, a variação da mistura de serviços e dos débitos binários dos serviços tem um impacto particular no número de células obtidas. O número de células urbanas para o cenário focado no serviço de voz diminuiu cerca de 12% em relação ao cenário ROM, enquanto que para o cenário com débito binário menor, o número de células urbanas diminuiu cerca de 41% em relação ao cenário ROM.

Palavras-chave

LTE, Dimensionamento, Cobertura, Capacidade, Número de Células, Lisboa.

Table of Contents

List of Figures

List of Tables

List of Acronyms

16-QAM	Four bits per symbol Quadrature Amplitude Modulation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
64-QAM	Six bits per symbol Quadrature Amplitude Modulation
ABS	Almost Blank Sub-frames
AMBR	Aggregated Maximum Bit rate
AMC	Adaptive Modulation and Coding
ANACOM	Autoridade Nacional de Comunicações
BER	Bit Error Rate
BLER	Block Error Rate
BS	Base Station
CA	Carrier Aggregation
CC	Component Carriers
CoMP	Coordinated Multi-Point
CP	Cyclic Prefix
CRE	Cell Range Extension
CSG	Closed Subscriber Group
DL	Downlink
EDGE	Enhanced Data Rates for GSM Evolution
EIRP	Effective Isotropic Radiated Power
eICIC	Enhanced Inter Cell Interference Coordination
eNB	Evolved Node B
EPC	Evolved Packet Core
EPS	Evolved Packet System
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FB	Frequency Band
feICIC	Further Enhanced Inter Cell Interference Coordination
FDD	Frequency Division Duplex
FTP	File Transfer Protocol
GBR	Guaranteed Bit Rate
GSM	Global System for Mobile
GSM1800	GSM 1 800 MHz frequency band
HetNet	Heterogeneous Network

HSPA	High Speed Packet data Access
HSS	Home Subscription Server
ICI	Inter Cell Interference
ICIC	Inter Cell Interference Coordination
IP	Internet Protocol
ISI	Inter Symbol Interference
LTE	Long Term Evolution
LTE1800	LTE 1 800 MHz frequency band
LTE-A	Long Term Evolution Advanced
MAPL	Maximum Allowed Path Loss
M2M	Machine-to-Machine
MBR	Maximum Bit Rate
MIMO	Multiple-Input Multiple-Output
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
P2P	Peer-to-Peer
PBCH	Physical Broadcast Channel
Pcell	Primary Cell
PCRF	Policy Control and Charging Rules Function
PDCCH	Physical Downlink Control Channel
PDN	Packet Data Network
PDSCH	Physical Downlink Shared Control Channel
P-GW	Packet Data Network Gateway
PRACH	Physical Random Access Channel
P-SS	Primary Synchronisation Signal
PUCCH	Physical Uplink Control Channel
PUSCC	Physical Uplink Shared Control Channel
QCI	QoS Class Identifier
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RB	Resource Block
RE	Resource Element
RLB	Radio Link Budget
ROM	Residential, Office and Mix scenario
SAE	System Architecture Evolution
Scell	Secondary Cell
SC-FDMA	Single Carrier Frequency-Division Multiple Access
S-GW	Serving Gateway
SINR	Signal to Interference Noise Ratio

SMS	Short Message Service
SNR	Signal-to-Noise Ratio
S-SS	Secondary Synchronisation Signal
TDD	Time Division Duplex
TMA	Tower Mounted Amplifier
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
VoIP	Voice over IP
VoLTE	Voice over LTE
WCDMA	Wideband Code Division Multiple Access
WWW	World Wide Web

List of Symbols

α	Path loss exponent
α_{pd}	Average power decay
η	User density
η_{cell}	Cell capacity ratio
τ_{TTI}	Time transmission interval
γ	SINR requirement for the uplink or downlink traffic channel
ρ_{IN}	SINR
$\rho_{IN_{i,k}}$	Available SINR from i^{th} link in each single sub-carrier (k)
σ	Standard deviation
φ	Street orientation angle
$\overline{\Delta L_{p,int}^{p\%}}$	Average indoor slow fading margin
$\overline{\Delta L_{p,out}^{p\%}}$	Average outdoor slow fading margin
A_c	Site coverage area
A_d	Target area
$B_{i,k}$	Fading channel gain for donor cell
$B_{j,k}$	Fading channel gain for neighbouring cell
B_{RB}	Bandwidth of one RB
C_m	Extended Okumura-Hata model variable
d	Distance between the BS and the UE
$D_{i,k}$	Distance from user to donor base station
$d_{j,k}$	Distance from user to neighbouring cells
f	Frequency band
F_N	Noise figure
G_r	Gain of the receiving antenna
G_t	Gain of the transmitting antenna
G_{TMA}	Tower Mounted Amplifier gain
G_{Tx}	Diversity Gain
H_B	Buildings height
h_B	Effective height of BS antenna
h_m	User equipment height
H_{mu}	Okumura-Hata model variable
I_m	Interference Margin
K_f	Okumura-Hata model correction factor

L_o	Free space propagation path loss
L_c	Losses in the cable between the transmitter and the antenna
L_p	Path loss coming from the COST-231 Walfisch-Ikegami or Okumura-Hata model
$\overline{L_{p,indoor}}$	Average path loss coming from indoor penetration
$L_{p,max}$	Maximum path loss
$\overline{L_{p,outdoor}}$	Average path loss coming from the propagation models
$L_{p,total}$	Total path loss
L_r	Loss in the UE for the DL, or loss in the cable between the transmitter and the antenna for the UL
L_{rm}	Attenuation due to diffraction from the last rooftop to the UE
L_{rt}	Attenuation due to propagation from the BS to the last rooftop
L_t	Loss in the cable between the transmitter and the antenna for the DL, or loss in the UE for the UL
L_u	Loss in the UE
M	Modulation's order
M_F	Fading Margins
N	Noise Power
$N_{n,cell}$	Number of neighbouring cell
N_{RB}	Total number of RBs
$\overline{N_{RB}^{Q}}$	Number of RBs required in QPSK
$\overline{N_{RB}^{16}}$	Number of RBs required in 16-QAM
$\overline{N_{RB}^{64}}$	Number of RBs required in 64-QAM
$N_{RB,cell}$	Maximum available number of RBs per cell
$\overline{N_{RB,required}}$	Average total number of required RBs
$\overline{N_{RB,required}^{n}}$	Average number of RBs required of each modulation n
$N_{RB/U}$	Number of RBs allocated to a user
$\overline{N_{RB,users,s}}$	Average number of required RBs per user for each service and modulation
N_{sites}	Number of sites or cells
$N_{streams}$	Number of streams
$N_{symbols/subframe}$	Number of OFDM symbols per sub-frame
N_U	Number of total users in system
$N_{u,16QAM}$	Number of served users in 16-QAM
$N_{u,64QAM}$	Number of served users in 64-QAM
$N_{u,cell}$	Number of active users per cell
$N_{u,cell}^{n}$	Number of served users by modulation n
$N_{u,QPSK}$	Number of served users in QPSK
$N_{u,s}$	Number of active users in the service s

P_{EIRP}	Effective Isotropic Radiated Power
P_i	Transmit power of donor base stations
p_{ind}	Percentage of indoor users
P_j	Transmit power of neighbouring base stations
p_{out}	Percentage of outdoor users
P_r	Power available at the receiving antenna
P_{Rx}	Power at the input of the receiver
$P_{Rx,min}$	Power sensitivity at the receiver antenna
P_t	Power fed to the transmitting antenna
$p_{traffic}$	Percentage of traffic
P_{Tx}	Transmitter output power
$P_{u,s}$	Subscriber percentage of a service s
R	Maximum radius from coverage or capacity estimation
R_b	Data Rate
$\overline{R_{b,cell}}$	Average throughput per cell
$\overline{R_{b,RB}^{n}}$	Average throughput per RB of each modulation n
$\overline{R_{b,user,s}}$	Average throughput of user in service s
R_{max}	Maximum cell radius
$\overline{r_{cell}}$	Average cell radius
$\overline{r_{ind}}$	Average indoor cell radius
$\overline{r_{out}}$	Average outdoor cell radius
S	Maximum coverage area
w_b	Building separation
w_s	Street width

List of Software

Microsoft Visual Studio 2015	C# App Development Environment
Google Maps	Geographic plotting tool
Microsoft Office Excel 2016	Spreadsheet application
Microsoft Office Power Point 2016	Presentation and slide program
Microsoft Office Word 2016	Word processor
Microsoft Visio 2016	Flow chart and diagram software

Chapter 1

Introduction

This chapter gives a brief overview of the mobile communications system evolution, in terms of technology and consumer demand, with a particular focus on LTE and LTE-A. Furthermore, the thesis motivation and work structure is also presented.

1.1 Overview

Over the past years, several mobile communication systems were introduced and have known great technological developments in order to fulfil consumers' needs. These needs have changed throughout the years, and mobile voice traffic growth is expected to remain limited compared to the explosive growth in data traffic; however, both mobile voice and data are rapidly becoming an essential part of consumer´s lives. This huge growth is due to both the rising number of smart devices subscriptions and the increasing data consumption per subscriber. According to a study conducted by [Eric15b], the number of subscribers, which is also growing rapidly, is lower than the number of subscription – with around 5 billion subscribers versus 7.2 billion subscriptions.

According to [Eric15a], data traffic grew around 10% quarter-on-quarter and 65% year-on-year, reaching 5.3 ExaBytes of total monthly traffic in 2015. The evolution of the mobile traffic for voice and data services, accessed by different devices, is presented in Figure 1.1. Smart devices, and more specifically smartphones, recent popularity strongly contributes to these expectations, mainly due to the need for more demanding services in terms of throughput and latency. These devices accounted for 89% of the global mobile data traffic in 2015, even though they represented 36% of the total mobile devices and connections. By 2020, it is expected that smart devices will represent 67% of the total mobile devices, generating 98% of the global mobile traffic, [Cisc15].

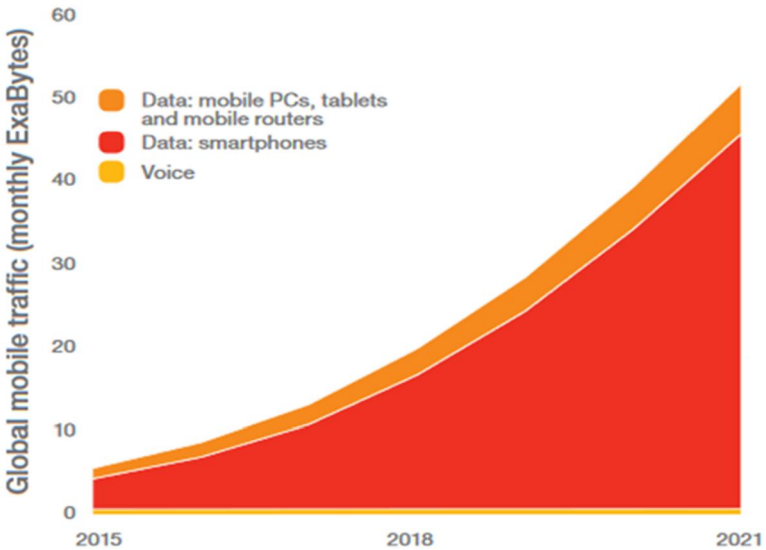

Figure 1.1 - Global mobile traffic for voice and data, 2015-2021 (extracted from [Eric15a]).

Considering the growing need for higher data speeds, which ensures a better user experience, more efficient and new mobile communications systems were deployed over the last years. The Third Generation Partnership Project (3GPP) was created, comprising seven Organisational Partners, being involved in the development of the latest releases concerning mobile communications technologies: Universal Mobile Telecommunications System (UMTS), also known as 3rd Generation (3G), and Long Term Evolution (LTE), so called 4th Generation (4G). Moreover, the major focus of 3GPP´s Releases is both backward and forward compatibility wherever possible, in order to ensure that the operation of user

equipment is un-interrupted. Figure 1.2 illustrates the time schedules of 3GPP specifications and its commercial deployments. For 3G, Wideband Code Division Multiple Access (WCDMA) Release 99 specification work was completed at the end of 1999, being followed by the first commercial deployments during 2002. The High Speed Packet Access (HSPA) standards were completed in March 2002 (High Speed Uplink Packet Access) and December 2004 (High Speed Downlink Packet Access), and the commercial deployments followed in 2005 and 2007, respectively. The first phase of HSPA Evolution (HSPA+) was completed in June 2007, and the deployments started during 2009. The LTE standard was approved at the end of 2007, backwards compatibility started in March 2009 and the first commercial networks started during 2010. 3GPP has introduced advanced features of LTE referred to as LTE-Advanced (LTE-A), which was approved in December 2010 and is currently in the deployment phase, includes new capabilities, such as Carrier Aggregation (CA), Heterogeneous Networks, enhanced MIMO and ICIC, reaching up to 1 Gbps, the target value of the International Mobile Telecommunications (IMT) –Advanced.

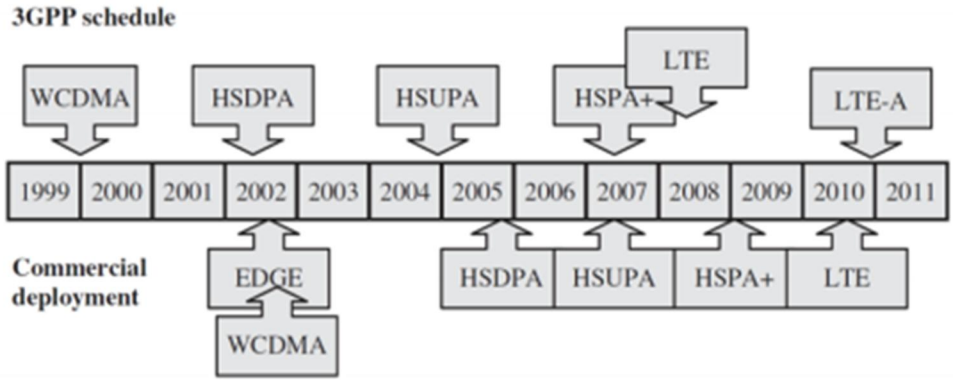

Figure 1.2 - Schedule of the 3GPP standards and their commercial deployment (adapted from [HoTo11]).

Since its commercial release, the number of LTE subscriptions has grown rapidly, and currently sits at around 850 million. In order to illustrate this growth, Figure 1.3 presents the evolution of the number of global mobile subscriptions since 2011 for different technologies; according to [Eric15a], there will be a shift from a world dominated by GSM-EDGE-only subscriptions in 2015 to a world dominated by LTE and WCDMA/HSPA-subscriptions in 2021. In fact, LTE subscriptions will make up the largest share of all subscriptions by 2021, totalling 4.1 billion.

As the demand in terms of traffic and capacity increases, LTE and LTE-A need to be widely deployed in order to satisfy them, being estimated that both systems will cover approximately 72% of the world's population, [Cisc15]. This will include the deployment of heterogeneous networks, which comprises several types of cells with various sizes, being considered as the most promising approach to enhance network capacity, overall performance, and to increase coverage in a cost effective way.

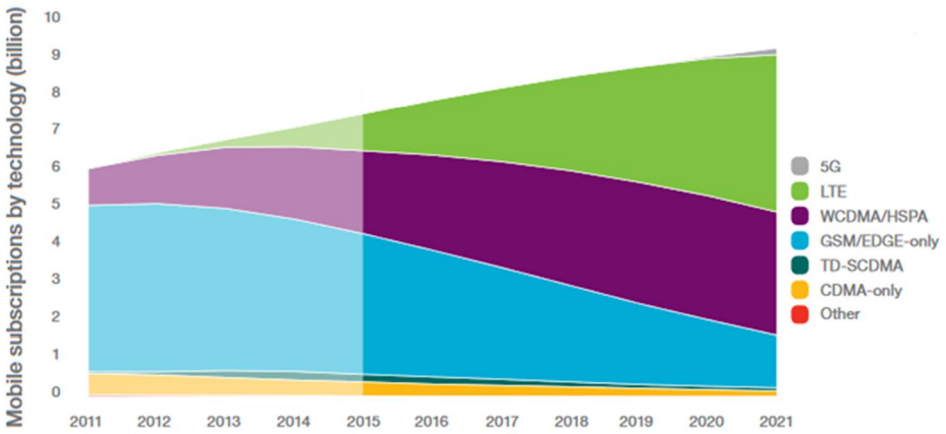

Figure 1.3 - Area chart with the number of global mobile subscriptions for different technologies, 2011-2021 (extracted from [Eric15a]).

1.2 Motivation and Contents

The growth in mobile data traffic is due to both the rising number of smartphones subscriptions, in particular LTE smartphones, and the increasing data consumption per subscriber. The vast cost of keeping with demand for mobile data is intensifying the pressure on mobile operators' CAPEX budgets and accelerating their moves to improve their infrastructure cost base. However, the increase in network costs and in the total data traffic will be quite a limitation for mobile operators in the future. The need to reduce networks costs is also driving operators to out-source their whole Radio Access Networks (RANs), and to seek new mechanisms to acquire and manage sites – frequency and channel bandwidth selection strategy, type of technology, service coverage design and architecture structure. The purpose of dimensioning is to estimate the required number of radio base stations needed to support a specified traffic load in an area, [Syed09]. This number has a fundamental role in cost planning, giving an idea of the economic impacts in the countries under study.

The main scope of this thesis is to study and describe the nominal RAN planning in LTE, and to compute the number of cells needed to cover a given area with all the input parameters that the dimensioning process requires, for different scenarios. Network planning is not a new concept, and has already been addressed and studied for previous technologies, such as 3G. However, the methods, and some considerations implemented, are different, as well as the implementation in different scenarios, generally taking interesting case studies into account, as the Lisbon region with different terrain morphologies and user densities. Methods and models for coverage and capacity planning are listed and explained in detail, studying mainly the effects of the number of users in the network, different bandwidths, frequency band, service throughputs and traffic profiles on a LTE network scenario with multiple-input multiple-output (MIMO) 2x2.

The traffic distribution depends on the network deployment, country geography and number of active

users. Taking the different traffic profiles used in this work into account, it is possible to determine if cells are limited by coverage or capacity, and due to the use of the frequency domain, load is defined as a percentage of used Resource Blocks (RBs) over the total available in the system. If the network is overloaded, the cell is limited by capacity. However, it is important to notice that the load is not directly proportional to the number of users, because they may require different services and experience different channel conditions, [Guit16]. Traffic is not equally distributed over a 24-hour period. The busy hour in data networks is typically in the evening, but data traffic is also generated during the night, [Noki14]. As such, dimensioning involves planning for peak-hour or busy-hour traffic, i.e., the hour in the day during which traffic intensity is at its peak. For that reason, only the busy hour is taken into account in this study.

This thesis was developed in collaboration with Celfinet Portugal, an important global telecommunications consulting firm. The main output of this thesis is a dimensioning tool that implements the proposed models, simulates and computes the number of base stations for different possible scenarios considering different configuration parameters. By varying different input parameters, the focus is on understanding the impact of these variations on the number of base stations and, consequently, the cost effectiveness of the network.

In terms of contents, this thesis is divided into five chapters, followed by a set of annexes that serves as a complement of the developed work. The present chapter makes a brief overview of mobile communications history evolution, showing the motivation behind the thesis.

In Chapter 2, some fundamental aspects regarding this work are introduced. It provides a brief description of LTE´s network architecture and radio interface, presenting its main elements. The description of the services and applications requirements and priorities, followed by the coverage and capacity considerations. This chapter also presents information about heterogeneous networks, mainly focusing on the challenges of interference management. To conclude this chapter, one presents some of the previously developed works related to interference management methods and dimensioning models, taking cost planning into account.

A full description of the models used in this thesis is provided in Chapter 3, starting by explaining the various considerations that are of relevance for the development of the present work, such as, coverage, capacity and throughput calculations, and the relationship in between them. The description of the implemented simulator is also presented in this chapter, where an illustration shows the simulator workflow followed by a textual description to facilitate the understanding of the different elements that compose it. In the end, a brief assessment of the presented models, ensuring that the obtained results are indeed relevant for this study.

Chapter 4 presents the scenarios description along with the models outputs and their respective analysis. It begins with a description of the reference scenario, containing all the parameters used in the simulator. Then, follows the analysis of the results that enables the study of the different parameters that are of interest, such as cell radius, number of active users and number of cells. Afterwards, relevant results and figures obtained from the measurements performed in the city of Lisbon and its surrounding areas are presented.

Chapter 5 contains the main conclusions of this thesis, an analysis of the overall obtained results followed by suggestions for future work.

Some auxiliary information to this thesis is provided in annexes. Annex A presents the expressions that relate the signal-to-noise-ratio with the throughput per resource block. Path loss was computed using the COST-231 Walfisch-Ikegami and Okumura-Hata model, detailed in Annex B. Finally, Annex C presents all the municipalities and its districts under study in this thesis, taking into account the area and number of inhabitants of each district, as well as the reference user density used in the simulations.

Chapter 2

Fundamental Concepts and State of the Art

This chapter provides an overview of LTE and LTE-A systems, mainly focussing on coverage and capacity dimensioning. The overall network architecture is presented in Section 2.1, the main technical features of the radio interface is presented in Section 2.2. The services and applications are analysed in Section 2.3, while the study of coverage and capacity planning, and also heterogeneous networks aspects that are more relevant for this thesis, are presented in Section 2.4 and 2.5, respectively. Finally, the state of the art concerning the scope of this thesis is presented in Section 2.6.

2.1 Network Architecture

In this section information on LTE and LTE-A architecture is introduced, based on [3GPP16], [Alca09], [HoTo11].

LTE and LTE-A were designed with the purpose of developing a radio access technology in which services are packet-switched rather than being circuit-switched, the latter being the model in earlier systems. Additionally, the standards evolution of mobile communications has been accompanied by an evolution of the complete system resulting in the System Architecture Evolution (SAE), which includes the Evolved-Packet-Core (EPC)-network. The Evolved-Packet System (EPS) is constituted by the LTE radio and SAE, and both the radio and network-core access are packet-switched.

The evolution of the LTE architecture is characterised by progressively lower latencies, reduced costs and optimised network performances. To achieve these requirements, as well as reducing the complexity experienced in previous network architectures, LTE was designed to contain fewer network nodes.

Figure 2.1 shows the system architecture for EPS, which provides all IP based connectivity. As Figure 2.1 shows, the architecture is divided into four main sections: User Equipment (UE), E-UTRAN, EPC and Services Domain.

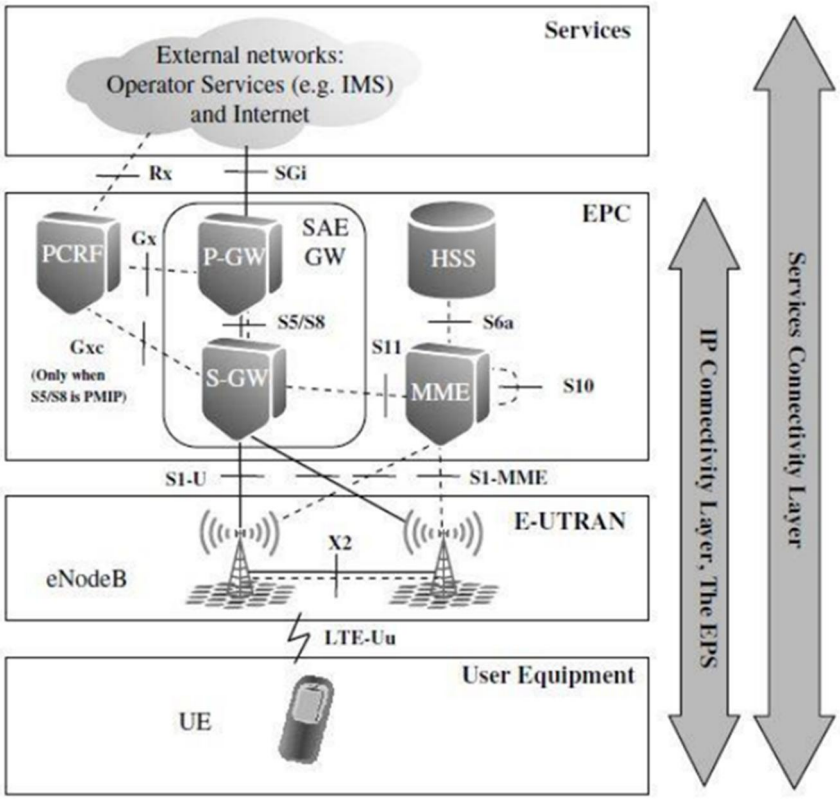

Figure 2.1. System Architecture for E-UTRAN only Network (extracted from [HoTo11]).

At the highest level, two main components should be addressed: the core Network (EPC) and the Access-Network (E-UTRAN). While the core network consists of some logical nodes, the access network is built around one node called the Evolved Node B (eNB), which connects to the UEs.

The eNBs are typically interconnected via the interface, known as X2, and the connection between this network element and EPC is achieved through the S1 interface. For normal user traffic, as opposed to broadcasting, there is no centralised controller E-UTRAN, therefore the E-UTRAN architecture is said to be flat.

LTE´s RAN is also responsible for all radio related functions, including Radio Resource Management, which covers functions related to the Control Plane, Header Compression helping to ensure an efficient use of radio interface by compressing the IP Packets headers, and Security where all data sent over the radio interface is encrypted. These functions are responsible for improving radio interface performance, which is further discussed in what follows.

The EPC is responsible for the overall control of the UE and establishment of bearers. The main logical nodes of the EPC are Packet Data Network (PDN) Gateway, Serving Gateway (S-GW) and Mobility Management Entity (MME). All logical nodes and their functions are discussed in further detail below:

- Home Subscriber Server (HSS): A central database that contains users SAE subscription data and also provides support functions in access authorisation, user authentication, call and session setup and mobility management.
- Policy Control and Charging Rules Function (PCRF): It is responsible for efficient policy and charging control. The PCRF function is part of the larger Policy Charging Control (PCC) architecture, which also includes Policy and Charging Enforcement Function (PCEF), located in the P-GW. Combined, the elements of the PCC provide quality-of-service (QoS) control.
- Packet Data Network Gateway (P-GW): Provides connectivity between UE and external IP packet data networks. It is responsible for IP address allocation for the UE and covers functions like charging support, policy enforcement and lawful interception of user traffic.
- Serving Gateway (S-GW): The transfer of all user IP traffic is ensured by this node, which connects E-UTRAN and EPC. It acts as the anchor for mobility between LTE and other 3GPP technologies (such as UMTS) and as the mobility anchor for the user plane.
- Mobility Management Entity (MME): It is considered the main control node for the LTE access network. It processes the signalling between the UE and the EPC. The MME functions covers security, mobility management, authentication and retrieval of subscription information from the HSS.

2.2 Radio Interface

This section presents an overview of the radio interface for LTE and LTE-A, based on [3GPP13], [3GPP15b], [Bryd13], [HoTo11].

LTE operates in different arrangements of frequency and bandwidth, depending on the region where it is implemented. In Portugal, through an auction conducted by ANACOM, the Portuguese telecommunications authority, the three frequency bands chosen for LTE were 800 MHz, 1800 MHz and 2600 MHz, [ANAC16]. Accordingly, with 3GPP specifications, there are currently 27 frequency bands for Frequency Division Duplex (FDD) and 12 for Time Division Duplex (TDD), including the three previously mentioned bands. Table 2.1 presents the specific frequencies for each band. Only FDD is considered in this thesis, as it is the widely adopted duplex mode in Europe.

Table 2.1 – LTE FDD frequency bands used in Europe (adapted from [HoTo11]).

Band Designation	Uplink Band [MHz]	Downlink Band [MHz]	UL/DL Bandwidth [MHz]
3	[1710; 1785]	[1805; 1880]	75
7	[2500; 2570]	[2620; 2690]	70
20	[832; 862]	[791; 821]	30

These three bands have different transmission bandwidths, depending on the frequency band (FB) that is allocated by network operators. This differentiation is essentially based on spectrum availability and on the operators' investment capabilities. The 800 MHz band, previously used for terrestrial TV broadcasting in Europe, is particularly relevant in the design of coverage solutions. In this band, 30 MHz are available in UL and DL, originating a three operators scenario where 10 MHz are made available for each. On the other hand, 2600 MHz and 1800 MHz bands are preferably used when implementing capacity solutions. The preferred frequency arrangement for the 2600 MHz band is, once again, 60 MHz of available bandwidth for UL and DL, giving place to a three operators scenario with 20 MHz available to each. Having 20 MHz bandwidth is particularly important for network operators, because it allows for a large capacity. Using the 1800 MHz band and depending on the area and operator, 10, 15 or 20 MHz bandwidths for both LTE1800 and GSM1800 are applicable, knowing that the maximum bandwidth can be split or rearranged between the two. This band can also provide up to 20 MHz of capacity, given that the operator has bought the bandwidth.

In order to reduce implementation error effects and the Doppler Effect without too much deterioration to sub-carrier´s orthogonality, LTE specifies a 15 kHz constant spacing between sub-carriers. The Inter-Symbol Interference (ISI) may be avoided by inserting a guard interval into the timing at the beginning of each data symbol. It is then possible to copy a section from the end of the OFDM symbol to its beginning, known as Cyclic Prefix (CP), which is used in both UL and DL multiple access transmission schemes. There are two sets of CP based on their duration; the extended CP with a duration of 16.67 μs and the short CP with a duration of 5.21 μs. The length that characterises the CP plays an important role: if too short, it becomes impossible to avoid the multipath reflection delay spread, but if too long, it narrows the data throughput capacity.

LTE uses OFDMA for DL and SC-FDMA for UL. SC-FDMA allows improved device battery life and UL-

range, which justifies the different access techniques for UL and DL. The problem associated with OFDMA in the UL is its high peak to average power ratio (PAPR), which requires high linearity in the transmitter; because of this, the operating point of the power amplifiers in the transmitter needs to be lowered off, which in turn lowers the amplifier efficiency, hence the logical use of SC-FDMA in UL, providing a better power amplifier efficiency. Despite the challenges OFDMA poses to UL, this modulation scheme benefits over other transmission schemes, having better performance in frequency selective fading channels, lower complexity of base-band receiver, good spectral properties, handling multiple bandwidths, link adaption, frequency domain scheduling and compatibility with advanced MIMO technologies.

LTE uses QPSK, 16-QAM and 64-QAM modulation schemes: 64-QAM carries 6 bits per symbol, whereas QPSK and 16-QAM carry 2 and 4 bits per symbol, respectively. These last two schemes are available in all devices, while support for 64-QAM in UL is a UE capability. Adaptive Modulation and Coding (AMC) was proposed for LTE, as well as to many other 3GPP systems, essentially in order to improve system capacity and also coverage reliability. By matching coding rates and modulation schemes to the channel conditions, this system makes possible the efficient and better use of channel capacities. For any given modulation scheme, the appropriate code rate can be chosen, depending on channel quality. In order to maximise system throughput and to achieve the maximum channel quality, higher order modulation schemes and higher code rates can be selected.

For each of the types of duplexing, there is an associated type of frame structure. While Frame Structure 1 is used in FDD, Frame structure 2 is used in TDD. As show in Figure 2.2, LTE radio frames are 10 ms in duration, these are divided into 10 sub-frames, each sub-frame being 1.0 ms long. Each sub-frame is further divided into two slots, each with a duration of 0.5 ms. One sub-frame is also the Transmission Time Interval (TTI). Systems tend to evolve to shorter TTIs, which helps to achieve the requirements of low latency.

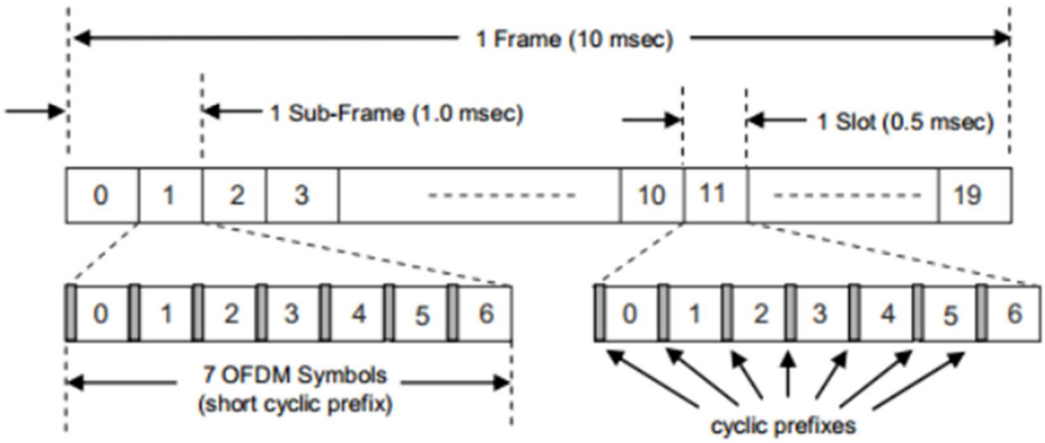

Figure 2.2 - Frame Structure type 1 with short CP (extracted from [Share16]).

Dynamically allocating resources in the frequency domain is another of LTE's specifications and DL physical resources can be seen as a time-frequency grid, as illustrated in Figure 2.3.The basic unit of this grid is the Resource Element (RE) consisting of one sub-carrier during one OFDM symbol. Resource

Elements are grouped into Resource Blocks (RBs), each of which consists of a group of 12 sub-carriers, using a total bandwidth of 180 MHz, and 7 OFDM symbols, when CP has normal length, or 6 symbols if the extended CP configuration is used. Thus, each RB can have 84 or 72 REs per slot in the time domain, depending on the CP length.

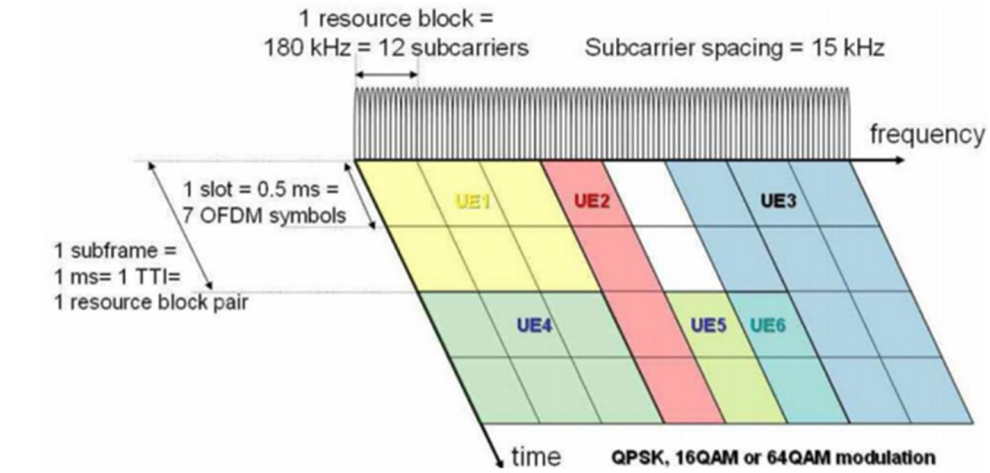

Figure 2.3 - OFDMA resource allocation in LTE (extracted from [Corr16]).

LTE specifications define bandwidths ranging from 1.4 MHz to 20 MHz. In LTE-A, one of the most required feature is carrier aggregation (CA), which is used in order to increase bandwidth and, consequently, the bitrate. Each aggregated carrier is referred to as Component Carrier (CC). LTE-A allows the aggregation of up to 5 component carriers, each having a bandwidth from 1.4 MHz to 20 MHz, thus, achieving a maximum aggregated bandwidth of 100 MHz. CA can be used in both TDD and FDD to facilitate an efficient use of the fragmented spectrum. In FDD, the number of UL component carriers is always equal or lower than the number of DL component carriers. Table 2.2 shows the relationship among available bandwidth, number of sub-carriers and the maximum number of allocated RBs.

Table 2.2 - Relationship among bandwidth, number of sub-carriers and of RBs (adapted from [Corr16]).

Bandwidth [MHz]	**1.4**	**3**	**5**	**10**	**15**	**20**
Number of sub-carriers	72	180	300	600	900	1200
Maximum number of RBs	6	15	25	50	75	100

One of the fundamental improvements in LTE is the use of multiple antenna techniques, which were introduced to achieve enhanced system performance both in capacity and coverage. The most common technique is Multiple Input Multiple Output (MIMO), which enables radio systems to achieve significant performance gains by using multiple antennas at their transmitters and receivers.

The use of MIMO adds advantages to systems, including greater spectral efficiency, more robust operations in poor signal conditions and increased data rates for users. MIMO is considered important

in urban environments, where multipath propagation is significant. In open areas, such as rural locations, where there is a strong line of sight between the transmitter and receiver, MIMO is less useful.

MIMO can be sub-divided into three main configurations. Spatial multiplexing is one of the configurations used, which consists of sending signals from two or more different antennas with different data streams. Subsequent developments have extended this operation and currently LTE-A supports 8x8 MIMO in DL and 4x4 UL. Transmit Diversity is a different configuration, where the same signal is sent from different antennas with the same coding, in order to exploit the gains from independent fading between antennas. Finally, MIMO also relies on Pre-Coding, which exploits transmit diversity by weighting information streams, i.e., the transmitter sends the coded information to the receiver in order to estimate radio channel conditions and maximise the received Signal-to-Noise Ratio (SNR).

Concerning the physical layer, one common characteristic of physical channels is that they all convey information from higher layers in the protocol structure. This contrasts with physical signals, which convey information that is used exclusively within the physical layer. As shown in Figure 2.4, DL´s frame structure is divided into physical channels and physical signals. DL's main signals are the Reference Signal (RS), which is used to obtain an estimation of the channel, and the Primary and Secondary Synchronisation Signals (P-SS, S-SS), which are used for cell search and UE network synchronisation. DL's main physical channels are the Physical Broadcast Channel (PBCH) that carries system information for UEs requiring to access the network, the Physical Downlink Control Channel (PDCCH) that carries information regarding resource allocation for both DL and UL and the Physical Downlink Shared Channel (PDSCH) that is considered the main DL physical channel for user data, broadcast system information and paging messages.

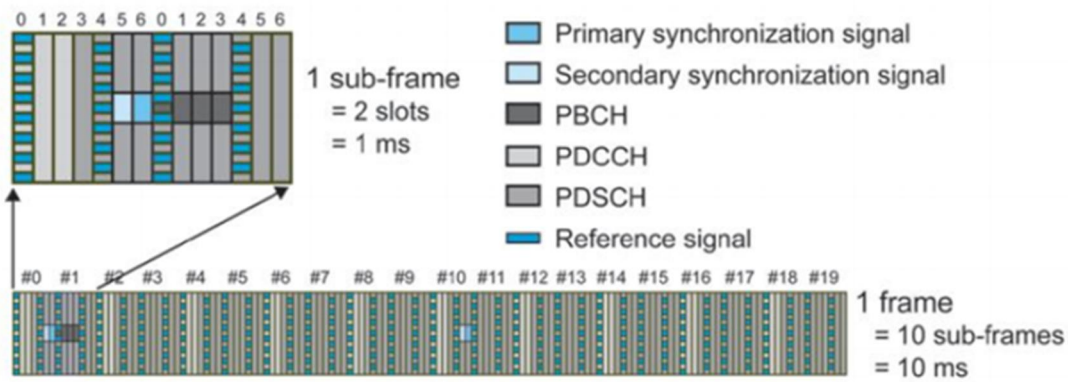

Figure 2.4 - DL frame structure with normal CP (extracted from [Agil09]).

UL's main physical channels are the Physical Uplink Control Channel (PUCCH) and Physical Uplink Shared Control Channel (PUSCC). These channels have the same functions as the PDCCH and PDSCH in UL, respectively. The Physical Random Access Channel (PRACH), which is another physical channel used in UL, is only used for random access functions.

2.3 Coverage and Capacity

The information in this section regards coverage and capacity planning in LTE-A networks based on [Syed09], [SeTB11], [Aldh13].

Coverage estimation and capacity evaluation are carried out in Radio Network Dimensioning, which main objectives are to determine the areas that need to be covered and to calculate the number of base station sites required to cover the target areas, while fulfilling the capacity and coverage requirements. In order to fulfil these goals, Network Dimensioning relies on some fundamental parameters, such as allocated bandwidth, subscriber population, frequency band, geographical area to be covered and traffic distribution. Radio Link Budget (RLB) is at the heart of coverage planning, where the calculation of the maximum path loss is based on the required SINR level at the receiver, taking the extent of the interference caused by traffic into account. The maximum path loss and the minimum received signal in both UL and DL is converted into the cell radius. This is done using an appropriate propagation model, which, if required, can be edited to fit the specifications of the deployment area. For a given throughput, cell edge is defined according to the required SINR, one of the main performance indicators in LTE. However, if the minimum guaranteed bit rate and subscriber density are given, then it is the cell size that should be determined.

On the other hand, capacity planning also estimates resources needed to support a specific traffic with a certain level of QoS (such as throughput). Capacity planning is evaluated by the number of UEs that can be served by the eNB with a desired quality of service. A UE is considered to be served if it is receiving RBs from the eNB, and those RBs are able to provide a minimum throughput, depending on the type of service the UE is using. Having guaranteed a minimum throughput, and knowing the cell size, it is possible to know the maximum number of users in the network; in this process, the available spectrum and bandwidth configuration used by the system are particularly important parameters.

For a given estimation of capacity and coverage, the number of RBs available for each user is, [Dout15]:

$$N_{RB/U} = \left\lfloor \frac{N_{RB}}{N_U} \right\rfloor \tag{2.1}$$

where:

- N_U is the total number of users in the system.
- N_{RB} is the total number of resource blocks.

The physical layer bit rate for each user, $R_{b/U}$, can be calculated as follows:

$$R_{b/U_{[\mathrm{Kbps}]}} = \frac{N_{sub-carrier/RB} \cdot N_{RB/U} \cdot N_{symbols/sub-frame} \cdot \log_2(M) \cdot N_{streams}}{\tau_{TTI_{[\mathrm{ms}]}}} \tag{2.2}$$

where:

- $N_{sub-carrier/RB}$ is the number of sub-carriers per RB (12 for a 15 kHz sub-carrier spacing);
- $N_{symbols/sub-frame}$ is the number of symbols per sub-carrier (depending on the CP length);
- M is the modulation´s order;

- $N_{streams}$ is the order of the MIMO configuration;
- τ_{TTI} is the time transmission interval (1 ms).

Thus, with (2.1) and (2.2) an estimation of the network capacity can be calculated:

$$N_U = \left\lceil \frac{N_{sub-carrier/RB} \cdot N_{RB} \cdot N_{symbols/sub-frame} \cdot \log_2(M) \cdot N_{streams}}{R_{b/U_{[\mathrm{Kbps}]}} \cdot \tau_{TTI_{[\mathrm{ms}]}}} \right\rceil \tag{2.3}$$

The coverage area radius of a cell is estimated as follows:

$$R_{max_{[\mathrm{km}]}} = 10^{\frac{\mathrm{P}_{t[\mathrm{dBm}]} + G_{t[\mathrm{dBi}]} - \mathrm{P}_{r[\mathrm{dBm}]} + \mathrm{G}_{r[\mathrm{dBi}]} - L_{p,total[\mathrm{dB}]} - M_{F[\mathrm{dB}]}}{10\alpha_{\mathrm{pd}}}} \tag{2.4}$$

where:

- P_t is the transmitted power;
- G_t and G_r are the gain of the transmitting and receiving antennas, respectively;
- P_r is the minimum receiving power required by the UE;
- $L_{p,total}$ is the reference path loss;
- M_F refers to the margins;
- α_{pd} is the average power decay.

Regarding frequency bands, it is pertinent to notice that different carrier frequencies originate different path losses and, consequently, different coverage areas, as illustrated in Figure 2.5. Lower frequencies using the 800 MHz band are used in order to provide larger coverage, while higher frequencies in the 1800 MHz and 2600 MHz bands are useful in providing larger capacities.

Figure 2.5 - Example of different carrier frequencies and respective coverage area.

In order for interference to be considered in system performance, and when information on RB distribution among users and their respective SNRs is accessible, the available SINR from the ith link in each single sub-carrier (k) is calculated through the following expression, [Aldh14]:

$$\rho_{IN_{i,k[\mathrm{dB}]}} = 10 \cdot \log_{10}\left(\frac{P_{i_{[\mathrm{mW}]}} \left|B_{i,k}\right|^2}{N_{[\mathrm{mW}]} + \sum_{j=0}^{N_{n,cell}} P_{j_{[\mathrm{mW}]}} \left|B_{j,k}\right|^2}\right) \tag{2.5}$$

where:

- P_i and P_j : Transmit power of donor and neighbouring base stations, respectively;

- $B_{i,k}$ and $B_{j,k}$: Fading channel gain for donor and neighbouring cell, respectively;
- N: Noise power;
- $N_{n,cell}$: Number of neighbouring cells.

In a severely interference limited scenario, the noise power can be ignored to simplify the calculations and the above expression can be written as:

$$\rho_{IN_{i,k[\mathrm{dB}]}} = 10 \cdot \log_{10}\left(\frac{P_{i_{[\mathrm{mW}]}} LD_{i,k[\mathrm{m}]}{}^{-\alpha}}{\sum_{j=1}^{N_{n,cell}} P_{j_{[\mathrm{mW}]}} L_j d_{j,k[\mathrm{m}]}{}^{-\alpha}}\right) \tag{2.6}$$

where B being a function of path loss leads to $|B|^2 = LD^{-\alpha}$, with L being a constant, L= $G_t G_r$ depending on the infrastructure of sender and receiver, α is the path loss exponent, $D_{i,k}$ and $d_{j,k}$ are the distances from user to donor base station and neighbouring cells respectively as shown Figure 2.6. In addition, the transmit powers P_i and P_j are calculated using the expressions in Annex A.

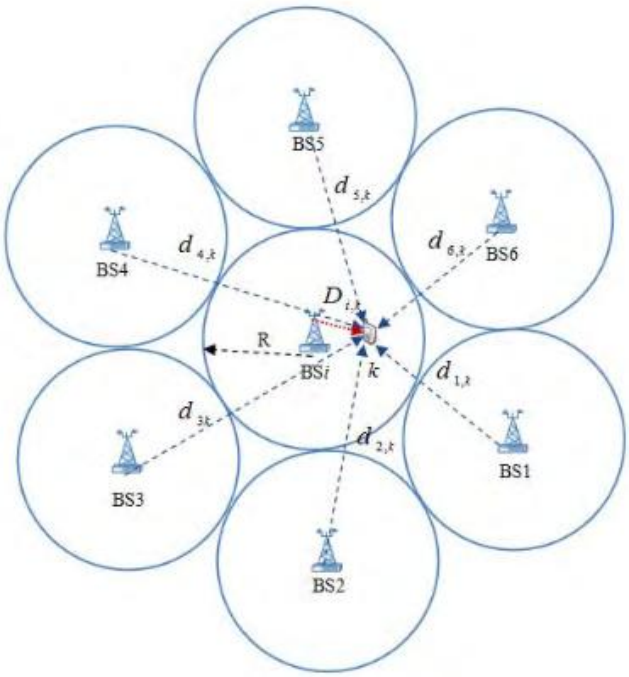

Figure 2.6 - Example of interference scenario in LTE-A Network (extracted from [Aldh13]).

Interference can lead to a severe degradation of SINR and spectrum efficiency, which decreases the overall capacity of the network, and the expected user's throughput will not be achieved, especially regarding cell-edge users. Only the interfering signals that have a power equal or greater than the noise power are considered, since only these may negatively impact system performance. The increase in interference and noise generated by the increasing number in users decreases cell coverage, forcing the cell radius to be smaller and having lower data rates. So, higher data rates are achieved when the available SINR is high. This performance indicator also depends on MCS, being known that lower order modulations, e.g., QPSK, are more robust and can better tolerate higher levels of interference, but lower transmission bit rates are achieved, and for this reason high order modulations are also considered, such as 16-QAM and 64-QAM, which offer better bit rates, although they are more susceptible to errors

due to their sensitivity to noise, interference and channel estimation errors.

If the SINR is sufficiently high, a high-order modulation is more useful and usually preferred. The code rate can be chosen depending on channel conditions, a higher code rate being used when the SINR is high, while a lower code rate is used in poor channel conditions. As shown in Figure 2.7, data rates decrease strongly with the reduction of the SINR, which leads to a reduction of channel capacity. This problem is particularly relevant in indoor scenarios, because of the extra attenuation associated with building penetration, which leads to a significant decline of SINR.

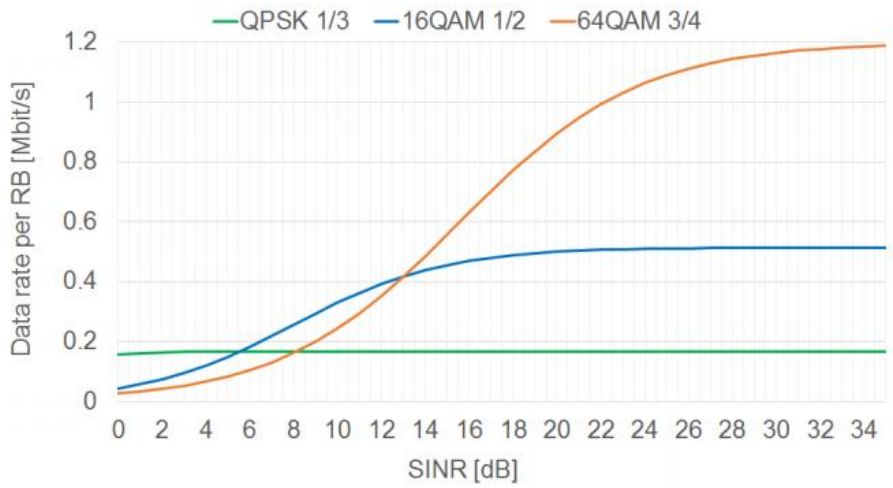

Figure 2.7- Throughput per RB in DL vs. SINR for different MCS (extracted from [Pire15]).

Table 2.3 and Table 2.4 show the peak data rates for UL and DL, respectively: UL ones are usually lower than DL's due to the limitation of the UE. These peak data rates are calculated by considering the normal CP usage and the correspondence between bandwidth and available number of RBs for data, as illustrated in Table 2.2. The bit-rate increases with the bandwidth, the number of RBs, the order of the coding scheme and ratio, and the order of MIMO.

Table 2.3 – UL peak data rates not considering MIMO (extracted from [Alme13]).

		UL Peak Data Rates [Mbps]					
		Bandwidth [MHz]					
MCS	**Bits/Symbol**	**1.4**	**3.0**	**5.0**	**10**	**15**	**20**
QPSK ½	1.0	1.0	2.5	4.2	8.4	12.6	16.8
16QAM ½	2.0	2.0	5.0	8.4	16.8	25.2	33.6
16QAM ¾	3.0	3.0	7.6	12.6	25.2	37.8	50.4
16 QAM 1/1	4.0	4.0	10.1	16.8	33.6	50.4	67.2
64QAM ¾	4.5	4.5	11.3	18.9	37.8	56.7	75.6
64QAM 1/1	6.0	6.0	15.1	25.2	50.4	75.6	100.8

Table 2.4 - DL peak data rates (extracted from [Alme13]).

			DL Peak Data Rates [Mbps]					
			Bandwidth [MHz]					
MCS	**Bits/Symbol**	**MIMO usage**	**1.4**	**3.0**	**5.0**	**10**	**15**	**20**
QPSK ½	1.0	-	1.0	2.5	4.2	8.4	12.6	16.8
16 QAM ½	2.0	-	2.0	5.0	8.4	16.8	25.2	33.6
16 QAM ¾	3.0	-	3.0	7.6	12.6	25.2	37.8	50.4
64 QAM ¾	4.5	-	4.5	11.3	18.9	37.8	56.7	75.6
64 QAM 1/1	6.0	-	6.0	15.1	25.2	50.4	75.6	100.8
64 QAM ¾	9.0	2 x 2 MIMO	9.1	22.7	37.8	75.6	113.4	151.2
64 QAM 1/1	12.0	2 x 2 MIMO	12.1	30.2	50.4	100.8	151.2	201.6
64 QAM 1/1	24.0	4 x 4 MIMO	24.2	60.5	100.8	201.6	302.4	403.2

2.4 Services and Applications

The information in this section regards services and applications based on [3GPP15a], [Corr16], [HoTo11].

Demand for new services and applications is on the rise. Therefore, these days, users face a huge variety of services and applications with different requirements and purposes. However, the most popular and also oldest service is voice. With the emergence of data services, voice popularity has been declining, but it still remains one of the most important services for operators This service is very predictable, with a constant bit rate, allowing operators to ensure its performance without much effort. The concern from operators is delay, as it is the main responsible for the phone call overall quality. On the other hand, data services require more attention from operators, since these services are very demanding in terms of bitrate, delay and duration, but also because they generate huge data traffic. Data services, such as video streaming and web browsing, require more traffic capacity than ever, and pose greater challenges to operators. In order to face these challenges, and especially to provide QoS guarantees, 3GPP proposed four different QoS classes related to the desired type of service and quality:

- Conversational Services comprises voice and real-time multimedia messaging, such as VoIP and Video Conferencing. In real time conversations, it is fundamental to preserve time relation

(variation) between information entities in the stream and guarantee low transfer delays. This is the most delay sensitive service class.

- Streaming Services are still dependent on the time relation between both ends of the stream, but delay requirements are not as strict as in Conversational, since these services have unidirectional data flows. Video on demand is an example of this class.
- Interactive Services include web browsing, automatic data base enquiries and server access. This class is applied when one end-user requests data from remote equipment, e.g., a server, and is characterised by requesting a response pattern from the end-user and preserving the payload contents.
- Background Services, where one end-user sends and receives data-files in the background, are mainly characterised by the fact that the destination is not expecting the data within a certain time frame and it can be stored to be read later on, thus being less delivery-time sensitive, e.g., e-mail, SMS, databases download and reception of measurement records.

Table 2.5 presents the QoS classes mentioned above, namely real time requirements, data flows, symmetry, guaranteed bit rate necessity, time delay, restrictions, extended use of data buffers and traffic burstiness. Included among the specifications are the limited set of signalled QoS parameters, which were then optimised for SAE:

- QoS Class identifier (QCI) is an index that identifies a set of values for priority, delay and loss rate. QCI is signalled instead of separately signalling the values of these parameters. Operators can create additional classes within their network.
- Allocation and Retention Priority (ARP) indicates the priority of the bearer compared to other bearers, providing the basis for admission control in bearer set-up and in congestion situations if bearers need to be dropped.
- Maximum Bit Rate (MBR) identifies the maximum bit rate for the bearer.
- Guaranteed Bit Rate (GBR) identifies the guaranteed bit rate to the bearer.
- Aggregated Maximum Bit Rate (AMBR) indicates the total maximum bit rate a UE may have for all bearers in the same PDN connection.

Table 2.5 - QoS service classes summary, according to 3GPP (adapted from [3GPP15a]).

Service Class	Conversational	Streaming	Interactive	Background
Real Time	✓	✓	×	×
Symmetric	✓	×	×	×
Bit Rate	Guaranteed	Guaranteed	Non-Guaranteed	Non-Guaranteed
Delay	Minimum fixed	Minimum variable	Moderate Variable	High variable
Buffer	×	✓	✓	✓
Bursty	×	×	✓	✓
Example	Voice/Video Call	Video Streaming	Web Browsing	SMS, E-mail

Table 2.6 shows the nine QoS Class Identifiers and the associated set of QoS characteristics, as defined in 3GPP standards. Resource Type indicates which classes are categorised as GBR and which are categorised as non-GBR, Priority defines the priority for the packet scheduling and higher-priority packets. A rating of 1 corresponds to the highest priority. Delay Budget helps the packet scheduler to maintain the delay requirements for the bearers, and Loss Rate defines the percentage of higher layer packets, e.g., IP packets, that are lost when the network is not congested, and also helps to use appropriate Radio Link Control (RLC) settings.

Table 2.6 - QoS parameters for QCI (extracted from [SeTB11]).

QCI	Resource Type	Priority	Packet Delay Budget [ms]	Packet Error Loss Rate	Example Services
1	GBR	2	100	10^{-2}	Conversational Voice
2		4	150	10^{-3}	Conversational Video (Live Streaming)
3		5	300	10^{-6}	Non-Conversational Video (Buffered Streaming)
4		3	50	10^{-3}	Real Time Gaming
5	Non-GBR	1	100	10^{-6}	IMS Signalling
6		7	100	10^{-3}	Voice, Video (Live Streaming), Interactive Gaming
7		6	300	10^{-6}	Video (Buffered Streaming)
8		8	300	10^{-6}	TCP-based (e.g. www, e-mail, chat, FTP, p2p file sharing, progressive video, etc.)
9		9			

In the event of capacity shortage, given the increasing number of mobile broadband data users and bandwidth intensive services, the QoS for end users may be degraded. All these services have data rate requirements that vary depending on their purpose. While voice services require lower data rates with only tens of kbps, web browsing, file transfer and streaming require higher bit rate transmissions going up to several tens of Mbps. Conversational and Streaming services can be used for applications that have an associated GBR, e.g., voice usually requires 8 to 64 kbps and music streaming 128 to 320 kbps constant data rate over the network, [AnJa15], these values for guaranteed bit-rate services being highlighted in bold in Table 2.7. On the other hand, Interactive and Background services, such as web browsing and FTP applications, do not guaranteed any particular bit-rate, as the nature of these applications requires them to fluctuate according to user's requirements.

The service's minimum and maximum throughputs are presented in Table 2.7, with their respective service class. The maximum values try to guarantee a high QoS, and while these can be raised even

further in most cases, like streaming and browsing, guaranteeing an even higher QoS, VoIP is capped by the value shown. The considered minimum throughputs are the ones that guarantee a minimum QoS.

Table 2.7 - Services characteristics.

Service	**Service Class**	**Minimum Throughput [Mbps]**	**Maximum Throughput [Mbps]**
VoIP	Conversational	***0.032***	***0.064***
Chat	Background	0.064	0.384
Streaming	Streaming	***1***	***13***
Web Browsing	Interactive	1	150
FTP	Interactive	1	150
Email	Background	1	150
P2P	Interactive	1	150

2.5 Heterogeneous Networks

This section discusses specific aspects of heterogeneous networks and advanced approaches for optimised interference management, based on [3GPP16b], [3GPP16c], [YeTa11], [Ali15].

Mobile broadband traffic is growing rapidly, thanks to the increasing popularity of connected devices and rising data consumption per user. Consumers have come to expect a consistent, high quality and seamless mobile broadband experience wherever they are. In order to fulfil these demands and intensifying competition, operators need to improve network performance by expanding capacity and coverage in a smooth, cost-effective way. One of the most promising low-cost approaches is to deploy a Heterogeneous Network (HetNet), which involves a mix of radio technologies and cell types working together to spread traffic loads and also to deliver the additional capacity, coverage and speed needed to maintain perform and service quality, while reusing spectrum most efficiently. In HetNets, the cells of different sizes are referred to as macro-, micro-, pico- and femto-cells, listed in order of decreasing transmission power and implementation cost. Macro-cells provide wide coverage area, up to a few tens of kilometres, while micro- and pico- can have a coverage range from a few hundred metres to a few kilometres; femto-cells cover an even smaller area, such as a house or an office, so their coverage range is up to a few tens of metres. While macro- and micro-cells provide essential coverage, small ones like pico- and femto-cells can be deployed as hotspots in capacity starved locations, but also to eliminate coverage holes in a macro-cell network. The relay node approach is another type of low-power base station added to Release 10 specifications and relay stations serve similar sizes of footprints as

pico-cells. To expand an existing macro-cell network, operators need to improve and densify it, adding more sectors per eNB or deploying more macro-cells eNBs, and add integrated small cells within their existing network, in strategic locations. With these deployment strategies, high traffic volumes and data rates can be supported. An overview of a HetNet is illustrated in Figure 2.8.

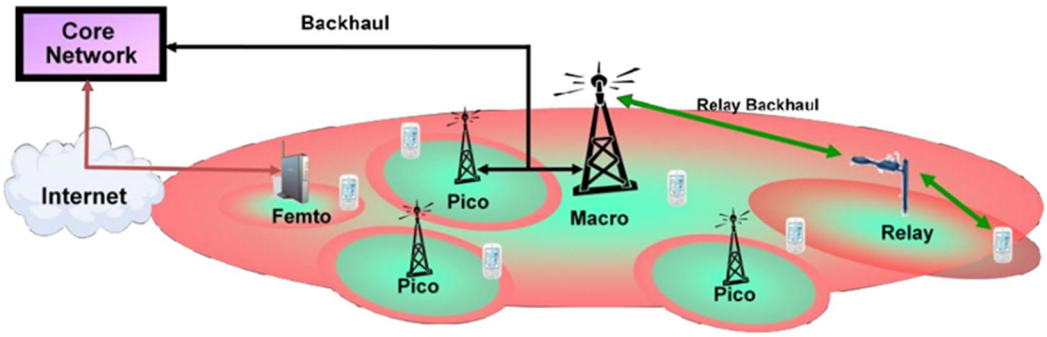

Figure 2.8 – LTE-A Heterogeneous Network (extracted from [JaMa13]).

One of the main challenges of HetNets is the severe interference between neighbouring small cells and between small and macro-cells. Generally, there are two types of interference, co-tier or intra-cell interference. and cross-tier or inter-cell interference; while the former occurs among network elements that belong to the same tier in the network, the latter occurs among network elements that belong to different tiers of the network. These types of interference occur when macro- and small cells are operating simultaneously in the same spectrum.

As a more usual implementation mode, Closed Access mode is generally deployed in private scenarios, and a group of registered users called Closed Subscriber Group (CSG) has the permission to access the femto-cell, hence CSG may cause excess interference to the surrounding network when sharing the same spectrum with other tiers. Thus, it is essential to adopt an effective and robust interference management and intelligent bandwidth allocation among tiers, in order to enhance the performance of the multi-tier networks.

Concerning operators that own more than one frequency band, the simplest type of spectrum planning consists of assigning different operating frequencies to users being served by first tier-devices, like macro-cells, and to users served by second-tier services, like small ones. Using a dedicated carrier in small cells avoids interference with macro-cells, and the former can absorb larger amounts of traffic coming through the macro-cell network, enabling wider coverage areas. Although shared-carrier deployments offer lower coverage ranges than one with dedicated carriers, it is often an effective solution for coverage, especially indoors. With shared carriers, small cells use one of the same carriers assigned to the macro tier, however, these cannot be placed too close to the high-power macro-cell. When operators have low spectrum-holdings, shared carrier is the only option available for deployment of small cells. On the other hand, for operators with some available spectrum, each second-tier device can choose from multiple accessible frequency bands for one at which it will transmit and as a result interference from same-tier devices is further mitigated. Although most network operators are capacity constrained due to the limited spectrum, those who can spare the extra spectrum can consider carrier

aggregation in order to improve channel utilisation efficiency. When using carrier aggregation, there is a serving cell for each carrier. The coverage of these cells may differ, since carriers in different frequency bands experience different path losses, which increase with frequency. One of the serving cells is designated the Primary Cell (PCell), while the rest are known as Secondary Cells (SCells), Figure 2.9.

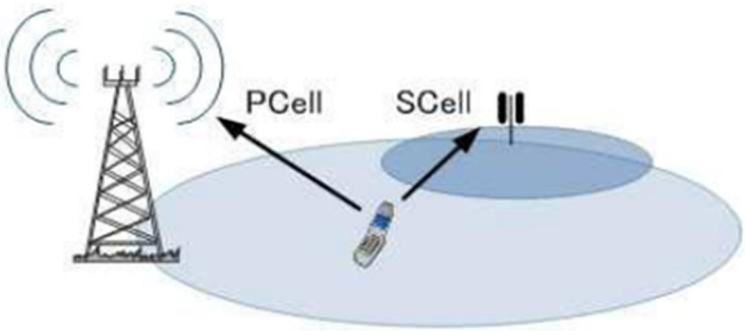

Figure 2.9 – LTE-A HetNet Multi-Site Carrier Aggregation (extracted from [Ali15]).

Initially, macro-cells with full coverage area can serve as PCells and small cells as SCells, based on the centralised architecture, but when considering that requiring a centralised architecture is not in the goal of LTE-A networks, macro- and small cells may operate with their own control and signalling on both frequency layers. In this case, both macro- and small cells allocate different frequency layers to their respective PCells and SCells. Scells may transmit data with lower power to avoid interfering with the Pcells of the other layer; depending on the implementation of the radio resource management and scheduling algorithm, UEs close to the base station can be scheduled with low power Scell allocations, while cell edge ones are allocated to the Pcell. Using CA with cross-carrier scheduling, for full protection of the control region, it is possible to map the Physical DL control channels (PDCCH) on different carriers in the large and small cells, hence, reducing the risk of PDCCH interference.

Additionally, one of the major issues in HetNet planning is to ensure that small cells properly serve enough UEs, which can be guaranteed by extending the coverage area served by the small cells, which is achieved by the use of a positive cell selection offset to the strongest received DL signal of the small cell. This extended area is called Cell Range Extension (CRE). However, ICI has become a more severe problem in the CRE area, which can be mitigated by using Enhanced Inter-Cell Interference Coordination (eICIC), an advanced ICIC technology introduced in 3GPP Release 10, which has evolved to better support heterogeneous network deployments, especially interference management for control and data channels. This advanced technique uses a power and frequency domain, but the major change compared to ICIC is the addition of a time domain ICIC, made possible through the use of Almost Blank Sub-frames (ABS). ABS only includes control channels and cell-specific reference signals, user data is left out, being transmitted with reduced power. When eICIC is used, ABS patterns are configured in semi-statically and signalled between the macro- and small cells over the X2 interface. ICIC has evolved in LTE Release 11 to further enhanced ICIC (feICIC), the focus being interference handling by the UE through ICI cancellation for control signals, enabling even further cell range extension. It is also important to notice that eCIC and feICIC are especially important when CA is not in use. Another way to limit ICI, while further exploiting the benefits of distributed multiple antenna systems, is to use

Coordinated Multi-Point (CoMP), introduced in LTE-A Release 11. The main reason to introduce CoMP is to improve network performance, especially at cell edges, where performance may be degraded, the basic idea being to transform ICI into a useful signal. With CoMP, a number of transmission and reception points can be dynamically coordinated to provide a service and to ensure that a UE is using both the best DL and UL carriers in a heterogeneous network.

2.6 State of the Art

This section presents previous work developed by a variety of authors on coverage and capacity dimensioning, its associated costs, as well as interference management, showcasing their main conclusions and results obtained through simulations and algorithm analysis.

[HaHe11] investigates the performance of an LTE-A based network in different spectrum bands. The authors analyse the performance of a single carrier in different bandwidths in two different spectrum bands, 800 MHz and 2.6 GHz. Simulations show that an increased system bandwidth may not necessarily result in a higher system throughput, since in some cases a low frequency (i.e., 800 MHz) system is superior to a high frequency deployment (i.e., 2.6 GHz), although the operating bandwidth of the former is half of the one of the latter. The authors also verified that the deployment of a CA-based system increases cell and user throughputs significantly by extending the operating bandwidth.

[AnMa16] presents a comparison between two scenarios of CA, one that combines low and high spectrum bands (e.g., 800 MHz and 2.6 GHz) and the other combining mid and high spectrum bands (e.g., 1800 MHz and 2.6 GHz). In both cases, CA provides benefits by improving the peak speeds to compatible devices within the coverage area of the two bands. However, the combination of bands that are more closely matched in frequency, such as 1800 MHz with 2.6 GHz, offer a better synergy for operators from a capacity and coverage perspective.

[NiJa14] introduced a model for evaluation of the total deployment costs of heterogeneous wireless access networks. The model uses up to date inputs of the unit cost of particular base station classes, which is characterised with specific coverage and capacity parameters. The authors analysed deployments in both the 800 MHz and 2.6 GHz bands, as well as the scenario of aggregated carriers in these bands. They concluded that while the re-use of the existing macro-cell sites with the low-end frequency carriers at 800 MHz represents moderate cost-efficiency, the solution to deploy the denser network at 2.6 GHz with re-use of existing sites is more cost-efficient than the solution to construct new sites with 800 MHz. Hence, the key finding is that the use of CA for moderate demand levels will significantly increase the cost-effectiveness of the macro-cell cellular deployment. On the other hand, indoor deployed femto-cells are most cost efficient only for the higher to extreme user demand.

[Garc13] focuses on the development of a strategic network planning tool and a set of optimisation algorithms to solve the services distribution problem over a set of technologies, and minimise the total cost of network deployment. The approach is divided into two main parts, a dimensioning and planning

module, and a bio-inspired optimisation one. The goal of both modules is to provide a set of algorithms capable of performing the dimensioning process of a multi-technological RAN, providing information about the number, type and location of the required base stations in order to satisfy specific coverage and capacity constraints, and the optimisation of the traffic demand's distribution over the different technologies to be deployed. The author has tested the proposed algorithms in a set of different scenarios. Moreover, a study simulating the deployment of a LTE network with different spectrum allocation in the 800 MHz, 1800 MHz, and 2600 MHz has been carried out. Improvements, in terms of investment cost, and thus a reduction on services provision costs, are observed for all simulated cases. The experiments performed in this work are focused on the Spanish case, but the algorithms can be easily adopted to carry out similar studies in any other European country.

The authors of [AtZa14] present a partially combinatorial optimisation algorithm positioning of heterogeneous cells with relay nodes for an LTE network with non-uniform throughput user requirements. The main goals of this algorithm are to exploit LTE characteristics and to identify an optimum solution that meets the operator's requirements in terms of coverage and capacity in a given area, with the minimum number of base-stations, and hence, cost.

[ShIs13] analysed the efficiency of different deployment locations of femto-cells. Simulations show that by deploying femto-cells at an appropriate location, femto- to macro-cells interference can be mitigated, coverage almost reaching the double, while the data rate received by the end user increases by 28% on average, compared to a random deployment.

[VuKw15] proposed an algorithm aimed to select an appropriate ABS ratio based on the SINR for macro- to femto-cell networks, in order to reduce the dominant cross-tier interference. Authors also proposed a coalition algorithm to help small cells collaborate efficiently in order to reduce mutual interference. Taking various environments into account, simulations show that the small cell performance of their proposed algorithm is better than that of the existing ABS frameworks with a high rate in terms of user throughput.

Fractional Frequency Reuse (FFR) is a simple and effective mechanism for interference management in OFDMA-based HetNets. In [SaHo13], the authors presented a broad comparison among three traditional FFR schemes and proposed a FFR scheme for two-tier HetNets in LTE-A. This comparison is performed by using Monte Carlo simulations considering performance metrics such as outage probability, network throughput, and spectral efficiency. Simulation results show that the average gains in spectral efficiency (b/s/Hz) of the network are significantly higher for the proposed scheme compared to the other three FFR schemes.

[Alme13] focuses on evaluation of LTE performance in urban scenarios concerning ICI via antenna aspects. This analysis addressed the 800 MHz, 1800 MHZ and 2600 MHz bands. Most performance enhancements are achieved when electrical down-tilt variations are considered, followed by the height of the antennas, the transmitter output power and mechanical down-tilt. The author also concluded that for the low load scenario, the 800 MHz band suffers the highest interference impact. For the high load scenario, simulations results show that the ICI impact on throughput increases with the frequency band while the reduction of SNR into SINR decreases.

In [Seif12], a detailed LTE radio network dimensioning procedure, including frequency, coverage and capacity analysis, has been performed in order to prepare a radio planning guideline considering possible network implementation in the city of Tripoli (Libya). With this aim in mind, a step-by-step method followed, starting from gathering planning information, which went up to coverage and capacity analysis. In terms of coverage, the cell radius and the required number of cells for dense urban, urban and suburban scenarios were computed, taking the link budget and propagation model calculations into account. The obtained cell radius, for dense urban scenario, is higher than the one for the other scenarios. As for capacity, the number of cells was computed for the same environments, considering three different service packages. In order to satisfy the traffic requirements of both coverage and capacity, the maximum number of sites obtained from capacity and coverage calculations was chosen. At the end, the link level of the LTE network is simulated for both UL and DL, in order to get a closer view of the impact of the SNR on Bit Error Rate (BER) and Block Error Rate (BLER). From the link level, the authors concluded that, as the BER or BLER increases, the SNR decreases, and vice-versa. It was also verified that the relation BER vs. SNR or BLER vs. SNR varies depending on many parameters, such as modulation scheme, code rate, channel type and antenna configuration. For instance, it is shown that BER and BLER can be improved by increasing the number of receiving antennas, even though the number of transmitting antennas does not affect them. Another conclusion was that receiver diversity affects the SNR. With the increase of MIMO order, an increase on SNR was verified.

[IbHa14] indicates the implementation of a dimensioning tool for the LTE planning process that follows the dimensioning algorithms designed by Ericsson [Eric10]. The model consider the concepts and calculations associated with coverage and capacity planning that are essential to the dimensioning process. The tool was developed using C# (C Sharp) programming language and two case studies were analysed. In the first case, some parameters were varied in relation to the reference scenario, such as the environment, eNB noise figure and height. The authors concluded that the number of cells increases due to the increase in noise. In addition, areas with dense urban characteristics need more sites to meet the required bitrate, and, in rural areas with fewer users, the number of sites was lower compared to the one obtained for the urban ones. They also verified that the decrease in height results in a smaller coverage area, which leads to an increase in the number of sites. In the second case, the area and most of the inputs are different in relation to the reference scenario, but the main parameter studied was the antenna gain. The authors concluded that the area type and decreased gain were the primarily responsible elements for the several reduction in the area covered by each site. Though there is a slight decrease in the noise figure, it does not gravely affect the site's coverage area.

Chapter 3

Models and Simulator Description

A description of the models used in this thesis is provided in this chapter, in which their mathematical formulation and implementation are detailed. At the end of this chapter, a brief assessment of the presented simulator is done.

3.1 Model Development

This section provides a description of the models developed in this thesis, with their mathematical formulation.

3.1.1 Dimensioning Process

Dimensioning is the initial phase of network planning. It provides the first estimate of the network element count as well as the capacity of these elements. The purpose of dimensioning is to estimate the required number of base stations needed to support a specified traffic load in an area [Syed09]. Dimensioning is a part of the whole planning process, which also includes detailed planning and optimisation of the radio network. The aim of this whole exercise is to provide a model to design the cellular network such that it meets the quality requirements set forth by service providers, operators or even the end-users. However, the difficulty lies on combining all requirements in an optimal way and to design a cost-effective network [Seif12]. The cellular network dimensioning can be divided into different phases as seen in Figure 3.1.

Dimensioning provides the first, quick assessment of the probable radio network configuration, and this process varies from place to place, depending on the dominating factor, which can be capacity or coverage. This is a very important process in network deployment, because it can be modified to fit any needs of any cellular network.

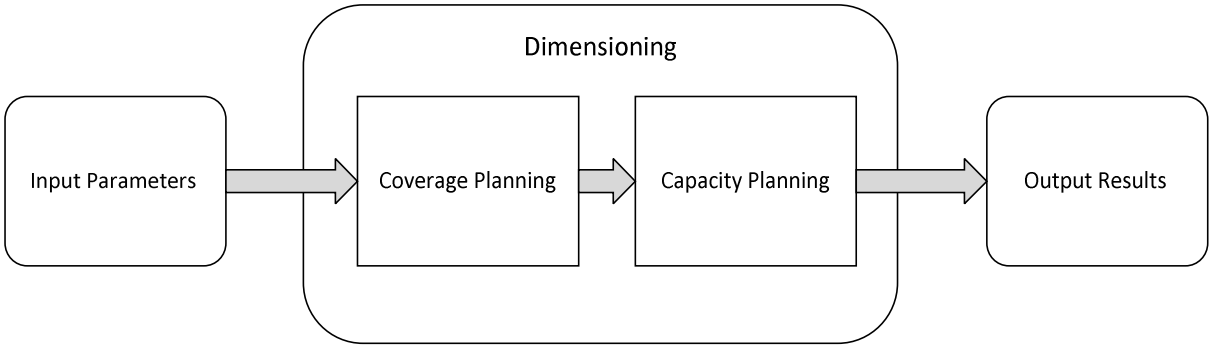

Figure 3.1 - LTE network dimensioning.

Dimensioning uses relatively simple models and methods that reduce the time required for this process. On the other hand, a dimensioning tool should be accurate enough to provide results with an acceptable level of accuracy, when loaded with subscriber base and expected traffic profile, and a proper set of inputs is vital to yield accurate outputs. LTE planning inputs is the first step in dimensioning, and can broadly be divided into coverage-, capacity- and quality-related, which are technology dependent [Seif12]. These inputs as well as outputs are briefly discussed in the following section. The basic requirements for the cellular network are to meet coverage, capacity and quality targets. These requirements are also related to how the end user experiences the network. According to, [Seif12], the

dimensioning process is generally carried out as follows. In a first approach, the maximum allowable network load is considered to determine the site density through the link budget, which is called a coverage limited planning; coverage estimation is used to determine the maximum coverage area of each base station, but it is not necessary that a suitable connection between the eNB and UE can be established in the coverage area. Furthermore, coverage planning also includes coverage analysis, one of the most critical step in the design of an LTE radio network. In the second approach, the user profile is used to iteratively determine the site density, i.e., the network planner must specify the traffic profile loading of the network, including data rates and coverage requirements along with the maximum permissible network load; after computing the cell radius from coverage planning, the number of users inside the cell is computed, and the traffic profile of each user is considered to determine if the maximum permissible network load is exceeded. In this case, the planning is limited by capacity. Based on such criteria, the final target of planning, namely, defining network design and deployment requirements can be achieved. Last but not least, the outputs of the dimensioning phase are used to estimate the feasibility and cost of the network, being further used in the detailed network planning, and also for core network planning. For a clear understanding, each of the steps is thoroughly explained in the coming sections.

3.1.2 Inputs and Outputs of LTE Dimensioning

Radio cellular network dimensioning requires some fundamental elements, like geographical area to be covered, frequency band, allocated bandwidth, MIMO order, population density and traffic distribution. This section discusses all the dimensioning inputs used in the development of model. As can be seen in previous section, dimension inputs can be divided into three categories, i.e., quality-, coverage- and capacity-related ones.

In this thesis, quality-related inputs include the minimum throughput at the cell edge in DL and UL. These inputs are used to compute SINR, but are also connected to the investment that the operator wishes to make, and the quality that it wants to offer to the end-users at the cell edge. In terms of coverage, it is also important to notice that the considered minimum throughput per RB is obtained by taking the minimum reference throughput that end-users experience at the cell edge into account, guaranteeing 10% of RBs of the maximum number of RBs of each bandwidth. Basically, the minimum throughput per RB is obtained by dividing the reference throughput by the ensured number of RBs at the cell edge. In this case, 10% of the maximum number of RBs associated with each frequency is taken as reference.

Radio Link Budget (RLB) is of central importance to coverage planning, inputs including transmitter power, transmitter and receiver antenna systems, number and type of antennas, propagation models and their respective parameters, and conventional system gains and losses. Additionally, channel types (Pedestrian, Vehicular) and geographical information, such as area information (urban, suburban, rural) and size of each area type to be covered, are needed to start the coverage dimensioning exercise. Coverage depends on the area covered by the signal, which also depends on radio propagation characteristics in the given area, and varies from region to region, hence, it should be studied carefully. Furthermore, the required outdoor and indoor coverage probabilities play a vital role in the determination

of cell size. Even a minor change in coverage probability can greatly affect the result.

Capacity planning inputs give the number of subscribers in the network, their demanded services and subscriber usage level. The available channel bandwidth, traffic analysis and data rate to support the available services are also very important for capacity planning.

Regarding dimensioning outputs, the cell radius is the main output of the exercise. Two values of cell radius are obtained, one from coverage evaluation and another from capacity evaluation. The cell radius based on capacity evaluation is taken as the final output if the network capacity is exceeded, otherwise the cell radius based on coverage estimation is taken as the final output. Then, the cell radius is used to determine the number of sites. Assuming a hexagonal cell shape, the number of sites can be calculated by using simple geometry (this is explained in more detail in Section 3.1.5). The average cell throughput is obtained from the capacity evaluation, along with the number of supported active users.

3.1.3 Coverage Planning

Coverage planning gives an assessment of the resources needed to cover the area under consideration, without any capacity concern; in other words, there are no QoS concerns involved in this process. Coverage planning consists of evaluating DL and UL radio link budgets. The calculation of the maximum path loss is based on the required SINR at the receiver. The minimum of the link losses in UL and DL is converted into cell radius, by using a propagation model appropriate to the deployment area. However, the coverage limiting factor is, normally, in UL, and the corresponding link budget calculation needs to be done in advance to calculate the maximum allowable path loss. The propagation model selection is done according to planning parameters, such as frequency, environment and antenna height. Then, with real environmental information and path loss models, such as COST-231 Hata or COST-231 Walfisch-Ikegami [Corr16], the cell range can be estimated as shown in Figure 3.2. The dimensioning process starts with radio link budget calculations, used to determine the maximum path loss. The estimated cell size, obtained in this step, depends on the propagation models used and leads to the maximum allowed size of cells. Then, this parameter is used to determine the number of coverage cells in the area of interest. Thus, a rough estimate of the required eNBs is obtained.

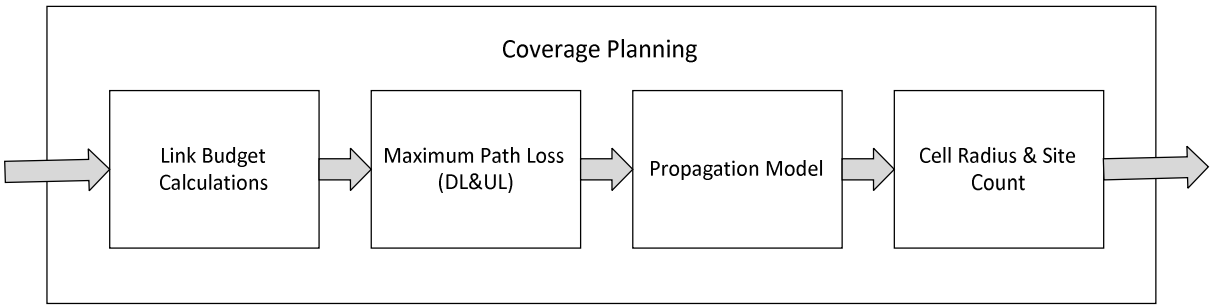

Figure 3.2 - LTE coverage planning.

RLB is an important tool for network planning, taking all gains and losses from the transmitter to the receiver into account, allowing one to calculate the maximum path loss. According to [Corr16], the power available at the receiving antenna can be expressed by:

$$P_{r_{[\mathrm{dBm}]}} = P_{t_{[\mathrm{dBm}]}} + G_{r_{[\mathrm{dBi}]}} + G_{t_{[\mathrm{dBi}]}} - L_{p,total_{[\mathrm{dB}]}} \tag{3.1}$$

where:

- P_t: power to fed to the transmitting antenna;
- G_r: gain of the receiving antenna;
- G_t: gain of the transmitting antenna;
- $L_{p,total}$: total path loss.

While the BS antenna gain depends essentially on the antenna type and on the number of sectors, the UE one depends on the type of device. The power fed to the transmitting antenna is defined as:

$$P_{t_{[\mathrm{dBm}]}} = P_{Tx_{[\mathrm{dBm}]}} - L_{t_{[\mathrm{dB}]}} \tag{3.2}$$

where:

- P_{Tx} : transmitter output power;
- L_t: loss in the cable between the transmitter and the antenna for DL ($L_t = L_c$), or loss in the UE ($L_t = L_u$).

According to [HoTo11], in DL the transmitter output power can range from 43 dBm to 48 dBm. For UL the transmitted power, it is assumed to be around 24 dBm. The power at the receiver, in UL, can be calculated as follows:

$$P_{Rx_{[\mathrm{dBm}]}} = P_{r_{[\mathrm{dBm}]}} - L_{r_{[\mathrm{dB}]}} \tag{3.3}$$

where:

- L_r: loss in the cable between the transmitter and the antenna for DL ($L_t = L_c$), or loss in the UE ($L_t = L_u$).

According to [HoTo11], the cable loss can range from 1 dB to 6 dB, depending on cable length and type, and frequency band. The loss in the UE is typically included for voice, where the terminal is held close to the user's head, and can range from 3 dB to 5 dB.

The receiver sensitivity in eNB, $P_{Rx,min}$, per resource block, can be expressed as:

$$P_{Rx,min_{[\mathrm{dBm}]}} = -174 + 10 \cdot \log\left(B_{RB_{[\mathrm{Hz}]}}\right) + F_{N[\mathrm{dBm}]} + \gamma_{[\mathrm{dB}]} \tag{3.4}$$

where:

- B_{RB} : bandwidth per RB, which is 180 kHz;
- F_N : the noise figure of eNB receiver;
- γ: SINR requirement for the UL or DL traffic channel.

From the above equations, the radio link budget equation is expressed as,

$$L_{p,max[\mathrm{dB}]} = P_{Tx_{[\mathrm{dBm}]}} - L_{t_{[\mathrm{dB}]}} - P_{Rx,min_{[\mathrm{dBm}]}} - L_{r_{[\mathrm{dB}]}} + G_{r_{[\mathrm{dBi}]}} + G_{t_{[\mathrm{dBi}]}} - I_{m[\mathrm{dB}]} + G_{Tx[\mathrm{dB}]} + G_{TMA\,[\mathrm{dB}]} \tag{3.5}$$

where:

- I_m : interference margin;

- G_{Tx} : diversity gain (2 or 4 antennas);
- G_{TMA}: Tower Mounted Amplifier (TMA) gain.

Regarding interference, the parameter that is taken in coverage estimation is the interference margin, which typically should be between 2 dB and 4 dB for coverage limited cells, and between 4 dB and 7 dB for capacity limited ones [Seif12]. A TMA reduces the BS noise figure and therefore improves its overall sensitivity. It compensates for cable losses, typically 3 dB, but introduces an insertion loss in DL (typically 0.5 dB).

Based on link budget calculations, the maximum allowed propagation loss is obtained for UL and DL. The maximum path loss is converted into distance by using appropriate propagation models, such as Okumura-Hata, COST-231 Hata or COST-231 Walfish-Ikegami [Corr16]; using these propagation models, presented in Annex B, plus the expressions that relate SNR with throughput, given in Annex A, it is possible to calculate the maximum distance between the BS and the UE, by means of the reference throughput. This distance or the radius of the cell is used to compute the number of sites required to cover the target geographical area. It is also important to notice that each model has its own limitation, input requirements and operation environment. Using COST-231 Walfish-Ikegami model, the distance or cell radius depends on parameters such as building height, building separation distance, street width, incidence angle, height of the transmitter and the receiver, and the transmission frequency, whereas the COST-231 Hata only depends on the transmission frequency, and mainly the building height. Moreover, it is also important to notice that the link budget also varies according to the desired goal of coverage, whether indoor or outdoor, as in each case propagation losses are different.

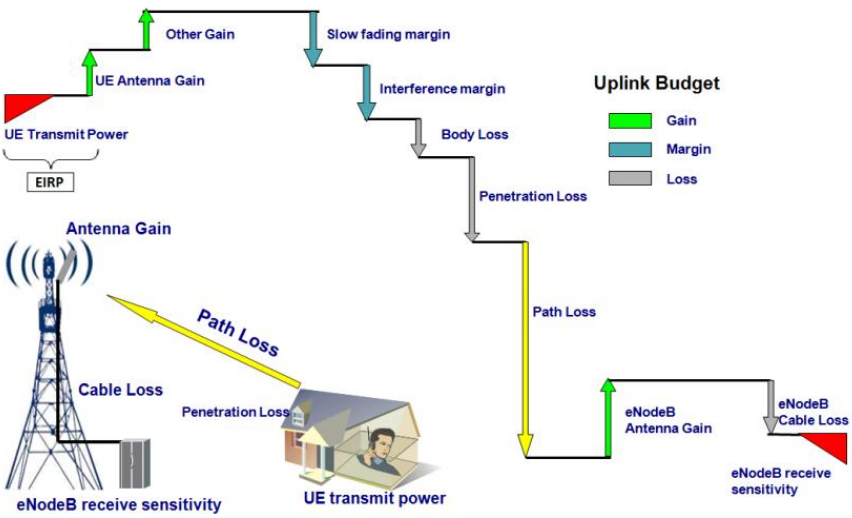

Figure 3.3 - UL Link Budget.

The outdoor and indoor path losses from (3.6) and (3.7) are converted into cell radius [Corr16]. The estimation of the outdoor path loss when the UEs are outdoors can be computed using:

$$\overline{L_{p,outdoor}}_{[\mathrm{dB}]} = L_{p,max}{}_{[\mathrm{dB}]} - \overline{\Delta L_{p,out}^{p\%}}_{[\mathrm{dB}]} \tag{3.6}$$

where:

- $L_{p,max}$: maximum path loss;
- $\overline{\Delta L_{p,out}^{p\%}}$: outdoor slow fading margin.

To calculate the indoor path loss when UEs are indoors, an extra attenuation coming from penetration into the buildings must be considered:

$$\overline{L_{p,indoor}}_{[\mathrm{dB}]} = L_{p,max}{}_{[\mathrm{dB}]} - \overline{\Delta L_{p,ind}^{p\%}}_{[\mathrm{dB}]} - \overline{L_{p,outdoor}}_{[\mathrm{dB}]} - \overline{\Delta L_{p,out}^{p\%}}_{[\mathrm{dB}]} \tag{3.7}$$

where:

- $\overline{\Delta L_{p,ind}^{p\%}}$: indoor slow fading margin.

The Log-Normal, slow, fading margin models the required area coverage probability, which is used for setting up and maintaining a connection at a given quality, using the mean, which is provided by the statistical path loss models, and the standard deviation, which estimation is typically based on the type of propagation environment. As such, this margin can vary according to the input parameters (indoor and outdoor coverage probabilities). On the other hand, the fast fading margin can be neglected, as it is not necessary in LTE, namely because no power control is used in DL, [HoTo11].

The mean cell radius for each modulation can be calculated using:

$$\overline{r_{cell}}_{[\mathrm{km}]} = p_{ind}{}_{[\%]} \cdot \overline{r_{indoor}}_{[\mathrm{km}]} + p_{out}{}_{[\%]} \cdot \overline{r_{outdoor}}_{[\mathrm{km}]} \tag{3.8}$$

where:

- p_{ind} : percentage of indoor users;
- r_{indoor} : maximum indoor radius;
- p_{out}: percentage of outdoor user;
- $r_{outdoor}$: maximum outdoor radius.

A percentage of indoor and outdoor users is defined, in order to get a more realistic approach and calculate the mean radius obtained in (3.7), by taking the scenario under analysis into account. For instance, in a residential environment, the percentage of indoor users is higher than outdoor ones, whereas in most commercial environments indoor and outdoor percentages are more balanced. In terms of radius, taking into account that, as a rule, indoor path loss is higher than outdoor one, the outdoor radius is higher than the indoor one, as seen in Figure 3.4.

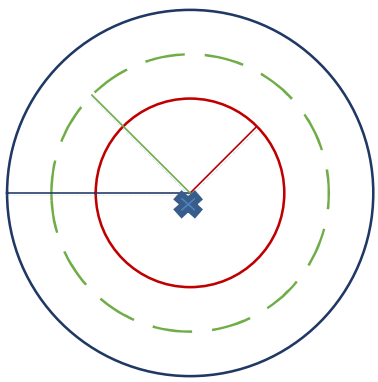

Figure 3.4 – Mean (green), outdoor (blue) and indoor radii (red).

3.1.4 Capacity Planning

After the site coverage area is calculated, capacity related issues are analysed. With a rough estimate of the cell size and site count, a verification of coverage analysis is carried out for the required capacity. If the coverage estimate for the given configuration fulfils capacity requirements, then, there is no addition to the previous plan; on the opposite, a suitable number of cell sites is added to achieve capacity targets. After computing the cell range, the number of users inside the cell can be calculated from:

$$N_{u,cell_{[\text{users}]}} = \eta_{[\text{users/km}^2]} \cdot S_{[\text{km}^2]} \tag{3.9}$$

where:

- η : user density in the target area;
- S : maximum area of coverage obtained.

The network dimensioning process is based on the assumption of a uniform distribution of users inside the coverage area. The number of users for each modulation corresponds to a percentage of the total one calculated in (3.9), taking the obtained radius for each modulation into account, a validation being done by the following expression, Figure 3.5:

$$N_{u,cell} = N_{u,QPSK} + N_{u,16QAM} + N_{u,64QAM} \tag{3.10}$$

where:

- $N_{u,QPSK} = \frac{R_4^2 - R_{16}^2}{R_4^2} \cdot N_{u,cell}$
- $N_{u,16QAM} = \frac{R_{16}^2 - R_{64}^2}{R_4^2} \cdot N_{u,cell}$
- $N_{u,64QAM} = \frac{R_{64}^2}{R_4^2} \cdot N_{u,cell}$

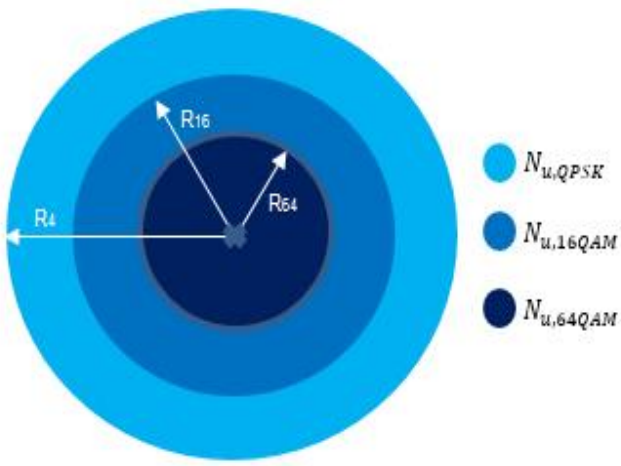

Figure 3.5 - Uniform distribution of users.

Furthermore, another factor that affects capacity requirements is the user traffic demands and the trend of each user type. It is well known that traffic distribution is not uniform, i.e., there are always cells that capture more traffic and reach their capacity limits much sooner than others, and that others usually operate at a lower traffic demand. For this reason, the traffic demand distribution regarding the provided

services and certain services at the busies types of the day are factors that are taken into account. Thus, in order to estimate the number of users that a single eNB can support and the average traffic load that it can hold, the information on possible different traffic types and their parameters is essential, i.e., the service mix, or service profile, which is given by the number of active users in a specific service and the total number of active users. With an assumption of user response and market trend, the service mix can be roughly estimated. Moreover, three different traffic types are considered: Residential, Office and Mixed. As such, the traffic of each user is considered to determine if the maximum permissible network load is exceeded, according to these three traffic profiles.

Then, capacity planning gives an estimate of the radio resources needed for supporting a specific offered traffic with a certain quality, [Syed09]. As previously detailed, the total number of RBs in a cell is fixed, usually taking the 2600 MHz carrier with a maximum number of 100 RBs, while the 1800 MHz with 75 RBs, and the 800 MHz with 50 RBs, meaning that each band has a bandwidth of 20 MHz, 15 MHz, and 10 MHz, respectively. The available channel bandwidth is very important for capacity planning, because it is directly connected to the capacity of the base station; the higher the bandwidth, the more traffic it can support. So, in order to evaluate the capacity of each band, it is important to analyse the average number of RBs that are requested by a single user for each service. In terms of capacity, the throughput per RB is obtained through the model in Figure 2.7, from which the respective average numbers for each modulation are estimated, taking the maximum and minimum throughputs for each modulation into account. For QPSK, the minimum value depends on the reference throughput; since the average throughput per RB is higher for higher order modulations, the number of required RBs for a user is lower for 64-QAM than for QPSK for the same service and respective throughput. Therefore, the average number of required RBs per user for each service and modulation can be obtained from:

$$\overline{N_{RB,user,s}} = \left\lceil \frac{\overline{R_{b,user,s}}_{[\mathrm{Mbps}]}}{\overline{R_{b,RB}^{n}}_{[\mathrm{Mbps}]}} \right\rceil \tag{3.11}$$

where:

- $\overline{R_{b,user,s}}$: average throughput per user of a service s;
- $\overline{R_{b,RB}^{n}}$: average throughput per RB of each modulation n.

From the total number of active users, a certain percentage of users corresponds to each modulation as shown in Figure 3.5, based on (3.10), hence, the number of required RBs is calculated for each modulation taking the provided services into account. The number of RBs obtained for each modulation is different, since the average throughput per RB and number of users in each of them is different, therefore, the total number of RBs required for each modulation can be obtained from:

$$\overline{N_{RB,required}^{n}} = \sum_{service} \overline{N_{RB,user,s}} \cdot N_{u,cell}^{n} \cdot P_{u,s_{[\%]}} \tag{3.12}$$

where:

- $N_{u,cell}^{n}$: number of served users by modulation n;
- $P_{u,s}$: subscriber usage percentage of a service s.

Finally, the total number of RBs required for a single cell can be obtained from:

$$\overline{N_{RB,required}} = \overline{N_{RB}^{Q}} + \overline{N_{RB}^{16}} + \overline{N_{RB}^{64}} \tag{3.13}$$

where:

- $\overline{N_{RB}^{Q}}$: number of RBs required in QPSK;
- $\overline{N_{RB}^{16}}$: number of RBs required in 16-QAM;
- $\overline{N_{RB}^{64}}$: number of RBs required in 64-QAM.

Seven types of services are considered for DL and four for UL. The number of covered users obtained from (3.8) and number of active (or served) users' needs to be equal when the system is coverage-limited, as all covered users are spending resources in the network in a specific time instance. Thus, $N_{RB,required}$ assumes an important role in capacity planning, because it determines if the system is coverage- or capacity-limited. If $N_{RB,required}$ exceeds the total number of RBs in a cell defined by available channel bandwidth, the network is considered capacity-limited and, consequently, the average throughput per cell and number of active users are reduced, as can be seen in Figure 3.6.

Regarding the definition of overload, one can use a generic formulation, by dividing the total available resources in a cell by the quantity of required resources. Moreover, the total number of RBs in a cell is fixed, therefore, one can use (3.14) to determine the respective cell capacity ratio:

$$\eta_{cell} = \frac{N_{RB,cell}}{\overline{N_{RB,required}}} \tag{3.14}$$

where:

- $\overline{N_{RB,required}}$: total number of required RBs in the respective cell;
- $N_{RB,cell}$: total number of RBs in the respective cell.

This value ranges from 0 to 1, with 1 indicating that a given cell is still limited by coverage. η_{cell} is used only when the total number of RBs in the cell is exceeded. When a cell is not overloaded, i.e,. the total number of RBs required is less than the total number of RBs in a cell, η_{cell} takes a value of 1 in (3.14).

The total average throughput of a cell can be obtained from:

$$\overline{R_{b,cell}}_{[\mathrm{Mbps}]} = \sum_{service} \overline{R_{b,user,s}}_{[\mathrm{Mbps}]} \cdot N_{u,s} \cdot \eta_{cell} \tag{3.15}$$

where:

- $N_{u,s}$: Number of active users in the service s.

The total throughput of the network obtained in (3.15) corresponds to the sum of the offered bit rate of all served users. The percentage of traffic that each service occupies in the network (traffic profile), is:

$$p_{traffic_{s[\%]}} = \frac{\overline{R_{b,user,s}}_{[\mathrm{Mbps}]} \cdot N_{u,s} \cdot \eta_{cell}}{\overline{R_{b,cell}}_{[\mathrm{Mbps}]}} \tag{3.16}$$

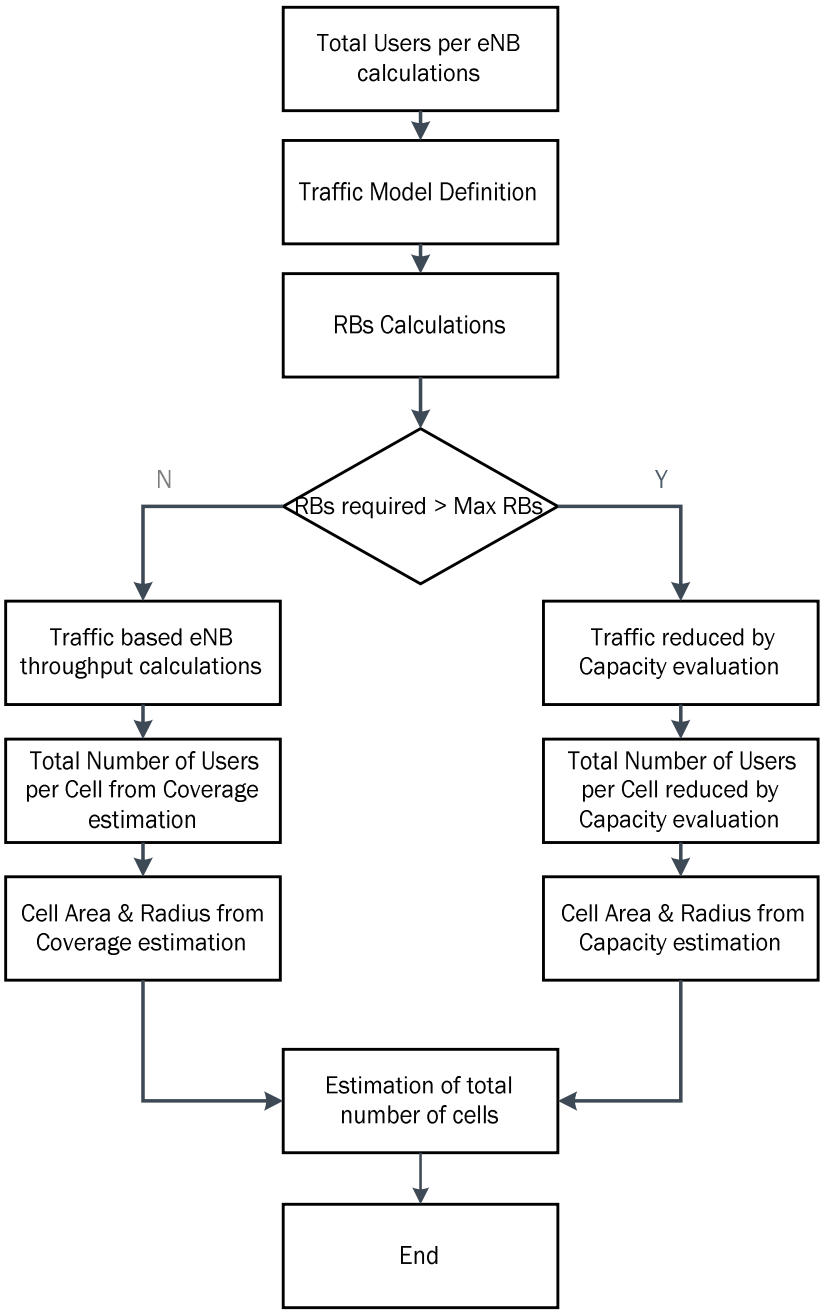

Figure 3.6 - Capacity planning.

3.1.5 Cellular Planning

The maximum allowed path loss (MAPL) has different values for urban, suburban and rural scenarios (UL and DL), and also for each carrier frequency. So, the calculation must be done for every condition and scenario, and from these results the cell radius can be calculated for each case. At the end, the minimum cell radius from UL and DL cell radii is chosen for each scenario. There are three different cell radii, since each scenario has its own cell radius. With the knowledge of cell size estimate and of the area to be covered, an estimate of the total number of sites is found. This estimate is based on coverage

requirements and needs to be verified for capacity requirements. So, after determining the cell radius for each scenario, the cell coverage area is calculated for an assumed cell structure or type. The cell structure can be circular or hexagonal. Both are ideal representations, where circular cells give a simple analysis and hexagonal ones give a best fit coverage site without any overlap and gaps. However, no handovers occur between cells taking hexagons' regularity, hence, a percentage for handover has to be defined, which is used to reduce the maximum radius obtained from capacity or coverage evaluations, so that handovers between cells can occur. One assumes a hexagonal cell structure, where the cell area depends on the site configuration, being calculate, for a tri-sectorised site, as:

$$A_{c[\mathrm{km}^2]} = \frac{3}{2} \cdot \sqrt{3} \cdot R^2_{[\mathrm{km}]} \tag{3.17}$$

where:

- R: maximum radius from coverage or capacity estimation.

The number of sites to be deployed can be easily calculated from the cell area and the deployment one:

$$N_{sites} = \left\lceil \frac{A_{D[\mathrm{km}^2]}}{A_{c[\mathrm{km}^2]}} \right\rceil \tag{3.18}$$

where:

- A_D: studied area of deployment.

The total number of cells is one of the main objects of study along the considered network, while other important parameters, such as the cell radius from coverage or capacity evaluation and the number of RBs allocated in each carrier frequency and in each type of service, are also analysed so that it is possible to optimise the main outputs of the dimensioning process.

3.2 Model Implementation

The models described in Section 3.1 were implemented using a simulator developed with the C# (C Sharp) programming language, which was adapted from the simulator supplied by the partner company. Although the simulator was not done from scratch, it was restructured and based on work developed in previous theses, such as [Guit16], followed by alterations under the scope of this thesis. This dimensioning tool is designed to carry both coverage and capacity calculations. It performs the required calculations, providing the site count on the basis of traffic forecast as the final result. The work previously developed in this simulator considers only LTE, using a snapshot approach, where results refer to the behaviour of the network at a given time instant, being like a "snapshot" of the busy hour traffic. As one can see in Figure 3.7, the simulator workflow is represented by three main types of blocks, with rounded purple corresponding to the modules where the user actually interacts with and inserts the input parameters. All input data corresponds to the scenario under analysis, regarding information about the environment and the coverage and capacity requirements. All the inputs can be entered in one class, 'techDim.cs', the purpose being to allow users to easily change dimensioning inputs in one place.

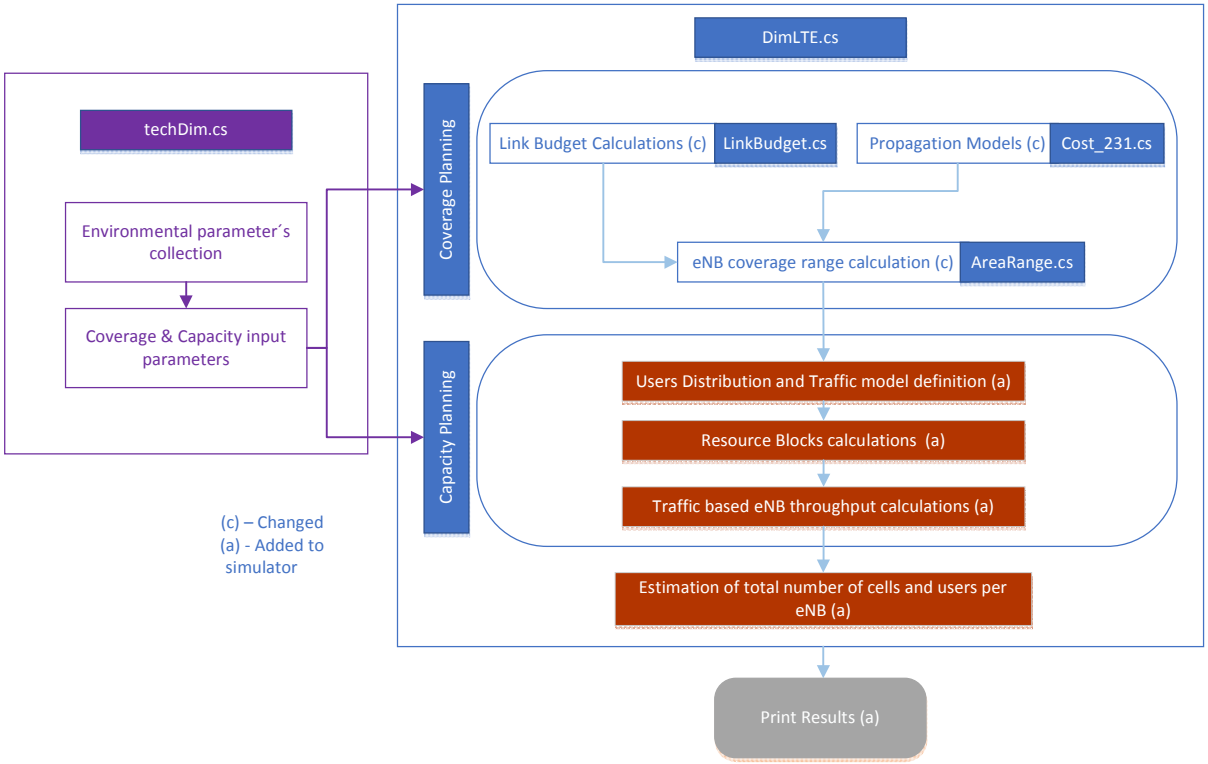

Figure 3.7 - Simulator Workflow.

Blue modules are intended to carry out the coverage and capacity calculations, being implemented in 'DimLTE.cs'. The path loss procedure for UL and DL presented in Section 3.1.3 can be found in the 'LinkBudget.cs' class, where the main inputs of the function that is responsible for calculating the maximum path loss are the BS and UE transmission power and antenna gain, user and cable losses, interference margin, noise figure and diversity gain. As previously described, the COST-231 propagation model can be divided into two sub-models, Okumura-Hata and Walfisch-Ikegami; it was implemented in two different approaches using the expressions presented in Annex B. The first approach is the implementation as a classic propagation model that allows the propagation loss calculation, and the second one is giving a specific maximum propagation loss for the maximum cell distance calculation. All functions regarding the propagation model can be found in the 'Cost_231.cs' class, where the main inputs are the environment (rural, suburban or urban), angle between UE plane and direct line to the BS, mean building height, mean UE height, BS height, mean streets width and building separation, or only the environment, UE and BS heights, depending of the propagation model. The 'AreaRange.cs' class has the ownership of the functions related to the cell area and radius calculations, which was implemented in order not to replicate blocks of code. 'DimLTE.cs', one of the most important classes, calls the functions presented in the classes referred above to compute the main coverage outputs. The outdoor and indoor coverage probabilities, outdoor and indoor standard deviations, and percentages of indoor and outdoor users are also taken into account; the importance given to indoor users and the definition of a traffic profile is its main innovation. All capacity and site count calculations described in Subsections 3.1.4 and 3.1.5 are implemented in 'DimLTE.cs', where inputs like frequency, channel bandwidth, environment, target area, user density, MIMO order, minimum cell-edge throughput, user

requested throughput per service, percentages of service usage (service mix) and percentage profiles of user traffic for UL and DL, are also taken into account.

A lot of effort was put into the change of the existing implementation, in order to get a more realistic approach of the network´s behaviour. Considering link budget calculations and propagations models, as well as the possibility to have both outdoor and indoor users, and throughput calculation based on the expressions provided in Annex A, a more realistic approach in capacity planning based on the service usage distribution was implemented from scratch (highlighted in red in Figure 3.7). Some other changes were also made, since only LTE is considered; as such, legacy parameters related to other systems were removed from the simulator, in order to reduce running time and get a more efficient approach – the simulator was restructured to accommodate the changes introduced in this thesis.

In order to typify the list of errors from the development of the code for the radio dimensioning, two classes were created: 'Strings_Reference.cs' and 'Return_Object.cs'. The former does not contain any method, only global public variables, in order to centralise and typify the error messages in one place. The latter only contains three public variables, referring to 'Name', 'Value' and 'Error'. The "Print Results" module corresponds to the block where the generated output files are. In order to create an Excel file with its outputs, it was necessary to create a class called 'Results.cs'.

In the last module, "Print Results", some output files are created:

- DimLTECoverage-DL.csv: mean indoor and outdoor cell radii, for each modulation, and the maximum coverage area, for DL.
- DimLTECapacity-DL.csv: cell area and radius obtained from capacity estimation, taking the handover rate into account, for DL.
- DimLTEOutputs-DL.csv: main output parameters of the dimensioning process, i.e., number of cells of each district, cell radius, number of active users per cell, and average throughput per cell regarding the services used by active users in each district, for DL.
- DimLTECapacity-UL.csv: the same information as DimLTECapacity-DL.csv, but for UL.
- DimLTEOutputs-UL.csv: the same information as DimLTEOutputs-DL.csv, but for UL.
- DimLTEOutputs-Tot.csv: basically, the same information as DimLTEOutputs-DL.csv or DIMLTEOutputs-UL.csv, depending on which link has a higher number of cells.

After the introduction of all parameters, a preliminary study on coverage is done, where the coverage area for each of the frequency bands is calculated. It is based on a reference minimum throughput, which is translated into a minimum SINR via (A.2), taking into account that, at the cell edge, QPSK is the modulation scheme being used, as it is the most robust one, enabling realistic throughputs at a relatively low SINR. When the throughput increases the distance decreases, until the maximum defined for each modulation is achieved, and vice versa. The maximum cell distance calculation approach was developed through reverse engineering the appropriate propagation model described in Annex B. As a starting point for this approach, a specific maximum propagation loss allowed between the BS and the UE has to be given as input. This propagation loss is obtained at a first stage by the classic link budget procedure, taking noise power into account where the calculated SINR is translated into a minimum

received power, being then possible to extract the maximum cell radius for each modulation and carrier frequency through the reversed model.

At this moment, the total number of covered users in a single cell is computed from (3.9), being uniformly distributed regarding the maximum radius of each modulation, as seen in Figure 3.5. Each cell has a number of RBs dictated by the bandwidth being considered, according to Table 2.2. Users are given all the RBs they need in order to receive the maximum throughput associated with the service they are requesting, if radio channel conditions support it; at this step, system capacity is not taken into account. UEs demand different numbers of RBs, taking the received SINR into account. Bad SINR conditions that correspond in most cases to a higher number of used RBs for a given throughput, and vice-versa. Taking into account the uniform distribution of users, it is possible to verify that, for the same provided service, a user in QPSK requires more RBs than one in 64 QAM.

In order to able to calculate the number of RBs that a user needs in order to fulfil the desired data rate, the throughput for a single RB is calculated based on the model in Figure 2.7, with an average value for each modulation. Resource allocation is done on an RB basis instead of on a sub-frame one, since the simulator is snapshot based. The user´s desired throughput is divided by the throughput for a single RB (being picked the integer ceiling value), in order to have knowledge, in a first approach, of the number of RBs requested by the user.

Considering that the minimum allocation unit is the resource block and the average throughput per RB is around 200 kbps in QPSK, there will be a huge difference between the offered and the processed capacity for voice service. Voice is a service with an average bit rate of 12.2 kbps, the resource allocation does not need to be performed every time-slot, instead being processed every 20 ms. This means that the number of active voice users is computed by dividing the number of covered voice users by 20.

The simulator checks if the number of RBs required by users is lower than the maximum number of RBs in a cell, the system being considered coverage-limited in this case, otherwise it is considered capacity-limited. After the calculation of RB, based on user´s requested throughput, it is checked if those are coherent with the network capacity; if no reduction has to occur, users are not requesting more resources than the ones the network is able to provide them; if required, a reduction is carried out via (3.14), where, in a first approach, the requested throughput is decreased until the capacity limit is achieved. At this stage all cells are in their capacity limits.

To conclude, when the system is coverage-limited, the cell radius is not initially changed, but only when the handover percentage is multiplied to the obtained radius, with a reduction of the radius being done according to the defined handover percentage (usually around 95%). The number of coverage cells is then calculated by (3.18). If the number of required RBs for the active users is higher than maximum, a reduction of the number of users in the cell is verified, thus forcing the radius to decrease. The cell radius obtained is divided by the maximum area of coverage (being picked the integer floor value), in order to have knowledge of the number of users supported by single a cell. After the multiplication of the obtained capacity radius by the same handover percentage, the number of capacity cells can be determined, as seen in Figure 3.6. It is important to notice that the obtained number of cells corresponds to the number of sites needed to fulfil all requirements. As previously mentioned, all sites are considered tri-sectorised.

Finally, some Excel files are automatically created with the output values, serving as a tool to study and compare the number of cells for different traffic scenarios and different carrier frequencies. All files are generated for each simulation, containing the results for a specific combination of the input parameters.

An extension to the simulator, to study UL dimensioning using the same methods as in DL, was also implemented. The main difference between the two links is the number and type of required services and throughput associated with them. Usually, the user´s requested throughput for UL is lower than DL.

3.3 Model Assessment

During model development, in order to validate its implementation, the obtained results were subjected to a set of empirical tests. A careful examination off all variables and formulas was made, in order to check if they were coherent and also accurate from a theoretical viewpoint. Some intermediate and different tests were carefully chosen to cover all calculations done by the implementation of both model approaches, which are detailed in Section 3.2. The results of the simulation, as previous discussed, were saved in Microsoft Excel files, which enabled a more efficient validation of some tests, such as the cell radius from coverage or capacity evaluation and, consequently, the number of cells in UL and DL, as well as the total number of active users supported by a single cell.

A list with the most critical tests performed for the coverage model approach is provided in Table 3.1. Table 3.2 presents a list with tests made for the capacity model approach.

Table 3.1 - List of empirical tests performed to validate the implementation of the coverage model.

Test	Validation
1	Check if an error message is shown after all input parameters are inserted.
2	Validation of the link budget and propagation models calculations: using a scientific calculator to compute some specific intermediate values and compare them with the ones obtained in the simulator.
3	Verify if the minimum path loss between UL and DL is chosen.
4	Verify if the radius of each cell in the 3 frequency bands varies according to different input parameters.
5	Verify if the cell radius is decreasing with the increase of modulation order.
6	Check if the number of coverage cells increases with the increase of frequency band.
7	Check if the .xlsx output file, with the coverage outputs results, exists and is located in the Output Directory.

Table 3.2 - List of empirical tests performed to validate the implementation of the capacity model.

Test	Validation
1	Check if an error message is shown after all input parameters are inserted.
2	Validation of the number of RBs requested by a user in each service: using a scientific calculator to compute some specific values and compare them with the ones obtained in the simulator.
3	Verify if the number of active users and total number of users per cell are equal when the total number of RBs is lower than the maximum number of RBs that can be served in a cell.
4	Check if the percentage of active users per cell decreases with the increase on the total number of users when the system is capacity-limited.
5	Verify if the total number of cells increases with the increase on the total number of users.
6	Verify if the total number of cells, for the same channel bandwidth, increases with the increase of frequency band.
7	Check if all .xlsx output files exist and are located in the Output Directory.

To check the accuracy of the simulator, in terms of number of cells for a certain area, a number of simulations as done, varying the user density as well as the available channel bandwidth. The number of cells for 2600 MHz is expected to be higher than for the two other carrier frequencies for the same channel bandwidth, as shown in Figure 3.8. The channel bandwidth is 20 MHz for the three carrier frequencies. In the simulation with the highest frequency, one can conclude that while the network is limited by coverage, the number of cells remains constant. However, one can verify that the network load is exceeded with an increase in the number of cells, from the moment that the number of required RBs exceeds the allowed maximum being verified. Furthermore, it is important to notice that all simulations were tested for different environments and scenarios, but, for reasons of simplicity, in these simulations the Lisbon area with an urban environment was considered.

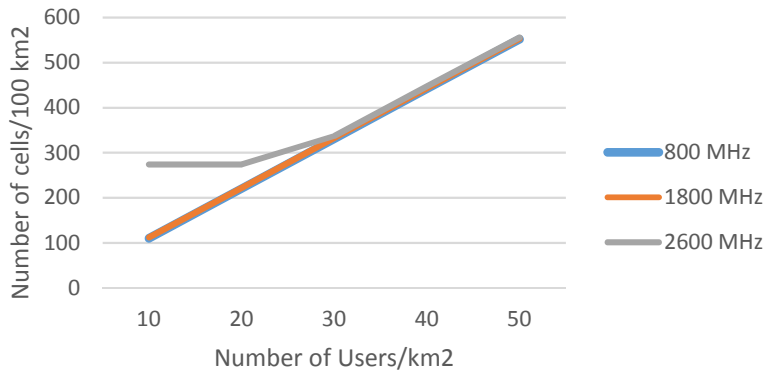

Figure 3.8 – Number of cells versus User density.

Based on the capacity calculations previous described, it is expected that the percentage of served users decreases with the increase of the total number of users (user density). Figure 3.9 represents the relation between the percentage of served users vs. covered ones; it is important to notice that the number of covered users is obtained from (3.8), where the maximum coverage area is computed taking into account the QPSK area and varying the user density, as detailed in Subsection 3.1.4. Assuming the traffic profile obtained in [Guit16], it is possible to verify the capacity limit in Figure 3.9 and Figure Figure 3.10 when both plots suffer some deviation, decreasing the number of active users and, consequently, the cell radius. One can verify that the capacity algorithm represented in Figure 3.6 is working correctly.

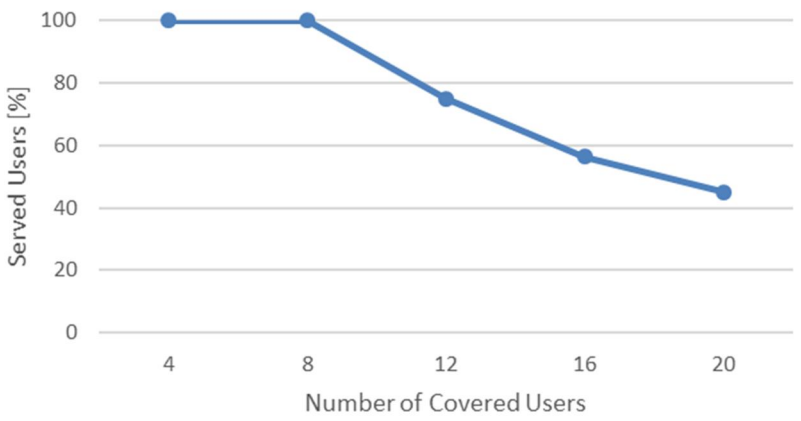

Figure 3.9 - Percentage of served users towards the covered ones.

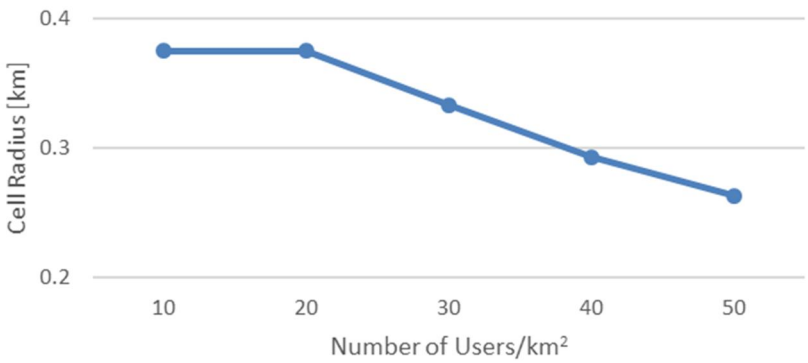

Figure 3.10 – Cell Radius versus User density.

As previously discussed, the distribution of users is uniform, i.e., the number of users for each of the modulation is determined based on the radius obtained for the three modulations. Taking this distribution into account, it is also important to notice that the total number of required RBs increases with the increase of the total number of users. Since the QPSK area is larger than the other two, a larger number of users in QPSK is obtained. As the throughput per RB is lower for QPSK, more RBs for each of the services are required. Then, taking into account that the number of users is greater for QPSK and more RBs are required to achieve the throughput required service, the cell features more RBs than expected, exceeding more quickly the cell boundary in terms of capacity, thus, leading to a lower number of users than expected.

Chapter 4

Results Analysis

This chapter provides a description of the reference scenario used in the simulations along with the obtained results and their respective analysis.

4.1 Scenarios Description

The reference scenario is the city of Lisbon and its surrounding areas. In Figure 4.1, the total area studied in the simulator is represented, which is divided into different municipalities with a different variety of users' density, and amount of generated traffic, meaning that each zone has different coverage and capacity requirements. It is important to notice that each municipality is divided into districts; as such, the model uses a granularity at the level of districts, each of the granular areas being classified according to one of the considered geotypes (urban, suburban and rural), which are defined according to the population density of each district. This approach leads the urban environment to be characterised by a high proportion of population, the contrary occurring for the rural environment. Therefore, the main output, i.e., the number of cells, is obtained for each district. The total number of cells of each municipality is obtained from the sum of the number of cells for each of the districts that belong to the municipality.

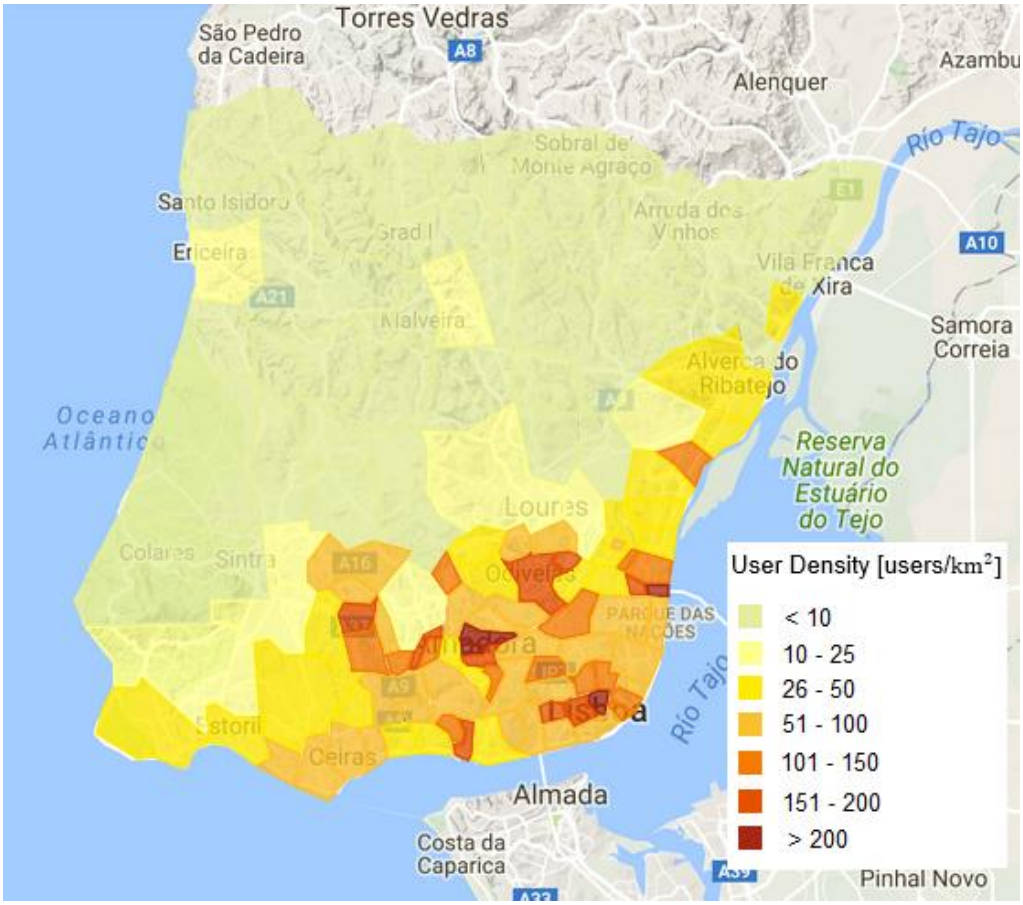

Figure 4.1 – Reference user density in the Lisbon City and its surrounding areas.

This region has an area of approximately 1500 km^2, where, as expected, the majority of the population is concentrated in the city. The percentages of urban and suburban scenarios were estimated to be 11% and 26%, respectively, and the remaining 63% for rural. The population density of Lisbon is not the highest, as seen in Figure 4.2.

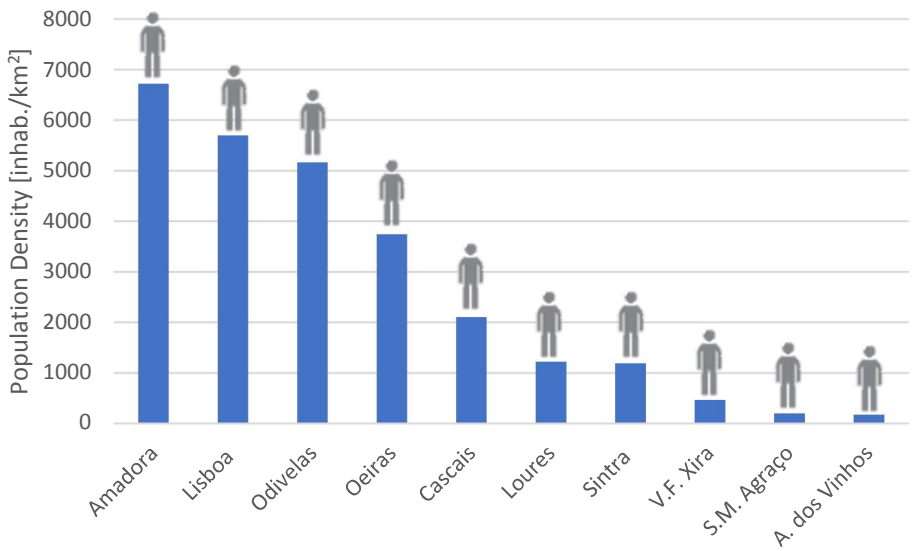

Figure 4.2 - Population density of each municipality.

This asymmetric distribution is reflected in the positioning of BSs, as presented in Figure 4.3, obtained from [Maro15] and showing the number of BSs for each municipality. Despite the number of sites present in each municipality, a specific traffic profile is not taken into account, which could be used in order to really compare the number of BSs present in each municipality, i.e., it is only possible to have an idea of the number of existing BSs in each municipality. According to [Maro15], there are 935 total tri-sectorised BSs in the studied area.

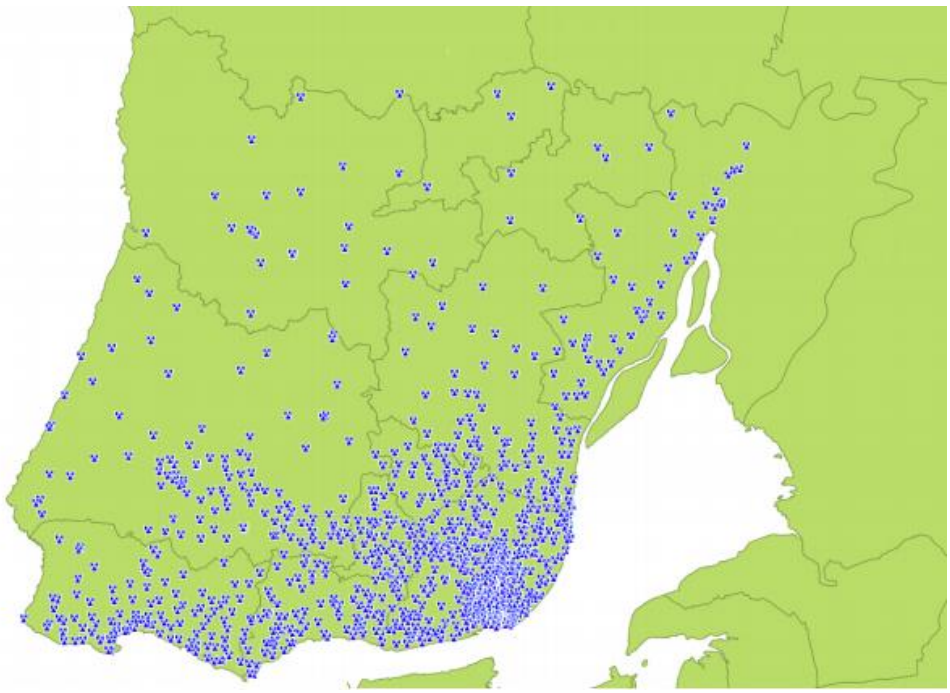

Figure 4.3 - BSs positioning in the Lisbon City and surrounding areas (adapted from [Maro15]).

Taking Figure 4.3 into account, it is easily deducted that for an urban environment like Lisbon, although the city population density is not the highest, as seen in Figure 4.2, the number of BSs is higher and they are more concentrated in the city. The total number of inhabitants in each district is divided by

district area (being picked the integer value), in order to know, in a first approach, the population density in each district. After that, the population density obtained of each district is multiplied by penetration and usage ratios. Using a snapshot approach, the real number of subscribers (instant active users) is used in capacity calculations. The penetration ratio corresponds to the percentage of users with smartphone internet access, while the usage ratio corresponds to the percentage of users who are enjoying some service at the instant of time under study. In the reference scenario, the penetration ratio is 15% and the usage one is 10%, but these values were changed in order to compare the total number of cells. The user densities presented in Figure 4.2 were obtained taking those ratios into account. The number of inhabitants for each district were obtained in [Stat16] and the area of each district in [Dire16].

It has been explained in the previous chapter that the path loss depends on coverage probability, interference margin and path loss model. Signal propagation fading determines the total attenuation level, and, as a result, the fading margin for each fading type, indoor and outdoor, is assumed as shown in Table 4.1 andTable 4.2, respectively. Fast fading was not taken into account, also as explained before.

Table 4.1 – Indoor Mean and Standard Deviation for each frequency band (extracted from [Corr16]).

Band [MHz]	Average [dB]	Standard deviation [dB]
800	2.6	9.2
1800	10.2	13.8
2600	13.6	15.9

Table 4.2 – Parameters for the reference scenario.

Parameter Description	Value
Reference throughput [Mbps]	2.0
Outdoor coverage probability [%]	90.0
Outdoor standard deviation [dB]	6.0 / 8.0
Indoor coverage probability [%]	90.0
Indoor Users [%]	70.0
Outdoor Users [%]	30.0
Penetration Ratio [%]	15.0
Usage Ratio [%]	10.0
Handover percentage [%]	95.0

In indoor and outdoor propagation, a statistical approach was used in order to compute the corresponding slow fading margin, i.e., the Log-Normal Distribution, giving the penetration attenuation for a given overall coverage probability. The differences found in slow fading are a consequence of the

standard deviation: in rural and suburban areas, the standard deviation is lower than in urban ones, hence, two different values being used, Table 4.2; the standard deviations in urban areas with highly integrated buildings layout and deeper indoor coverage is higher than in a suburban environment, the outdoor standard deviation being based on [Tele13] while the indoor one being defined for each frequency band, as seen in Table 4.1. In the dimensioning process, indoor or outdoor scenarios were taken, and it was considered that 70% of users are indoor and 30% are outdoor. This comes from the fact that nowadays, with a subscription of data plans, users consume more data services indoors, during work time, at the mall, or at home. The outdoor scenario corresponds to users that are walking on streets, and, for that reason, an extra attenuation was not considered. The indoor path loss is then higher than the outdoor one, and, consequently, the outdoor distance is greater than the indoor one.

The analysis of the outputs has been done taking the DL scenario into account, considering three different frequency bands associated with their maximum available bandwidths:

- 800 MHz with a bandwidth of 10 MHz, which provides coverage;
- 1800 MHz and 2600 MHz with a bandwidth of 20 MHz, which provide extra capacity.

The values presented in Table 4.3 are based on [Guit16], with the exception of the noise figure, diversity gain, interference margin and TMA gain, which were defined taking into account the values presented in [LTEE16]. UEs of Category 3 (which are able to support DL throughputs up to 100 Mbps) with a 2x2 MIMO configuration were considered, with an EPA5 channel.

Table 4.3 - Simulation Parameters.

Parameter Description	**Value**		
Frequency Bands [MHz]	800	1800	2600
Maximum Bandwidth [MHz]	10.0	20.0	20.0
DL transmission power [dBm]	42.0		
BS maximum antenna gain [dBi]	17.8		
Modulations	QPSK,16QAM, 64QAM		
UE antenna gain [dBi]	0		
UE losses [dB]	1.0		
Cable losses [dB]	2.0		
Noise figure [dB]	5.0 (UL) / 8.0 (DL)		
Diversity gain [dB]	3.0		
Interference margin [dB]	3.0		
TMA gain [dB]	2.0		
MIMO order [dB]	2.0		

As mentioned before, path loss is calculated using the COST 231 Walfish-Ikegami or COST 231 Okumura Hata models, presented in Annex B, and the parameters shown in Table 4.4: the former for both urban and suburban scenarios, and the latter for rural ones; the values for the parameters were based on [Guit16] for the urban environment; for the suburban and rural environments, the height of the BS antennas was increased compared to the urban environment, the width of the streets and the distance between the centre of the buildings was reduced for the suburban environment, taking into account the differences of the terrain morphology between urban and suburban environments. The UE height corresponds to the average holding height of the UEs for both data and voice usage.

Table 4.4 - Configuration of parameters for the propagations models.

Parameter Description	**Value**		
Environment	Urban	Suburban	Rural
Height of the BS antennas (h_b) [m]	25.0	28.0	30.0
Height of the buildings (H_b) [m]	21.0	21.0	-
Street width (w_s) [m]	30.0	20.0	-
Distance between building centre (w_B) [m]	50.0	30.0	-
Incidence angle (ϕ) [°]	90		
UE height (h_m) [m]	1.2		

Simulations were performed for 7 types of services for DL, i.e., voice (VoLTE), video calling, video and music streaming, web browsing, file sharing and e-mail, and 4 for UL, i.e., voice, video calling, file sharing and e-mail. Each one has minimum, average and maximum throughputs; however, the average throughput per user for the higher throughput services had to be adapted taking into account that the throughput values presented in [Guit16] were too demanding. Regarding voice, it was taken as VoLTE, as it is already under commercial implementation [Voda15]. The service mix was extracted from [Guit16], where the considered device is a smartphone. As one can see in Table 4.5, video streaming and web browsing use the majority of the resources, since with the current success of smartphones, the different sorts of internet based services incorporated in them, and also the effect of social networks, users are driven to use internet based services such as video and music streaming more often than other services. Social networking is evaluated as web browsing, so these two types of services were taken jointly. Users were also categorised as residential, office or mixed, based on their service requirement and traffic load that they place in terms of usage; as such, the service mix of each traffic profile is different according to the area and time instance under study. However, for the reference scenario, all users were considered as residential, hence, the service mix presented in Table 4.5 - Services characteristics (adapted from [Guit16]) is associated with a residential profile, where video streaming predominates. A study was done taking the three traffic profiles into account, where the percentages of services are changed according the type of user, i.e., the distribution of users considers the three variants in order to make a more realistic approach.

Table 4.5 - Services characteristics (adapted from [Guit16])

Service		Service Class	Average Bit Rate [Mbps]	Service Mix [%]
VoLTE		Conversational	0.022	22
Video	Calling	Conversational	0.384	8
	Streaming	Streaming	2	28
Music Streaming		Streaming	0.196	20
Web Browsing		Interactive	2	10
File Sharing		Interactive	2	8
E-mail		Background	1	4

As a first analysis, the impact on the number of cells for each municipality was studied, changing the total number of users. In this study, it is easily seen that the largest number of users the higher the amount of required cells to fulfil coverage and capacity requirements. Secondly, some variations for other inputs were performed. In the reference scenario, the frequency band and respective maximum bandwidth used are 1800 MHz and 20 MHz, respectively; however, the band and the bandwidth was varied, in which three cases were compared to the reference scenario, all of them at 10 MHz, 15 MHz and 20 MHz. Also, the impact of changing the minimum reference throughput was studied, as well as the services throughput, presented in Table 4.5. Regarding the input parameter service mix, one compared the network performance on the change in the percentage of each service. Two different service profiles were tested, adapted from those proposed by [Alme13] and [Ganc15], comparing the required number of cells for each scenario. In order to analyse what is the impact of the input parameters on the main output ones and extract conclusions, a variation of the former was done. All the analysed input and output parameters are presented in Figure 4.4, with purple and grey boxes, respectively.

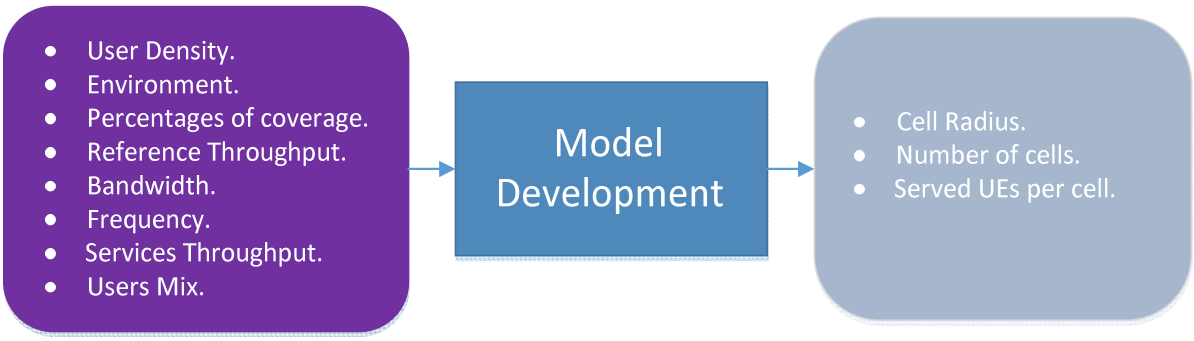

Figure 4.4 - List of analysed Input and Output parameters.

In order to provide a classification of the reference area as urban, suburban and rural, an approximation was considered, based on the number of users in each area. The areas with a high concentration of users were considered as urban or suburban, opposite to the case of rural ones, where the concentration of users is lower. In order to simplify the process, the areas corresponding to each environment are

outlined in Figure 4.5. Taking the area of each district into account, obtained in [Dire16], and the respective classification in terms of environment, the total area of each environment was computed.

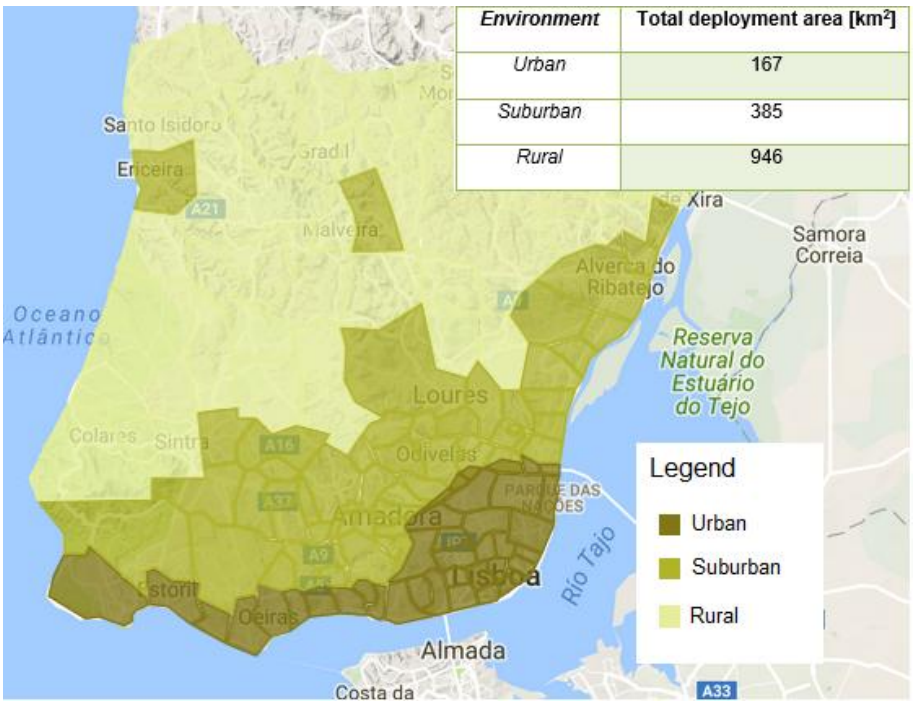

Figure 4.5 – Division of the reference area into environments (adapted from Google Maps).

Figure 4.6 represents the number of cells of each municipality obtained in simulations. Since each municipality has a number of districts with different areas and population densities, and consequently user densities, the user density and area of each district, presented in Annex C, are essential to compute these results, considering also the other parameters defined for the reference scenario. Taking the traffic profile presented in Table 4.5 into account, a total of 1243 BSs were obtained. As expected, the number of cells in Lisbon is higher, being reduced for the rural areas, since users' density is very low compared to urban areas.

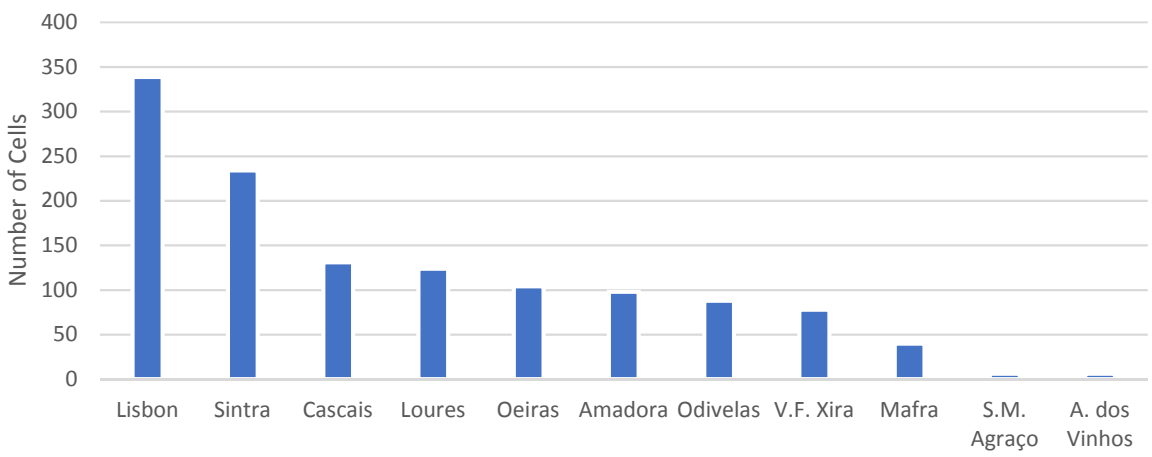

Figure 4.6 – Number of cells for each municipality taking the reference parameters into account.

Each environment is associated with a set of districts, and the number of sites presented in Figure 4.7

for each scenario was obtained by considering the sum of the required number of cells of each district in order to fulfil the coverage and capacity requirements defined in the reference scenario. In Figure 4.7, one can observe the number of cells per 10 km^2 for each environment; the number of urban cells is higher than the one for suburban and rural areas, as expected.

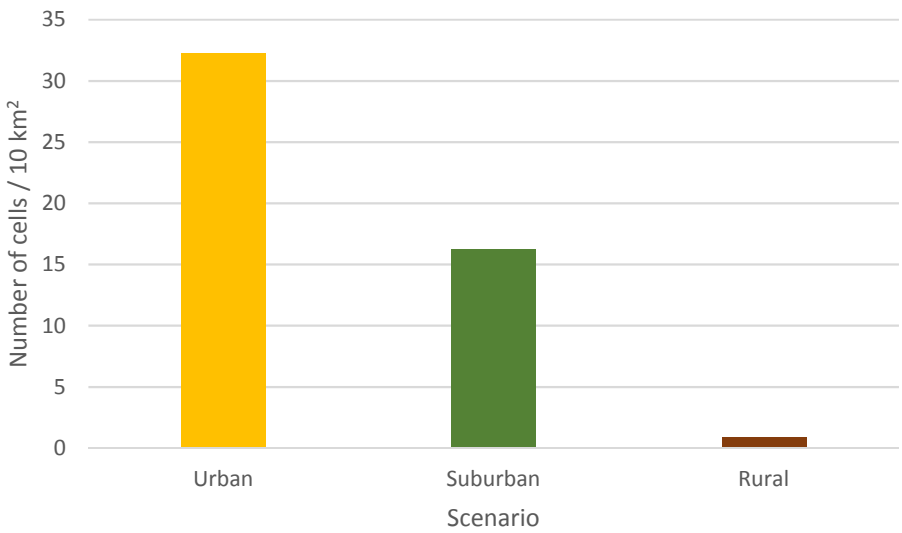

Figure 4.7 - Number of cells per 10 km^2 for each environment.

For each district, a number of sites with a certain radius was determined, Figure 4.8 showing the average cell radius obtained for each environment. As mentioned in the previous chapter, the maximum allowed path loss (MAPL) has different values for urban, suburban and rural. In terms of coverage, considering that a higher path loss corresponds a lower maximum cell radius, it is of no surprise that, for the urban environment, the mean cell radius is lower than for the suburban or rural ones, as seen in Figure 4.8, where for each analysis the average value of the studied parameter is presented, as well as the corresponding standard deviation of each simulation on the top of each bar. Taking these facts into account, it is necessary to have more urban cells than suburban and rural ones to fulfil coverage requirements. In terms of capacity, when increasing the user density more resources are required and the probability of the cell being limited by capacity is greater. When the cell is overloaded, the cell radius decreases in order to fulfil capacity requirements. For that reason, and considering that most of the obtained cells are limited by capacity, more cells are needed in areas with a higher user density. This fact can be confirmed by the number of cells presented in Figure 4.7.

Regarding cell radius, it is also verified that the average cell radius for the suburban scenario is slightly lower than the expected. This result can be explained by the definition of some of the propagation model parameters for the suburban environment, such as, BS antenna height, street width and building separation, but also by the fact that the environment classification of the districts is an approximation, as can be seen in Figure 4.8. Although some districts present a considerable reference user density, some of them were considered suburban taking their location into account. For this reason, the cell radii of those districts are lower than the ones obtained for most of suburban districts. As such, the average cell radius in suburban environment decreases in relation to the expected radius.

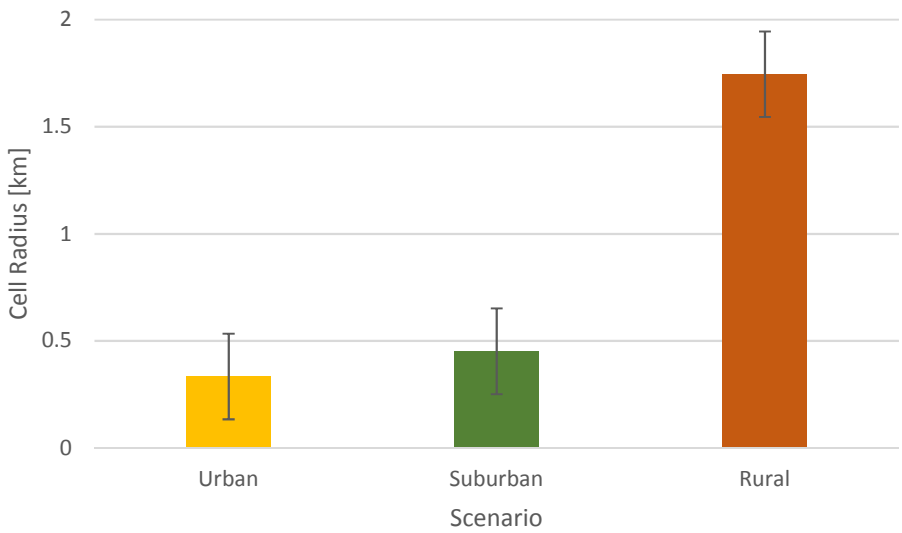

Figure 4.8 – Average cell radius for each environment.

4.2 Analysis on the Number of Users

In a first approach, the impact of varying the total number of users on the network performance was studied, regarding the number of active users that is obtained considering the application of the penetration and usage ratios in the total number of inhabitants in each district. For this analysis, as one can see in Table 4.6, only three different combinations were done. It is easily seen that increasing both ratios lead to an increase of users' density.

Table 4.6 - Penetration and Usage Ratio for each scenario.

Scenario	Penetration Ratio [%]	Usage Ratio [%]
Reference	15	10
Double	30	20
Triple	45	30

The algorithm provides RBs to users until there are no RBs left to be allocated. If a cell is overloaded, there must be a reduction in the number of RBs down to the limit allowed by the bandwidth. The total number of used RBs depends on the traffic profile of active users: if the traffic profile is heavier, i.e. the average throughput per user established for each of the services is too demanding in terms of capacity, it is seen that by increasing the number of active users in the network, more traffic is generated, thus, more RBs will be used. As previously discussed, a cell is limited by capacity when the number of RBs used by active users is higher than the maximum of available RBs, while, if after fulfilling the capacity requirements for all active users there are still available RBs, one considered that it is coverage-limited.

In the reference scenario, the services with the highest percentage of use are web browsing and video streaming. These services have the highest throughput, and therefore consume most of the available resources, thus leading to a higher percentage of cells limited by capacity.

Furthermore, increasing the population density means that users' density increases as well, independently of the area, which can be translated into a decrease in the cell radius and in the number of active users if the network is limited by capacity, leading to an increase in the number of cells, as one can see in Figure 4.9. When the cells of a district are limited by coverage, the cell radius and the number of active users remain constant. For the reference scenario, it is expected that the number of urban cells is higher than for the other two types of environments. Comparing the results from Figure 4.9, it is concluded that the number of urban cells is higher for the three defined scenarios due to the fact that the urban area presents a higher user density.

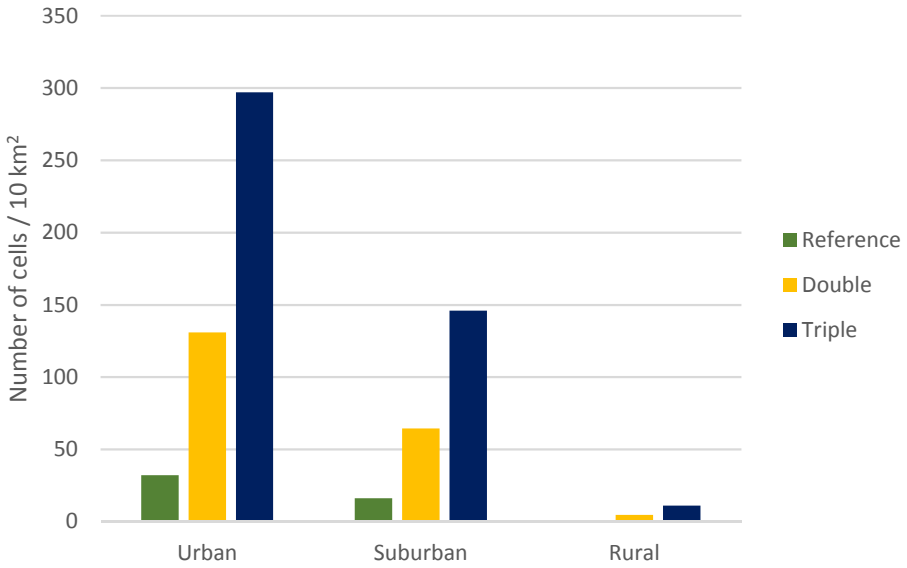

Figure 4.9 – Number of cells per 10 km² for different scenarios taking users' density into account.

When the penetration and usage ratios double the users' density quadruples, and when both ratios triple the users' density increases nine-fold. An interesting conclusion to be drawn from Figure 4.9 is that the number of cells increases proportionally with the number of active users.

4.3 Bandwidth and Frequency Band Analysis

In this section, the behaviour with the variation of the bandwidth in each band is analysed, for each case, the total number of cells required to cover the target area being presented. Varying the frequency band results in a change in the path loss used to calculate the maximum cell radius, resulting in different coverage areas. BSs having different coverage areas originate different network configurations, hence, the capacity limit does not change in a linear way.

Considering the propagation models' parameters that depend on the type of environment, the maximum

obtained cell radii for urban environments are lower than the ones obtained for suburban and rural environments. As seen in Table 4.7, for the same environment, the maximum obtained cell radius is higher for the lowest frequency and lower for the highest frequency, as expected, since the 800 MHz band has a lower path loss compared to the others.

Table 4.7 – Maximum radius of a cell for different bands.

Frequency Band [MHz]	**Environment**	**Cell Radius [km]**
800	U	1.91
	S	2.19
	R	15.12
1800	U	0.58
	S	0.79
	R	6.80
2600	U	0.31
	S	0.49
	R	5.00

In terms of capacity, one can distribute the scenarios in ascending order by *All 10 MHz, All 15 MHz, All 20 MHz*, where each frequency is associated with all bandwidths, as can be seen in Figure 4.10. When the bandwidth varies, the percentage of RBs guaranteed at the cell edge also varies; as previously mentioned, the percentage taken as a reference is 10.0%, but when the bandwidth decreases, for the same percentage the minimum throughput per RB exceeds the maximum defined for QPSK. The solution is to increase the percentage of guaranteed RBs at the cell edge when the bandwidth decreases, therefore, for 15 MHz the defined percentage was 13.3%, and for 10 MHz the percentage was 20.0%, to ensure that the minimum RB throughput does not exceed the allowed maximum.

Although greater bandwidths correspond to more available resources, and considering that the reference traffic profile is ambitious compared with the service throughputs required by users in reality, most cells remain limited by capacity. With the increase in available bandwidth, the network can provide more resources for services, meaning that the lower the bandwidth, the higher is the required number of cells, as shown in Figure 4.10, for the same frequency band. When comparing the three bands, it is seen that the number of cells for the highest frequency is higher than the other two, assuming that the bandwidth is equal for all bands. It was expected that, with the increasing frequency, the number of cells would increase. As seen in Figure 4.10, the number of cells obtained for the 800 MHz band is very similar to the one for 1800 MHz, considering that the bandwidth is equal, which is explained by the fact that capacity is the dominating factor, as less resources are available for these bands and the reference traffic profile is too demanding. However, the number of cells for 1800 MHz is always higher than the 800 MHz one, as expected.

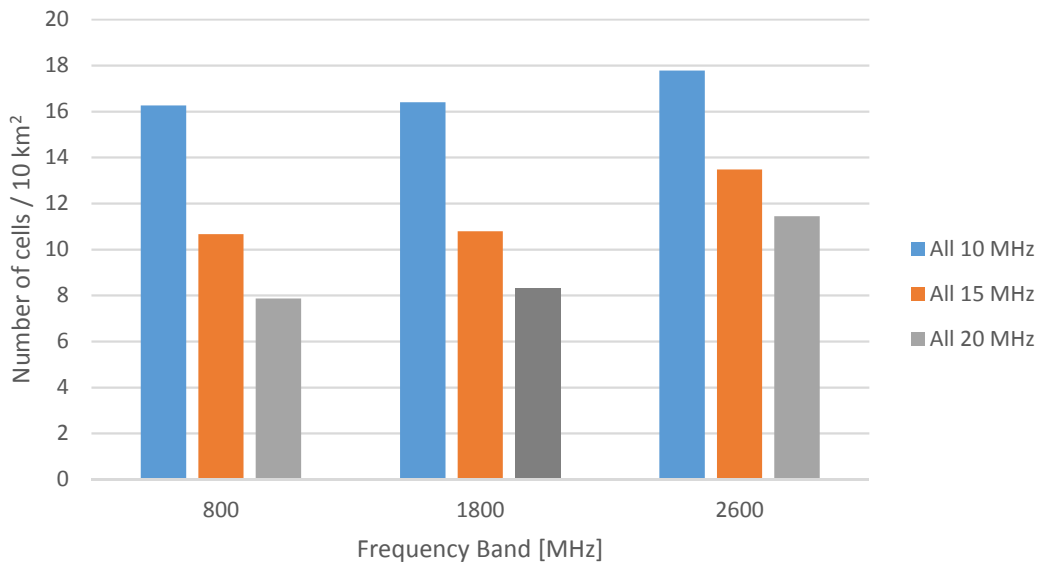

Figure 4.10 – Number of cells per 10 km² for different scenarios (reference scenario in darker grey).

Figure 4.11 shows the number of cells per 10 km² in each environment, taking different combinations of frequency band and channel bandwidth into account. The set of previous conclusions support the results provided in Figure 4.11, where one can see that, for the lowest frequency, the obtained number of cells is higher in each environment compared to the other three studied scenarios, which is due to the fact the lowest frequency shows a lower bandwidth. For the same reason, the number of cells required for each case of the second scenario is higher than the reference one. Both scenarios have the same frequency. However, the reference scenario has a higher bandwidth and, consequently, the number of available RBs is higher. It can be also seen in Figure 4.11 that, for the same bandwidth, comparing the two rightmost scenarios, the number of cells is higher for each environment if the frequency is higher.

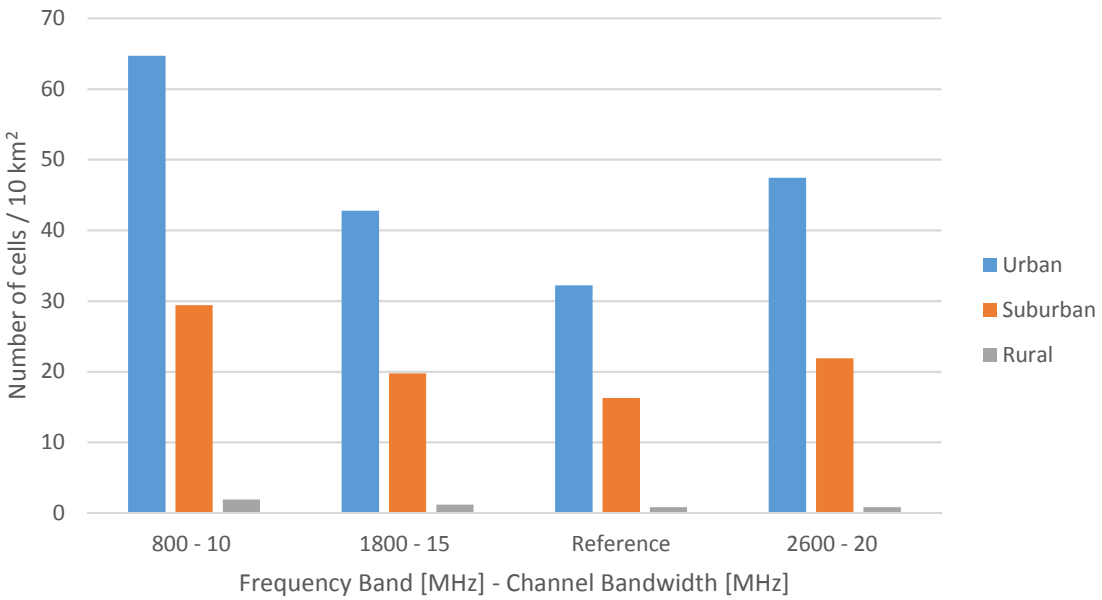

Figure 4.11 – Number of cells per 10 km² vs. bandwidths and frequency bands.

4.4 Analysis on Coverage Percentages

Since radio coverage is based on probabilities, indoor and outdoor coverage at a specific location from a BS can be specified for 50%, 90%, or even a higher probability. The slow fading margin is the "safety factor" used to determine the level of probability of successful radio communication. The higher the fading margin, the higher the probability that a usable communication signal is received, and the smaller the coverage area required to fulfil it. The previous statements support the results provided in Table 4.8, where the cells with higher probability present a lower radius.

Table 4.8 – Variation of the cell radius vs. outdoor and indoor coverage percentages.

District	Environment	Cell Radius [km]					
		Coverage Estimation			Capacity Estimation		
		85 %	Reference	95%	85%	Reference	95%
Ericeira	S	0.912	0.781	0.630	0.908	0.781	0.630
Loures	S	0.912	0.781	0.630	0.908	0.781	0.630
Alcabideche	S	0.912	0.781	0.630	0.816	0.781	0.630
Belém	U	0.697	0.579	0.579	0.644	0.579	0.579
Cascais	U	0.697	0.579	0.579	0.618	0.579	0.579
Sintra I	S	0.912	0.781	0.630	0.912	0.781	0.630
Sintra II	S						
V. Pinheiro	S						

As already mentioned, one of the determining aspects in the characterisation of cells is that the users' density is limited by coverage or capacity. If the density of users is low, the probability of being in the presence of cells limited by coverage is greater, depending on the traffic profile associated with users. As such, an area may have a low users' density, but if the users' traffic profile is very demanding, the probability of capacity predominance is higher. Considering the reference traffic profile presented in Table 4.5, it was possible to identify some suburban and urban districts in which cells are limited by coverage. In this section, the main objective is to understand the impact on the number of cells and whether the cells remain limited by the coverage, when the percentages of indoor and outdoor coverage are changed. The analysis is based only on districts that are constituted by cells limited by coverage, because it is possible to better understand the variation of coverage percentages on the required number of cells. When cells are limited by capacity, the obtained number of cells is equal for each one, even when varying the coverage percentages. For reasons of simplicity, the percentages of indoor and outdoor coverage are changed with the same value; these changes were done in the same simulation for each district limited by coverage.

With the increase of the percentage of outdoor and indoor coverage, the number of cells increases, as seen in Figure 4.12. All the districts presented in Figure 4.12 are constituted by sites limited by coverage

for 90% (reference) and 95%; however, it comes down to 85%, some districts have capacity-limited cells, with the reduction of the cell radius. This comes from the fact that the cell radius from coverage estimation is higher for 85%, hence, the number of active users is also higher, so the number of required RBs is higher, exceeding the maximum number of RBs allowed in the cell. As seen in Table 4.8, three districts maintain the cell radius, while in the remaining ones there is decrease of the cell radius caused by capacity. However, the path loss and, consequently, the cell radii are higher when both coverage percentages are lower, so when both percentages are higher, more cells are needed in order to fulfil the defined requirements, as seen in Figure 4.12.

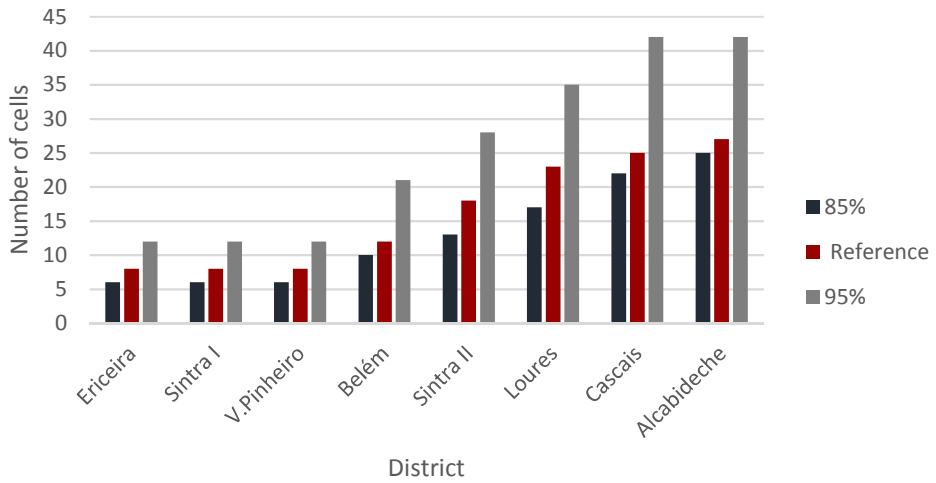

Figure 4.12 – Number of cells for each district vs. outdoor and indoor coverage percentages.

In Figure 4.12, Sintra appears twice due to the fact that the district of Sintra is subdivided into three sub-districts, two of them considered as suburban and one as rural. The districts presented in Figure 4.12 are the two suburban ones, as seen in Annex C. Sintra I and Sintra II correspond to Santa Maria and São Miguel) and to São Pedro de Penaferrim, respectively.

Usually, the users' density is low in rural areas, but in the reference scenario none of the rural districts appears in the set of districts whose cells are limited by coverage, since the cell radius for rural environments (and, consequently, the cell area) is significantly higher than in the other environments. By multiplying the obtained rural area by the user density existing in the rural districts, the total covered users number in the cell is obtained, being higher than that verified in other environments. Considering the reference traffic profile for rural areas, the number of RBs to satisfy all active users is very large, and for this reason rural cells are generally limited by capacity.

4.5 Traffic Profiles Analysis

For the analysis of traffic profiles, a scenario was chosen in which users have different traffic profiles. While at the beginning, all users have only one traffic profile, residential, from now on two other types

are taken into account, i.e., office and mixed. The percentages for each type of traffic profile were obtained by making an estimate that accounts for the location of hotspots in the urban area of Lisbon, as seen in Figure 4.13. Based on the orange (considered residential) and grey (considered office) areas in Figure 4.13, it was possible to reach the average percentages of each traffic profile presented in Table 4.9. For simplicity, the results were only obtained for the urban area outlined in Figure 4.13.

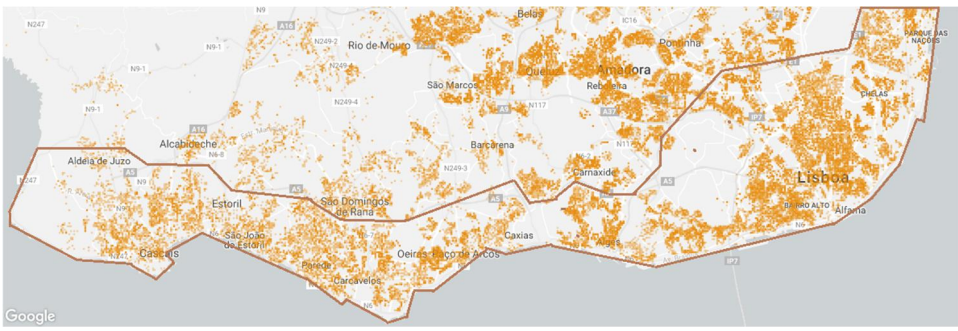

Figure 4.13 – Division of urban area into residential (orange) and office (grey) ones (extracted from [Fon16]).

In a real area, there are not only residential users or only business ones, but rather a mixture of the two. In Table 4.9, it is seen that the number of urban cells is higher in the ROM (Residential, Office and Mix) scenario than in the reference one, because of the introduction of the other two traffic profiles, especially the business traffic profile. The total use percentage of the services with higher throughput, like streaming, web browsing and FTP, is higher for the business profile, being a heavier traffic profile than the residential one, thus, the total number of cells in the ROM scenario is higher than the reference scenario one. It is important to notice that the services throughputs remain constant for each type of user profile, and only the percentages of use of the services change, depending on the environment (residential, office or mix). The only difference between these two scenarios is the introduction of two more types of user profiles (Office and Mix) and, consequently, the percentage of users of each type. All the other parameters defined, for the reference scenario, remain in the ROM scenario.

Table 4.9 – Total number of urban cells for different traffic profiles.

User Profile	**Scenario [%]**	
	Reference	**ROM**
Residential	100	60
Office	0	30
Mix	0	10
Total urban cells:	539	570

As seen in Table 4.10, while in the residential profile the service mix remains the reference one, in the service mix for the mixed profile the use percentage of each service corresponds to the average between the percentages of use for the same services in the residential and office profiles. The office service mix was obtained from [Pere13].

Table 4.10 – Service mix of each user type profile.

Service		Scenario [%]		
		ROM		
		Residential	Office	Mixed
VoLTE		22	20	21
Video	Calling	8	10	9
	Streaming	28	20	24
Music Streaming		20	10	15
Web Browsing		10	30	20
File Sharing		8	5	6
E-mail		4	5	5

A comparison between the ROM scenario and the proposed by [Alme13] and [Ganc15] on the service profile is done in what follows. As the type of services to be compared are not the same of this thesis, some adaptation was performed: for [Alme13], peer-to-peer was considered file sharing: the service mix of [Ganc15] does not have music, therefore machine-to-machine (M2M) were converted in music, taking the similarities of the average throughput of these services into account. The service mix values obtained in [Ganc15] for the voice centric scenario and in [Alme13] for video centric one were considered only for the residential profile. The office profile is maintained and the mixed profile is obtained by taking the residential and office profiles into account.

Table 4.11 – Service mix scenarios.

Service		Scenario [%]					
		Video Centric			Voice Centric		
		R	O	M	R	O	M
VoLTE		5	20	12	47.0	20	33
Video	Calling	8	10	9	3.6	10	7
	Streaming	40	20	30	18.0	20	19
Music Streaming		9	10	10	4.3	10	7
Web Browsing		24	30	27	10.0	30	20
File Sharing		9	5	7	8.1	5	7
E-mail		5	5	5	9.0	5	7

A real network needs to adapt to the new specifications according to different service profiles. It is also important to understand the network utilisation per user profile type, as, for instance, the behaviour of voice calls peak hour might be very different from data ones. Network traffic is typically a mix of various profiles that are weighted as a function of time and geographical area. This means, for instance, that the office usage profile is weighted at city centres during working hours, while the residential one is strengthened in urban areas during the evening. As such, two scenarios were established, one focused more on video streaming and another on voice, in order to analyse the impact on the number of cells when the service profile varies and to compare the results obtained with the reference service profile. As seen in The service mix values obtained in [Ganc15] for the voice centric scenario and in [Alme13] for video centric one were considered only for the residential profile. The office profile is maintained and the mixed profile is obtained by taking the residential and office profiles into account.

Table 4.11, the traffic profile is changed according to the scenario, and it can be seen that, in the profile focused on video streaming, the percentage is higher than in the ROM reference. As for the profile focused on voice, the percentage is also higher than the one established as reference. Since video streaming requires more RBs than voice, taking the higher associated average throughput per user into account, it can be concluded that the number of urban cells is greater for the traffic profile where the video is predominant, as seen in Figure 4.14. Consequently, for the ROM profile, the number of cells is higher than the required number of cells for the profile where voice is predominant, as for the last profile service percentages are less demanding in terms of capacity. Increasing the percentage of the most demanding services in terms of capacity, the number of cells needed to fulfil all requirements increases. It is also verified that substantially increasing the percentage of voice does not result in an increase in the number of cells compared to the ROM scenario, because the services that require more resources suffer a decrease in their percentage of use, reinforcing the previous ideas.

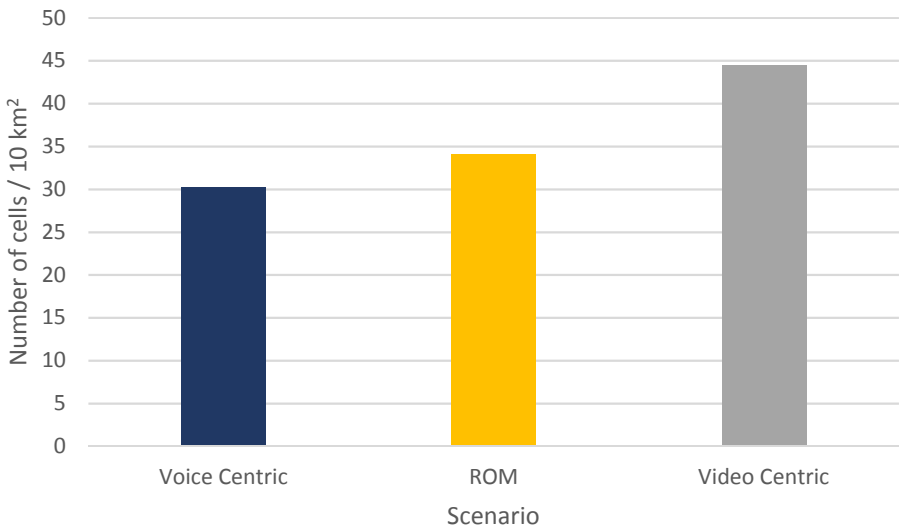

Figure 4.14 – Number of urban cells per 10 km^2, for different service profiles scenarios.

A comparison between the reference scenario and the ones proposed by [Guit16] on the traffic profile is performed next. As the average throughput required by the user is too demanding for some of the services considered in this thesis, there was a need to adapt the values for some services, namely for

the services with the highest throughput. The remaining services present the throughput values presented in [Guit16]. The main objective is to understand the impact, in terms of the number of cells, when the throughput required by the users for all services is increased or decreased; two traffic profiles have been created, Lower and Higher, in order to make a comparison with the throughputs defined as reference. Previously, it was the service mix that changed depending on the scenario, now it is the throughput that each user requires for each service that changes, maintaining the service mix.

Table 4.12 – Throughput values for the studied scenarios.

Service		**Bit Rate [Mbps]**		
		Lower	**Reference**	**Higher**
VoLTE		0.009	0.022	0.036
Video	Calling	0.231	0.384	0.422
	Streaming	1	2	4
Music Streaming		0.176	0.196	0.294
Web Browsing		1	2	4
File Sharing		1	2	4
E-mail		0.819	1	1.5

Figure 4.15 shows the number of urban cells per 10 km^2 for each of the established scenarios. As expected, it is seen that the scenario with a heavier traffic profile in terms of throughput has more cells, while the scenario with a lighter traffic profile presents fewer cells. The reason for this is also associated with the increase of the required RBs in order to satisfy the higher throughputs requested by users. With a heavier traffic profile, capacity prevails over coverage, and the cells' radius decreases, hence, more cells are needed in order to satisfy capacity requirements.

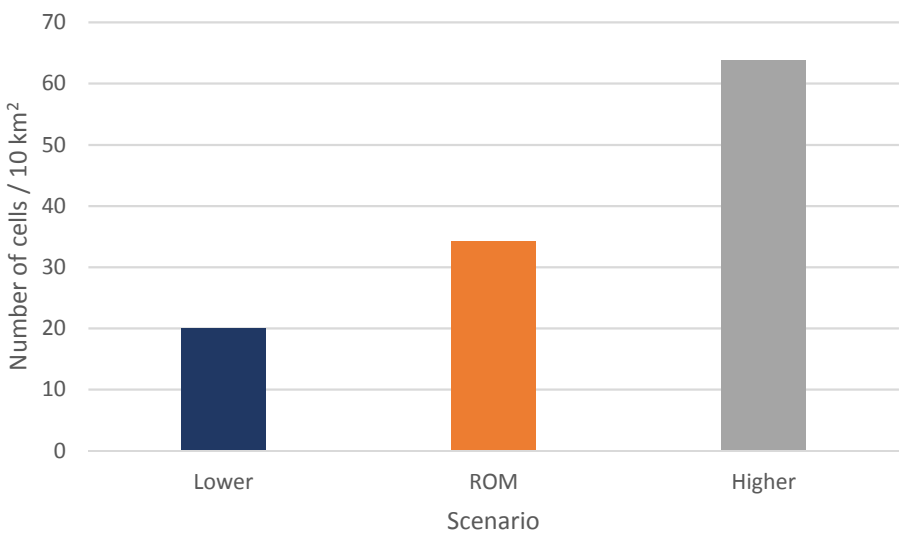

Figure 4.15 – Number of urban cells per 10 km^2 for each scenario.

4.6 Impact of Reference Throughput Analysis

In this section, the main purpose is to analyse the impact on the number of cells when the required throughput at the cell edge is changed. From the reference throughput, the throughput per RB is computed taking into account the percentage of guaranteed RBs at the cell edge. For this study, a couple of scenarios were proposed in order to compare with the obtained number of cells for the reference throughput, 2 Mbps. It was verified that there is a limitation with respect to values above 2 Mbps, since the obtained throughput per RB is always higher than the maximum throughput per RB, for QPSK, taking the reference percentage of RBs (10%) into account at the cell edge. Changing this percentage, as in the bandwidth analysis, can be done by lowering the throughput per RB until the maximum of QPSK is reached; however, the throughput per RB is equal to the one obtained for the ROM scenario, adding no value to the results, as such only the study for 1Mbps and 2 Mbps was made.

The change in the throughput value is directly related to distance, since with the increase of throughput, the distance decreases and vice versa, i.e., the higher the reference throughput, the higher the throughput per RB and, consequently, the lower the cell radius. Therefore, when decreasing the cell radius more cells are needed for the highest reference throughput, i.e., 2 Mbps, which is not verified.

When the number of cells is obtained for the 1 Mbps scenario, it is possible to verify a limitation at the level of the implemented model, considering that the obtained number of cells is higher in comparison with the ROM reference, which is not expected, but rather the opposite. Considering that the scenario with lower throughput is associated with a lower throughput per RB, it is possible to conclude that the cell radii obtained for this scenario are greater, and consequently the number of cells is smaller or equal, never higher, in comparison with the number of the ROM scenario one.

Considering the scenario with lower throughput, and the fact that cells are mostly limited by capacity for each district, the obtained radii are always lower than the ones obtained for the ROM scenario, which is not correct. This comes from the fact of the average throughput per RB is smaller than the reference one, thus, the number of RBs required for each service is higher, leading to a higher overload of the cell. It is a fact that, for the scenario with lower throughput, the maximum obtained cell radius is higher than the one for the ROM scenario, in terms of coverage; however, when capacity is taken into account, the radii of the cell from capacity estimation are lower than the ones in the ROM scenario, hence, the need for the implementation of the condition, so as to not contradict theory.

In order to solve this limitation, the following condition was imposed: when the throughput per RB is less than the maximum defined for QPSK, 200 kbps, and the obtained radius decreases due to capacity, the calculations are made according to the maximum throughput, so that the scenario with the lowest throughput does not present a radius smaller than the one obtained for the ROM scenario. Given this solution, the number of cells for each of the scenarios is equal, as a consequence from the fact that the maximum throughput matches the average throughput per RB for the scenario of 2 Mbps and the obtained cell radii, for each district, are equal in each scenario.

Chapter 5

Conclusions

This chapter summarises all the work carried out, and the main conclusions are presented. In the end, one gives a few recommendations for future work.

The main purpose of this thesis was to study the dimensioning and planning processes in an LTE network deployed over different scenarios, in order to understand the impact on the number of cells of the network when some of the input parameters vary. In order to accomplish this goal, a model was developed and several simulations were performed, analysing the impact of different user densities, areas, bandwidths, services throughputs, and the services percentages on the network performance. The region of Lisbon was chosen as a reference scenario, as it presents different municipalities with different varieties of user density and, considering that most of the data were collected from previous theses based on the same area, the definition of the inputs of the model became more accessible. Simulations were done for each district with different number of active users distributed along the network using either typical data download services or VoLTE.

The first chapter of this thesis is intended to briefly describe mobile communications evolution over time, followed by a short explanation of the growing data traffic demands, and finally addressing the motivation and contents that lead to the development of this thesis.

In Chapter 2, the theoretical background on LTE´s fundamental aspects is presented, concerning network architecture, radio interface, coverage and capacity aspects, and services and applications. Also, a description of some traffic services is presented, to help define the different types of traffic considered in this work. At the end of this chapter, a brief description of the state of the art on the thesis subject is provided, presenting some of the previously developed works that tackle dimensioning models and methods.

Chapter 3 starts by presenting the models that were developed in the scope of this thesis, as well as the simulator that implements them. The simulator addresses, in the most realistic way possible, the reality of an LTE network, considering aspects such as target area, different traffic profiles and different user density according to the zone of the municipality. Users, as a rule, are distributed non-uniformly over the entire target area, however, in this thesis, the network dimensioning process is based on the assumption of uniform distribution of users within the coverage area. This assumption has a limitation in terms of capacity, as the number of users is always higher for QPSK, as the QPSK area obtained is higher. In QPSK, more RBs are required to ensure the throughput of a service required by a user than in the other modulations, thus, the total number of RBs obtained for QPSK is higher as expected, taking into account that there are more users than in other modulations. However, the cell features more RBs than expected, exceeding more quickly the cell capacity limit, thus, leading to a lower number of users than expected. Moreover, in order to calculate the received power, a link budget taking only the slow fading margin into account is used. For the calculation of path loss, the COST 231 Walfisch-Ikegami and COST Okumura Hata models were considered according to the environment, as described in Annex B. Expressions for throughput calculation of each UE are presented in Annex A. Moreover, the whole process of traffic load calculation was implemented from scratch, to satisfy different service demands, while always taking the load of each cell into account. In the last part of the chapter, a model assessment is provided, confirming that the number of cells increases with the increase of user density, and that when cells are limited by capacity the cell radius and the number of active users inside the cell decrease. When the number of required RBs exceeds the maximum allowed for each bandwidth, the higher the

number of RBs required to satisfy the traffic profile, the lower the cell radius and consequently the number of active users. It is important to refer that the traffic studied under the scope of this thesis is only in downlink.

Chapter 4 starts by describing the reference scenario considered in this thesis, considering all parameters used in the simulator, as well as the set of input and output parameters to be analysed. The three frequency bands used by Portuguese mobile operators in LTE are used in this thesis; each of them has an associated bandwidth that usually depends on the carrier frequency. The lower the frequency band, the higher the costs, since lower frequency bands are better for providing a larger coverage area. The antennas parameters were chosen taking a given antenna as reference, and, although only the 1800 MHz band is used, with a bandwidth of 20 MHz, in the reference scenario, the other two frequency bands were also used in the results analysis, because they have particular characteristics worthwhile exploiting: different path loss (due to different frequencies), thus different coverage, and different available bandwidth, thus different capacities. Three different environments were considered for the region of Lisbon: urban, suburban and rural. The differences between the three environments are essentially based on different parameters for the propagation model, as well as user density. The result analysis includes the variation of the number of users, different frequency bands and bandwidths, coverage probabilities and, finally, the variation in the services throughputs and service mix taking different user profiles into account.

In the analysis of the impact of the number of users on the number of cells, three different combinations of penetration and usage ratios are taken. Each combination corresponds to a single scenario. In the double scenario, both ratios doubled compared to the reference, while in the triple scenario they triple. These ratios are applied to the total number of inhabitants of each district, in order to compute the users' density in each of the districts. It is easily seen that, by increasing both ratios, the users' density also increases. When the user density increases, the load in cells also increases, as the cell radius and the number of active users follow the opposite trend when the cells are capacity-limited, therefore, it can be concluded that the obtained number of cells increases when the users' density increases. As expected, the obtained number of cells for the reference scenario is lower than for the other scenarios. Considering that the user density quadruples when the ratios double and user density increases nine times when the ratios triple, it is also verified that the total number of cells quadruples and increases nine-fold compared to the obtained number of cells for the reference scenario, in double and triple scenarios, respectively.

Varying the bandwidth of each band has impact on the obtained number of cells and cell radius. In terms of cell radius, it is concluded that, for the lower frequency, the associated path loss is lower and, consequently, the maximum cell radius is also higher. As such, in terms of coverage, the required number of cells to cover a given area, for the lowest frequency, is lower. With the increase in available bandwidth, the network can provide more resources for services, meaning that the lower the bandwidth, the higher the required number of cells, for the same frequency band and traffic profile, and vice-versa. For instance, the obtained number of cells for the scenario with the combination (1800 MHz,15 MHz) increases by 33% over the reference scenario. Assuming that the available bandwidth is equal for all frequency bands, it is also verified that, for the higher frequency, the obtained number of cells is higher.

In fact, for the scenario with the combination (2600 MHz, 20 MHz), the number of cells increases by 47% over the reference scenario. However, it is possible to verify that, for the lower frequency and bandwidth, in comparison with the reference scenario or the scenario with higher throughput and bandwidth, the obtained number of cells is higher, given the available resources in each bandwidth.

For the indoor and outdoor coverage probabilities variation test, as expected, the impact is essentially verified in the cell radius. When the coverage probability increases, the obtained cell radius decreases. Decreasing the cell radius while maintaining the same traffic profile for each scenario, results in the need for more cells for the scenario with a higher coverage probability. It is also interesting to verify that, for the lower coverage probability, in some of the coverage-limited cell districts, these limitations switch to capacity ones, while increasing the cell radii. Considering that the increase of the cell radius allows the support of more users, the maximum capacity of the cell is reached, thus, a reduction of the radius is verified.

All of the previous analysis was made considering only residential users for the different environments. However, a distribution of users taking three different user profiles into account was developed in order to have a more realistic approach of the behaviour of a real network. A further analysis considers also this approach, where a percentage of residential, office and mixes users are defined. For simplicity, the urban scenario was the only scenario chosen. The number of urban cells obtained for the ROM scenario is higher than the one for the reference scenario. In fact, the number of cells for the ROM scenario increases by 6% over the reference scenario, where all users are considered as residential, given the introduction of two other profiles, especially the office profile, where higher service percentages for the most demanding services is verified.

The reference service profile, with the three user profiles, is compared with the ones proposed by [Alme13] (Video Centric) and [Ganc15] (Voice Centric). Video streaming is one of the most demanding resource services, since it has the maximum throughput. Therefore, the cells load for this test is much higher compared to the voice centric one. Obviously, the required number of cells for the scenario focused more on video service is higher than the one for the other scenarios. The number of cells for the video centric scenario increases by 30% over the ROM scenario. The obtained number of cells for the voice centric scenario is lower than the one obtained for the ROM scenario, as the percentages of the service mix of residential and mixed user profiles are lower for the services with higher throughput. The number of cells for the voice centric scenario decreases about 12% over the ROM scenario.

For the services throughputs variation test, two scenarios were proposed in order to compare the number of cells with the one obtained in the ROM scenario. As expected, the required number of cells for the scenario with higher throughputs in all services is higher than the ones for the ROM scenario and for the scenario with lower throughputs in all services. The number of cells for the scenario with higher throughputs increases by 85% over the ROM scenario, whereas, for the scenario with lower throughputs, the number of cells decreases about 41% over the ROM scenario. With higher throughputs, capacity is the dominating factor, leading to a higher number of cells needed to fulfil the users' requirements. Obviously, if services throughputs are not as demanding, the number of cells is lower.

For the analysis of the impact of the required throughput at the cell edge on the number of cells, a scenario with lower throughput was analysed and some limitations regarding the implemented model could be verified. At the beginning, for the scenario with lower throughput, the obtained radii were always lower than the ones obtained for the reference scenarios, in terms of capacity. Consequently, the obtained number of cells for the scenario with lower throughput was higher than the one obtained for the ROM scenario with higher throughput at the cell edge, which is not correct. The reason for this is associated with the throughput per RB used in the capacity calculations. Since it is smaller, more RBs are allocated and, for this reason, the radius is reduced, requiring a higher number of cells. In terms of coverage, the number of cells obtained for the scenario with lower throughput is lower than the one for the ROM scenario, as expected. Theoretically, the number of cells should be equal or higher for the ROM scenario. After the implementation of this condition, the obtained number of cells for both scenarios was equal.

A real mobile communications network is far more complex than the one analysed in this wotk. Other limitations of this work are related to the fact that neither the terrain profile or Lisbon's very irregular structure, which includes different buildings that may impose limitations to coverage areas and received power levels, are considered.

A great effort has been made in order to complete this work, but, as with all projects, there is always room for improvement and further enhancements. For future works that tackle a similar subject to the one of this thesis, an even more realistic scenario could be applied. Although the handover process is taken into account in this thesis, other limitation is interference coming from adjacent cells. Taking into account that inter-cell interference, or even intra-cell interference, can restrict the overall network in terms of throughput and spectral efficiency, especially for users located at the cell edge, interference management techniques could also be studied for future works, in order to know if they improve or not network performance in a real deployment. A better model of throughput as function of SINR could also be studied by taking different modes and coding rates in each modulation into account.

Another topic which could be addressed as future work is the usage of new LTE-Advanced functionalities, like Carrier Aggregation, where developments in terms of usage of different carrier frequencies in co-located sites should also be taken into account. The principle with Carrier Aggregation is to extend the maximum bandwidth by aggregating multiple carriers in order to improve network capacity. The use of this technique corresponds to a huge advantage in terms of achievable throughputs, since it should provide a better user experience by using two or more of these carriers to serve a given user and, therefore, enabling it to achieve higher throughputs.

Although this thesis only addresses communication via DL, the UL connection should also be analysed. It is also important to understand if and how mobile communications networks cope with challenging UL traffic loads resulting from services like Internet of Things (IoT), cloud enabled technologies and social networking. Even more so when taking into account that nowadays users are not only consumers of data, but are also starting to be active producers of content. For that reason, UL traffic has started to follow a growing trend, and today the asymmetry between DL and UL traffic is reduced.

Finally, the variation of other parameters, together with their implications on the subject under study, should also be analysed in order to have a better assessment of network capabilities. Different antenna configurations, such as another MIMO orders, transmitter output powers, antenna´s height and noise figure, for each environment, should be considered, so that one can better understand how these parameters can influence the required number of cells and how their variation can help in obtaining better results.

Annex A

SINR versus Throughput

The following annex provides an overview about the formulas that relate SINR and Throughput in LTE for a given set of system configurations.

In order to establish a relationship between SINR and Throughput, three expressions were derived for the three modulation types considered in both the uplink and the downlink: QPSK, 16-QAM and 64-QAM. These expressions represent the logistic functions that provide the best fit approach to a set of values collected by 3GPP based on throughput performance tests done by manufacturers, presented in [3GPP11]. In order to have a more realistic approach of the behaviour of a real network, the three modulation schemes are considered and each one is associated with the median value of the coding rates obtained according to the Channel Quality Indicator (CQI) reported by the UE, resulting in coding rates of 1/3 for QPSK, 1/2 for 16QAM and 3/4 for 64QAM. It is also important to refer that all users are considered to follow the EPA5 channel model.

For QPSK modulation, coding rate of 1/3 and considering MIMO 2x2, throughput per RB and the corresponding SINR can be given by:

$$R_{b[\mathrm{bps}]} = \frac{2.34201 \cdot 10^6}{14.0051 + e^{-0.577897 \cdot \rho_{IN}}} \tag{A.1}$$

$$\rho_{IN\ [\mathrm{dB}]} = -\frac{1}{0.577897} \cdot \ln\left(\frac{2.34201 \cdot 10^6}{R_{b[\mathrm{bps}]}} - 14.0051\right) \tag{A.2}$$

For 16QAM modulation, coding rate of 1/2 and considering MIMO 2x2, throughput per RB and the corresponding SINR can be given by:

$$R_{b[\mathrm{bps}]} = \frac{47613.1}{0.0926275 + e^{-0.29583\ 8\rho_{IN}}} \tag{A.3}$$

$$\rho_{IN\ [\mathrm{dB}]} = -\frac{1}{0.295838} \cdot \ln\left(\frac{47613.1}{R_{b[\mathrm{bps}]}} - 0.0926275\right) \tag{A.4}$$

For 64QAM modulation, coding rate of 3/4 and considering MIMO 2x2, throughput per RB and the corresponding SINR can be given by:

$$R_{b[\mathrm{bps}]} = \frac{26405.8}{0.0220186 + e^{-0.24491 \cdot \rho_{IN}}} \tag{A.5}$$

$$\rho_{IN\ [\mathrm{dB}]} = -\frac{1}{0.24491} \cdot \ln\left(\frac{26405.8}{R_{b[\mathrm{bps}]}} - 0.0220186\right) \tag{A.6}$$

Annex B

Propagation Models

Propagation Models used in this thesis are described in this annex.

B.1 COST-231 Walfisch-Ikegami Model

This model allows one to estimate the path loss between the signal emitted by the eNB to an UE as shown in Figure B.1.It is used when dealing with urban and suburban scenarios for distances shorter than 5 km, and also distinguishes between two different propagation scenarios: Line of Sight (LoS) and Non-Line of Sight (NLoS), according to [Corr16].

For LoS propagation in a street (ϕ = 0), and d > 0.02 km, path loss is defined as:

$$L_{p,outdoor[\mathrm{dB}]} = 42.6 + 26 \cdot \log\left(d_{[\mathrm{km}]}\right) + 20 \cdot \log(f_{[\mathrm{MHz}]}) \tag{B.1}$$

where:

- d: distance between the eNB and the UE;
- f: frequency of the signal being propagated.

For all other cases, path loss is defined as:

$$L_{p,outdoor[\mathrm{dB}]} = \begin{cases} L_{o[\mathrm{dB}]} + L_{rt[\mathrm{dB}]} + L_{rm[\mathrm{dB}]}, & L_{rt} + L_{rm} > 0 \\ L_{o[\mathrm{dB}]} & , L_{rt} + L_{rm} \leq 0 \end{cases} \tag{B.2}$$

where:

- L_o: free space propagation loss;
- L_{rt}: attenuation due to propagation from eNB to the last rooftop;
- L_{rm}: attenuation due to diffraction from last rooftop to the UE.

Being the path loss experienced in free space propagation defined as:

$$L_{o[\mathrm{dB}]} = 32.4 + 20 \cdot \log\left(d_{[\mathrm{km}]}\right) + 20 \cdot \log(f_{[\mathrm{MHz}]}) \tag{B.3}$$

The propagation from the eNB to the last rooftop experiences the following loss:

$$L_{rt[\mathrm{dB}]} = L_{bsh[\mathrm{dB}]} + k_a + k_d \cdot \log\left(d_{[\mathrm{km}]}\right) + k_f \cdot \log\left(f_{[\mathrm{MHz}]}\right) - 9 \cdot \log(w_{b[\mathrm{m}]}) \tag{B.4}$$

where:

- L_{bsh}: loss due to the height difference between rooftop and the antennas;
- w_b: distance between building´s centre.

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

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

in which:

- h_b: height of the BS antenna;

- H_B: height of the buildings.

Other correction factors are obtained from:

$$k_d = \begin{cases} 18 & , h_b > H_B \\ 18 - 15\dfrac{h_{b[\mathrm{m}]} - H_{B[\mathrm{m}]}}{H_B} & , h_b \leq H_B \end{cases} \tag{B.6}$$

$$k_f = \begin{cases} -4 + 0.7\left(\dfrac{f_{[\mathrm{MHz}]}}{925} - 1\right), \text{urban and suburban scenarios} \\ -4 + 1.5\left(\dfrac{f_{[\mathrm{MHz}]}}{925} - 1\right), \text{dense urban scenarios} \end{cases} \tag{B.7}$$

$$k_a = \begin{cases} 54 & , h_b > H_B \\ 54 - 0.8\left(h_{b[\mathrm{m}]} - H_{B[\mathrm{m}]}\right) & , d \geq 0.5\ km \wedge h_b \leq H_B \\ 54 - 1.6\left(h_{b[\mathrm{m}]} - H_{B[\mathrm{m}]}\right)d_{[km]} & , d < 0.5km\ \wedge h_b \leq H_B \end{cases} \tag{B.8}$$

Finally, the loss due to diffraction from the last rooftop to the UE is defined as:

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

where:

- w_s: street width;
- h_m: UE height;

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

$$L_{ori[dB]} = \begin{cases} -10.0 + 0.354\varphi_{[°]} & ,0° < \varphi < 35° \\ 2.5 + 0.075\left(\varphi_{[°]} - 35\right), 35° < \varphi < 55° \\ 4.0 - 0.114\left(\varphi_{[°]} - 55\right), 55° < \varphi < 90° \end{cases} \tag{B.10}$$

where:

- φ: angle of incidence of the signals in the buildings, on the horizontal plane;

The validity range for some parameters of this model imposes that:

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

The presented frequency range does not contain all the frequency bands studied in this thesis, therefore, one should consider higher relative errors than expected. The standard deviation of the model takes values in [4; 7] dB, and the error increases when h_b decreases relative to H_B. Some of the parameters used in this model are presented in Figure B.1. In the absence of specific values, the following are recommended [Corr16]:

- $w_b \in [20,50]$ m
- $w_s = w_b / 2$
- $\varphi = 90°$
- $H_{B[\mathrm{m}]} = 3 \cdot (\#floors) + H_{roof[\mathrm{m}]}$

where:

- $H_{roof} = \begin{cases} 3\text{, pitched} \\ 0\text{, flat} \end{cases}$

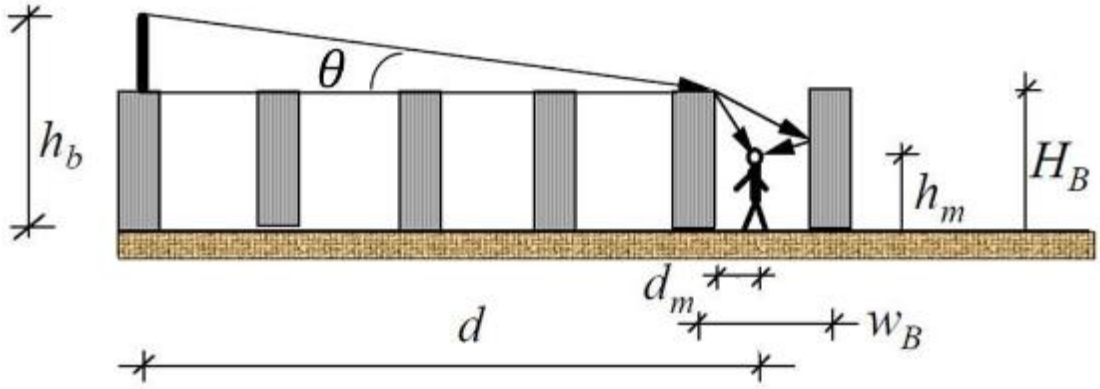

Figure B.1 - Parameters in the COST-231 Walfisch-Ikegami Model.

B.2 Okumura-Hata Model

This model assumes that there are no dominant obstacles between the BS and the MS, and that the terrain profile changes only slowly. It is used when studying rural, suburban and urban environments for distances larger than 5 km. The path loss for this model is described by:

$$L_{p\,[\mathrm{dB}]} = 69.55 + 26.16\log\left(f_{[\mathrm{MHz}]}\right) - 13.82\log\left(h_{b[\mathrm{m}]}\right) + (44.9 - 6.55\log(h_{b[\mathrm{m}]}))log\left(d_{[\mathrm{km}]}\right) - H_{mu[\mathrm{dB}]} - K_{f\,[\mathrm{dB}]} \quad \text{(B.11)}$$

where:

- f : frequency band;
- h_b : effective height of BS antenna;
- K_f: scenario correction factor;
- d : distance between the BS and the UE;

$$H_{mu\,[\mathrm{dB}]} = \begin{cases} \left(1.1 \cdot \log\left(f_{[\mathrm{MHz}]}\right) - 0.7\right)h_{m[\mathrm{m}]} - (1.56 \cdot \log\left(f_{[\mathrm{MHz}]} - 0.8\right)\text{, small city} \\ 8.29 \cdot (\log(1.54 \cdot h_{m[\mathrm{m}]})^2 - 1.10, \qquad f < 200\ Mhz\text{, large city} \\ 3.2 \cdot (\log(11.75 \cdot h_{m[\mathrm{m}]})^2 - 4.97, \qquad f \geq 400\ Mhz\text{, large city} \end{cases} \quad \text{(B.12)}$$

in which:

- h_m: user equipment height;

$$K_{f\,[dB]} = \begin{cases} 4.78 \cdot \left(log(f_{[\mathrm{MHz}]})\right)^2 - 18.33 \cdot \log\left(f_{[\mathrm{MHz}]}\right) + 40.98, \text{rural scenarios} \\ 2 \cdot (\log(f_{[\mathrm{MHz}]}\,/28))^2 + 5.4, \qquad \text{suburban scenarios} \\ 0, \qquad \text{urban scenarios} \end{cases} \tag{B.13}$$

This model has a standard deviation for urban, suburban and rural environments approximated by:

$$\sigma_{[dB]} = \begin{cases} 0.70 \cdot \log_{10}{}^2(f_{[\mathrm{MHz}]}) - 2.5 \cdot \log_{10}\left(f_{[\mathrm{MHz}]}\right) + 11.10, \text{urban scenarios} \\ 0.98 \cdot \log_{10}{}^2(f_{[\mathrm{MHz}]}) - 3.4 \cdot \log_{10}\left(f_{[\mathrm{MHz}]}\right) + 11.88, \text{suburban and rural scenarios} \end{cases} \tag{B.14}$$

and it is valid for the following values:

- $f \in [150, 1500]$ MHz
- $d \in [1, 20]$ m
- $h_b \in [30, 200]$ m
- $h_m \in [1, 10]$ m

It is noteworthy that the frequency range does not encompass the 1800 MHz and 2600 MHz frequency range most commonly used for fourth generation cellular system. This problem was solved by the COST-231 Hata Model, which extends the validity region to the 1.5-2 GHz range:

$$L_{p\,[\mathrm{dB}]} = 46.3 + 33.9 \cdot \log\left(f_{[\mathrm{MHz}]}\right) - 13.82 \cdot \log\left(h_{b[\mathrm{m}]}\right) - H_{mu[\mathrm{dB}]} + \left(44.9 - 6.55 \cdot \log\left(h_{b[\mathrm{m}]}\right)\right) \cdot log\left(d_{[\mathrm{km}]}\right) - K_{f[\mathrm{dB}]} + C_{m[\mathrm{dB}]} \tag{B.15}$$

where:

$$C_{m[\mathrm{dB}]} = \begin{cases} 0, \text{small cities} \\ 3, \text{urban centres} \end{cases} \tag{B.16}$$

Annex C

Districts

This annex presents the geographical area, number of inhabitants, reference user density and the considered environment (U – Urban, S – Suburban or R – Rural) for all districts defined for this thesis.

In this thesis, eleven municipalities were studied in the Lisbon region. As previously mentioned, each municipality is divided by districts and the main output of this thesis, the number of cells, is obtained for each district taking into account the values presented in the tables below. The area of each district was obtained in [Dire16] and the number of inhabitants in [Stat16]. The reference user density was obtained taking the reference penetration and usage rate into account. Therefore, all the studied municipalities and its districts are detailed in the following tables:

- **Lisbon Municipality**

Table C.1 - Lisbon Districts Characteristics.

District	Environment	Area [km^2]	Inhabitants	Reference user density [users/km^2]
Ajuda	U	3	15584	77
Alcântara	U	4	13943	52
Alvalade	U	5	31813	95
Beato	U	2	12429	93
Benfica	U	8	36821	69
Campolide	U	3	15460	77
Carnide	U	4	23316	87
Penha de França	U	3	27967	139
Parque das Nações	U	5	21025	63
Estrela	U	5	20128	60
Belém	U	10	16528	24
Lumiar	U	6	41163	102
Marvila	U	7	38102	81
S.D. Benfica	U	4	33745	126
São Vicente	U	2	15339	115
Santo António	U	1	11836	177
S.M. Maior	U	3	12822	64
Santa Clara	U	3	22480	112
Olivais	U	8	33788	63
Misericórdia	U	2	13044	97
Av. Novas	U	3	21625	108
Arroios	U	2	31653	237
Areeiro	U	2	20131	150
Campo Ourique	U	2	22120	165

- **Arruda dos Vinhos (AV) Municipality**

Table C.2 - AV Districts Characteristics.

District	Environment	Area [km^2]	Inhabitants	Reference user density [users/km^2]
Arruda dos Vinhos	R	34	8656	3
Arranhó	R	22	2381	1
Cardosas	R	6	836	2
Santiago dos Velhos	R	16	1518	1

- **Sobral Monte Agraço (SMA) Municipality**

Table C.3 - SMA Districts Characteristics.

District	Environment	Area [km^2]	Inhabitants	Reference user density [users/km^2]
Sobral de Monte Agraço	R	9	3406	5
Sapataria	R	14	3044	3
Santo Quintino	R	29	3706	1

- **Sintra Municipality**

Table C.4 - Sintra Districts Characteristics.

District	Environment	Area [km^2]	Inhabitants	Reference user density [users/km^2]
Algueirão Mem Martins	S	16	66250	62
Almargem Bispo	R	37	8983	3
Belas	S	22	26087	17
Colares	R	33	7628	3
Montelavar	R	12	3559	4
Queluz	S	3	26248	131
Rio de Mouro	S	16	47311	44
Sintra (Santa Maria e São Miguel)	S	12	9364	11
S.J Lampas	R	57	11392	2
Sintra (São Martinho)	R	24	6226	3
Sintra (São Pedro de Penaferrim)	S	27	14001	7
Terrugem	R	23	5113	3
Pêro Pinheiro	R	16	4246	3
Casal de Cambra	S	2	12701	95
Massamá	S	3	28112	140
Monte Abraão	S	2	20809	156
Agualva	S	8	35824	67
Cacém	S	2	21289	159
Mira Sintra	S	1	5280	79
S. Marcos	S	2	17412	130

- **Cascais Municipality**

Table C.5 - Cascais Districts Characteristics.

District	Environment	Area [km^2]	Inhabitants	Reference user density [users/km^2]
Alcabideche	S	40	42162	15
Carcavelos	U	5	23347	70
Cascais	U	20	35409	26
Estoril	U	9	26399	43
Parede	U	4	21660	81
S.D. Rana	S	20	57502	43

- **Odivelas Municipality**

Table C.6 - Odivelas Districts Characteristics.

District	Environment	Area [km^2]	Inhabitants	Reference user density [users/km^2]
Caneças	S	6	12324	30
Famões	S	5	11095	33
Odivelas	U	5	59559	178
O. Basto	S	2	5812	43
Pontinha	U	5	23041	69
P.S. Adrião	S	1	13069	196
Ramada	S	4	19657	73

- **Amadora Municipality**

Table C.7 - Amadora Districts Characteristics.

District	Environment	Area [km^2]	Inhabitants	Reference user density [users/km^2]
Alfragide	S	3	9904	49
Águas Livres	S	2	37426	280
Encosta do Sol	S	3	28261	141
Falagueira - V. Nova	S	3	23186	115
Mina de Água	S	8	43927	82
Venteira	s	5	18539	55

- **Mafra Municipality**

Table C.8 - Mafra Districts Characteristics.

District	Environment	Area [km^2]	Inhabitants	Reference user density [users/km^2]
Azueira	R	15	3164	3
Carvoeira	R	8	2155	4
Cheleiros	R	12	1347	1
Encarnacao	R	29	4798	2
E.Bispo	R	18	1740	1
Ericeira	S	12	10260	12
Gradil	R	8	1226	2
Igreja Nova	R	26	3037	1
Mafra	R	48	17986	5
Malveira	R	10	6493	9
Milharado	R	24	7023	4
S.E. Gales	R	18	1709	1
S. Isidoro	R	25	3814	2
Sobral A.	R	16	1152	1
V.F. Rosário	R	6	871	2
Venda Pinheiro	S	12	8146	10
S.M Alcainça	R	7	1764	3

- **Loures Municipality**

Table C.9 - Loures Districts Characteristics.

District	Environment	Area [km^2]	Inhabitants	Reference user density [users/km^2]
Apelação	S	1	5647	84
Bucelas	R	34	4663	2
Camarate	S	6	19789	49
Fanhões	R	12	2801	3
Frielas	R	5	2171	6
Loures	S	33	27362	12
Lousã	R	17	3169	2
Moscavide	U	1	14266	213
Sacavém	S	4	18469	69
S.I. Azóia	S	8	18240	34
S.A. Tojal	R	15	4216	4
S.J. Talha	S	6	17252	43
S.J. Tojal	R	13	3837	4
Unhos	S	4	9507	35
Portela	U	1	11809	177
Bobadela	S	3	8839	44
P. Velho	S	1	7136	107
S.A. Cavaleiros	S	4	25889	97

- **Oeiras Municipality**

Table C.10 - Oeiras Districts Characteristics.

District	Environment	Area [km^2]	Inhabitants	Reference user density [users/km^2]
Barcarena	S	9	13869	23
Carnaxide	S	7	25911	55
Oeiras	U	7	33827	72
Paço de Arcos	U	3	15315	76
Algés	U	2	22273	167
Cruz Quebrada	U	3	6393	31
Linda-a-Velha	U	2	19999	149
Porto Salvo	S	8	15157	28
Queijas	S	2	10377	77
Caxias	U	3	9007	45

- **Vila Franca de Xira (VFX) Municipality**

Table C.11 - VFX Districts Characteristics.

District	Environment	Area [km^2]	Inhabitants	Reference user density [users/km^2]
Alhandra	S	2	6047	45
Alverca Ribatejo	S	18	31070	25
Cachoeiras	R	10	766	1
Calhandriz	R	7	801	1
C. Ribatejo	R	15	7500	7
P.S. Iria	S	4	29348	110
S.J. Montes	R	18	6018	5
Vialonga	S	18	21033	17
Sobralinho	R	5	5050	15
Forte Casa	S	5	11056	33
Vila Franca de Xira	R	193	18197	1

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