Evaluation of 5G Cellular Network Implementation Over an Existing LTE One

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

To my beloved ones

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Abstract

The focus of this thesis was the design of a 5G radio access networks and the development of a tool capable of simulating and dimensioning. The main goal was to calculate the cell radius and respective usage percentage for different variations of a certain scenario. Thus, a model was developed, which consists mainly of coverage and capacity planning. Both downlink and uplink directions of the links between the base station and the user equipment were studied. In the downlink connection one only studied the 3500 MHz band, while in uplink the 800 and 1800 MHz bands were also studied. This thesis focuses on the study of urban environment, for which variations regarding some input parameters were taken like user density, frequency band and bandwidth, cell edge target throughput, traffic profile and MIMO. These parameters were studied in order to understand the impact on the cell radius and respective usage percentage. In this way, a model was implemented, which according to the input parameters, such as radio configuration and user density along with their traffic model, allocates the available resources in the cell to the total users. For these simulations, different numerologies were also considered. The use of higher numerologies results in a smaller cell radius and the respective usage is about 41 % lower for downlink and 13 % for uplink. When considering a service-centric approach to video usage, the cell usage percentage increases approximately 150 % in downlink and 180 % in uplink.

Keywords

5G, Dimensioning, Coverage, Capacity, Numerology, Cell Radius.

Resumo

O foco desta tese é o dimensionamento de uma célula com rádio 5G e o desenvolvimento de uma ferramenta para sua simulação. O principal objetivo é calcular o raio da célula e respetiva percentagem de utilização para diferentes cenários. Um modelo foi desenvolvido, que consiste principalmente num planeamento de cobertura e capacidade da célula. São estudadas as direções downlink e uplink das ligações entre a base station e o user. Em downlink é estudada apenas a banda 3500 MHz, enquanto em uplink são também estudadas as bandas 800 e 1800 MHz. Esta tese foca-se no estudo do cenário urbano, onde as variações dos parâmetros de entrada como densidade populacional, bandas de frequência e larguras de banda, perfil de tráfego e MIMO, foram estudadas para entender o impacto destes parâmetros no raio da célula e na respetiva percentagem de uso. Assim, um modelo foi implementado que considera parâmetros de entrada tais como a configuração de rádio e a densidade de utilizadores com o respetivo modelo de tráfego. De seguida, o modelo faz a alocação dos recursos disponíveis na célula perante o total dos utilizadores. Para estas simulações também são consideradas numerologias diferentes, em que o uso de numerologias superiores resulta num menor raio da célula e a respetiva percentagem de utilização é cerca de 41% menor para downlink e 13% para uplink. Com uma abordagem de utilização de serviços mais centrada em vídeo, a percentagem de utilização da célula aumenta aproximadamente em 150% em downlink e 180% em uplink.

Palavras-chave

5G, Dimensionamento, Cobertura, Capacidade, Numerologia, Raio da célula.

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List of Acronyms

16-QAM	16 Quadrature Amplitude Modulation
256-QAM	256 Quadrature Amplitude Modulations
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GC	5G Core
64-QAM	64 Quadrature Amplitude Modulation
AMF	Access and Mobility Management Function
ANACOM	Autoridade Nacional de Comunicações
BER	Bit Error Rate
BH	Backhaul
BLER	Block Error Rate
BS	Base Station
BSS	Business Support Systems
CN	Core Network
CP	Cyclic Prefix
DL	Downlink
DN	Data Network
E2E	End-to-end
EDGE	Enhanced Data rates for GSM Evolution
EIRP	Effective Isotropic Radiated Power
eMBB	enhanced Mobile Broadband
eNB	Evolved Node B
EPC	Evolved Packet Core
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
E-UTRAN	Evolved Universal Terrestrial Radio Access
FB	Frequency Band
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
FH	Fronthaul
FTP	File Transfer Protocol
GBR	Guaranteed Bit Rate

gNB	Next Generation Node B
GPRS	General Packet Radio Service
GSM	Global System for Mobile
HSS	Home Subscription Server
ICI	Inter Cell Interference
INI	Inter-Numerology Interference
IoT	Internet of things
IP	Internet Protocol
ISI	Inter Symbol Interference
LTE	Long Term Evolution
M2M	Machine-to-Machine
MANO	Management and Network Orchestration
MBR	Maximum Bit Rate
MIMO	Multiple-Input Multiple-Output
MME	Mobility Management Entity
mMTC	Massive Machine Type Communication
NFV	Network Functional Virtualisation
NG-RAN	New Generation Radio-Access Network
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexer
OFDMA	Orthogonal Frequency-Division Multiple Access
OOBE	Out-of-Band Emission
P2P	Peer-to-Peer
PBCH	Physical Broadcast Channel
PCEF	Policy and Charging Enforcement Function
PCRF	Policy and Charging Resource Function
PDCCH	Physical Downlink Control Channel
PDN	Packet Data Network
PDSCH	Physical Downlink Shared Control Channel
PGW	Packet Gateway
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PUCCH	Physical Uplink Control Channel
PUSCC	Physical Uplink Shared Control Channel
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Block
RE	Resource Element

RLB	Radio Link Budget
ROM	Residential, Office and Mix scenario
SC-FDMA	Single Carrier Frequency-Division Multiple Access
SCS	Sub-Carrier Spacing
SDM-C	Software-Defined Mobile network Control
SDM-O	Software-Defined Mobile network Orchestrator
SDM-X	Software-Defined Mobile network Coordinator
SDN	Software Defined Network
SGW	Serving Gateway
SINR	Signal to Interference Noise Ratio
SMF	Session Management Function
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TMA	Tower Mounted Amplifier
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
uMTC	Ultra-reliable and Low Latency Communications
UMTS	Universal Mobile Telecommunications System
UPF	User Plane Function
VIM	Virtual Infrastructure Manager
VNF	Virtual Network Function
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
ɣ	SINR requirement for the uplink or downlink traffic channel
η	User density
η_{cell}	Cell capacity ratio
$\eta_{u,cell}$	Percentage of active served users
μ	Numerology
ρ_{IN}	SINR
Δf	Carrier frequency
$\Delta f_{\max}$	maximum subcarrier frequency
A_c	Site coverage area
B_{RB}	Bandwidth of one RB
C_m	Extended Okumura-Hata model variable
d	Distance between the BS and the UE
f_c	Frequency band
F_N	Noise figure
F_S	Scale factor
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_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
N	Noise Power
N_{RB}	Total number of RBs
N_{rB}^{μ}	Total number of RBs for a certain numerology
N_{SC}^{RB}	Total number of subcarriers per RB
N_{symbol}^{SF}	Total number of symbols per sub-frame
$\overline{N_{RB}^{M}}$	Number of RBs required in M
$N_{RB,cell}$	Maximum available number of RBs per cell
$\overline{N_{RB,required}}$	Average total number of required RBs
$\overline{N_{RB,required}^{M}}$	Average number of RBs required of each modulation M
$\overline{N_{RB,users,s}}$	Average number of required RBs per user for each service and modulation
N_{symb}^{slot}	Number of symbols per slot
$N_{slot}^{frame,\mu}$	Number of slots per frame
$N_{slot}^{subframe,\mu}$	Number of slots per subframe
N_u	Number of total users in system
$N_{u,cell}$	Number of active users per cell
$N_{u,cell}^{M}$	Number of served users by modulation M
$N_{u,s}$	Number of active users in the service s
P_{EIRP}	Effective Isotropic Radiated Power
p_{ind}	Percentage of indoor users
p_{out}	Percentage of outdoor users
P_r	Power available at the receiving antenna
P_{Rx}	Power at the input of the receiver
$P_{r,min}$	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_Q	Radius of modulation QPSK
R_{16}	Radius of modulation 16-QAM
R_{64}	Radius of modulation 64-QAM
R_{256}	Radius of modulation 256-QAM
R_b	Throughput
$\overline{R_{b,cell}}$	Average throughput per cell
$R_{b,offered,s}$	Offered throughput for a given service s
$\overline{R_{b,RB}^{M}}$	Average throughput per RB of each modulation M
$R_{b,target,s}$	Target throughput for a given service s
$R_{b,teo}$	Theoretical Throughput
$\overline{R_{b,user,s}}$	Average throughput of user in service s
R_{max}	Maximum cell radius
$\overline{r_{cell}}$	Average cell radius
$\overline{r_{indoor}}$	Average indoor cell radius
$\overline{r_{outdoor}}$	Average outdoor cell radius
S	Maximum coverage area
T_s	Sampling time
T_{SF}	Sub-frame period
w_b	Building separation
w_s	Street width

List of Software

Microsoft Office Word 2016	Word processor
Microsoft Office Excel 2016	Spreadsheet application
Microsoft Office Power Point 2016	Presentation and slide program
Microsoft Visual Studio 2017	C# App Development Environment
Paint.NET	Image Editor

Chapter 1

Introduction

This chapter provides a brief overview of the mobile communications systems evolution, in terms of technology and consumer demand, with a strong focus on the latest network generations, LTE and 5G. It also discusses the motivation for this work and the structure of the thesis.

1.1 Overview

The world of mobile communications has radically changed the way people communicate with each other, from the pioneer generations that allowed two individuals to communicate by voice at a distance with wireless devices up to the 4th generation where the most consumed services are data. The most popular device that uses the mobile network is clearly the smartphone. Everyone has one or even two smartphones, to use in their daily lives. Their use is almost indispensable, to make voice calls or to use each other's favourite mobile applications. While in previous generations a mobile phone was only for making calls and sending SMS, nowadays, in addition to voice calls, users use their smartphone to communicate through social networks or watch videos.

In this way the demand for data services increases over the years, according to [Cisc17], the 4G network is the most used, Figure 1.1. While over the years the 2G network will be extinguished, the 3G network will still have some use since it can achieve the throughput required for services with low speed; but it is also necessary to maintain some old technologies like GSM, until there is a full migration of important services. So, for services that require a higher throughput, the 4G network is used, which currently occupies 69 % of the total traffic, about three times more than the 3G network, and will occupy about 79 % in 2021.

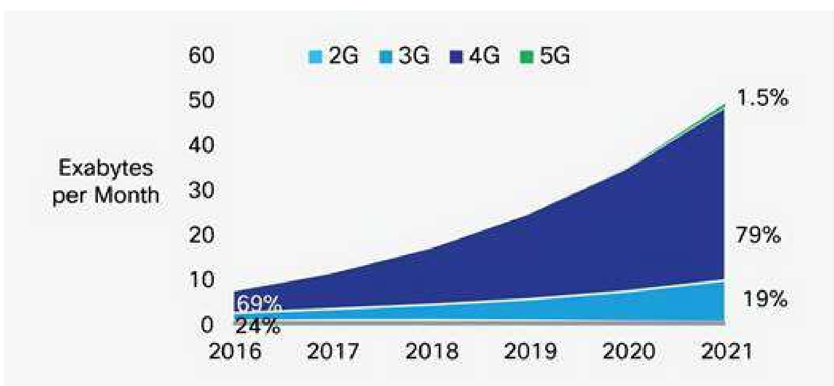

Figure 1.1. Network usage (extracted from [Cisc17]).

The growth in the use of the 4G network is due, therefore, to the great impact that mobile applications have on a daily basis. Increasingly, applications require more capacity on the part of the network, not only because of their wide frequency of use, such as social networks (e.g. Facebook) and messaging applications (e.g. Whatsapp), but also due to video applications (e.g. YouTube or Netflix), whose videos are increasingly quality, which requires transmissions with a higher throughput.

In this way, new devices are emerging as well as the evolution of smartphones. These devices are connected to the mobile network, such as smartTVs, laptops, tablets, wearables and IoT devices. IoT devices are one of the main factors responsible for the need to upgrade the network, since they have immense potential of use. Some services are already beginning to be replaced by IoT devices, as it is the case with electricity meters. The quantity of these devices tends to be enormous in the future, thus, a network with great capacity to serve all these devices is necessary. Another important benefit from an improvement of the network is the technology Wireless to the x (WTTx), which substitutes the Fiber to the x (FTTx) one, where the need of use of optical fibres is substituted by a wireless one in order to supply the demand services like triple play.

Another device with great impact on the network will be the wearables, which are small devices that are usually associated with a smartphone, however some are already starting to gain some autonomy and to connect directly to the mobile network. Also, for these devices a great growth is predicted in the next years, Figure 1.2. Currently, it is estimated that there are 593 million wearables being used against a forecast of 929 million in 2021, with 7.4 % of these being directly connected to the mobile network without any intermediate smartphone. These wearables can also be headsets that introduce Virtual Reality (VR) and Augmented Reality (AR). This technology, although currently very recent and still at an early stage, has a great potential of use in the day to day of users. And, therefore, the mobile network must be prepared so that the services of this technology can be used.

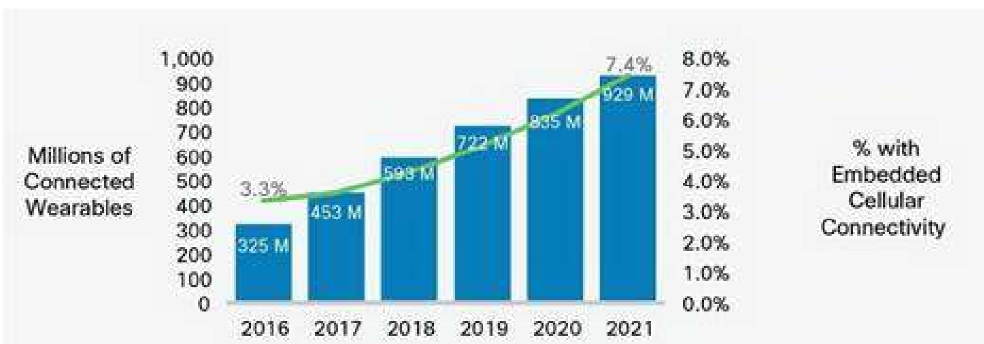

Figure 1.2. Wearables device usage (extracted from [Cisc17]).

To meet the requirements of these technologies and the extensive use of certain devices, the parameters of the current network must improve in some aspects. In particular, spectrum usage efficiency, device power consumption, device capacity, higher throughputs, and the ability to establish low latency connections. This is where the 5G network emerges as a response to these LTE network issues.

1.2 Motivation and Contents

The number of devices connected to the mobile network is increasing, requiring also connections with higher throughputs and low latency conditions. A new radio is therefore required in response to these requirements. Thus, emerges the new 5G radio (NR 5G) with features that enable the emergence of new services as well as the satisfaction of today service demand. According to [IMTV15] there are three categories in which 5G services can be divided: enhanced Mobile Broadband (eMBB), Massive Machine Type Communication (mMTC) and Ultra-reliable and Low Latency Communications (UrLLC). In order for quality of service (QoS) of these services to be satisfactory in the connections, several requirements are necessary to be fulfilled, among which the main ones are throughput, which must reach the Gbps order, network capacity, which must be able to support at least 10 times more devices, and latency, which should be below 5 ms.

The main objective of this thesis was to analyse how a 5G network behaves in an urban scenario, for which the cell radius and usage percentage are calculated for different variations of the input parameters. This network dimensioning process does not present new concepts, since the coverage and capacity planning explained in detail in this thesis is not new. However, the impact of variables with different values that were used in the technologies of previous generation networks is studied. The study done in this thesis mainly represents the analysis of aspects such as the density of users, different frequency bands and bandwidths, traffic profiles and distribution of users.

This thesis was developed in collaboration with NOS, a Portuguese telecommunications operator. The main output of this thesis is to show how the cell radius varies and the respective usage percentage of users served by it for the 5G conditions in various scenarios. These scenarios simulate several urban municipalities in the city of Lisbon. For this purpose, a tool capable of dimensioning the network for several scenarios by varying the input parameters was developed and implemented.

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

Chapter 2 presents an overview of the theoretical aspects related to this thesis. At the beginning, the general aspects of the 5G network are discussed, presenting their architecture and how it should interconnect with the LTE network. This section is followed by one detailing the new radio interface aspects. Following this section comes an analysis of the coverage and capacity theory applied in this thesis. The next section breaks down the new services that the 5G networks enables and what are the improvements in comparison with the LTE one. At the end of this chapter, a review is done of the state of the art related to this thesis.

Chapter 3, the description of the models and algorithms used in this thesis is made. The general operation of the model is briefly described below, followed by a more detailed explanation of its operation. Capacity and coverage plan, and other important aspects of these plans are described, such as Link Budget and throughput relations with Signal Interference plus Noise Ratio (SINR). The description of the simulator implementation is also made in this chapter, as well as the respective assessment.

Chapter 4 presents the description of the scenarios and the results of their analysis. One begins by describing the reference scenario that contains all the parameters used in the simulator. Next, the results of the analysis of the impact of different parameters, such as the cell radius and respective usage percentage are presented, depending on the variation of the scenario. The analysis is illustrated with graphs resulted from the implemented simulator.

In Chapter 5, the results are then globally analysed and respective conclusions are drawn. In addition, criticisms of the work and suggestions are also made for future work. A summary of all the work performed is also provided, so that one can have a general understanding of the thesis and the conclusions obtained in the end.

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Chapter 2

Fundamental Concepts and State of the Art

This chapter provides an overview of the 5G system. The 5G network architecture is presented in Section 2.1, followed by a discussion of the radio interface in Section 2.2. The study of coverage and capacity planning are presented in Section 2.3, while the services and applications are analysed in Section 2.4. Finally, the state of the art concerning the scope of this thesis is presented in Section 2.5.

2.1 Network Architecture

2.1.1 Overall Architecture

The 5G network is still being developed so there is no final consensus of its standardisation yet, though there are proposals for its implementation. Nevertheless, the specification of the general architecture of this new network is getting a final shape and has some similarity with the LTE one. In this section the overall architecture of the network is introduced based on [3GPP17a] and [3GPP17b].

Figure 2.1 shows an overview of the architecture proposed where the NG-RAN represents the New Generation Radio-Access Network and 5GC the 5G Core. The 5GC is composed mainly of the module Access and Mobility Management Function (AMF) and the module User Plane Function (UPF). The NG-RAN comprises the new radio base stations (gNB). To interconnect the system there are the NG and Xn interfaces, where Xn is used to connect the base stations between each other while NG connects the NG-RAN to the 5GC.

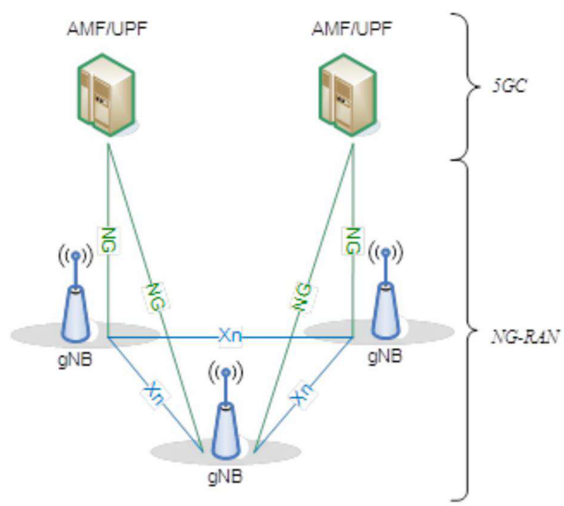

Figure 2.1. General 5G system architecture (extracted from [3GPP17a]).

This architecture is being updated as 3GPP makes a new release of the development of the 5G network. Currently Release 15 states a more complex and complete architecture presented in Figure 2.2.

The modules that are important for this thesis are the User Equipment (UE), RAN, UPF, AMF, SMF and DN. The other ones have functions related to management and policies of the network.

These modules can be described as:

- The User Equipment, UE, is the physical device that can be associated to a person or a network of devices and is connected to the RAN module.
- The Radio Access Network, RAN, is composed of the gNBs (NG-RAN). This module passes the connection to the AMF or to the UPF.

- The AMF is where the termination of the RAN and UE interface ends, N2 and N1 respectively. This module is responsible for the access authentication and authorisation process. It comprises the NAS Security and the Idle State Mobility Handling.
- The UPF is responsible for the anchor point for Intra/Inter Radio Access Technology (RAT) mobility, when applicable, and for the packet routing and forwarding, traffic usage reporting and QoS.
- The SMF, Session Management Function allocates the IP address for the UE and controls the packet data unit session.
- The Data Network, DN, represents the core of the internet that the 5G network is connected to.

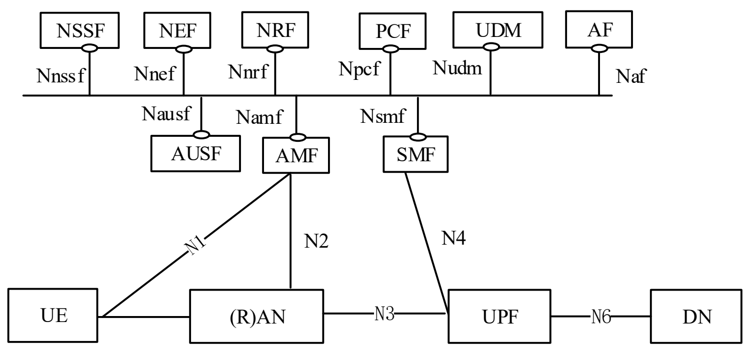

Figure 2.2. 5G System architecture (extracted from [3GPP17b]).

One of the main features of the 5G network is the enabling of network slicing that is explained in more detail in Section 2.1.2. For that purpose, each slice will be comprised of these modules and each module will have only the functions that are necessary to implement the requirements. So, the internal functions of the modules in each slice can be modified.

2.1.2 Network Slicing

The general organisations that are studying this matter have agreed to a main architecture that after some tests they believe is the right way to achieve the requirements expected for the 5G network introducing a new concept different from the legacy systems architecture. This section presents a new concept introduced on 5G based on [5PPP17], [5GNO16a] and [5GNO16b].

The new concept is network slicing that also handles multi-tenancy. This means that to provide services to the client requests, the network should be divided into slices and each one can have multiple services and tenants, Figure 2.3.

With a virtualised network and the use of Software Defined Network, SDN, the 5G system can implement slices that brings a better efficiency to the network transport.

While in legacy systems, e.g. LTE, the network is manually implemented to provide certain services (such as MBB, voice and SMS), Figure 2.4, network slicing aims to build automatically dedicated logical networks that consists of an end-to-end (E2E) system that begins at the mobile edge and goes up to the core network (CN), incorporating the fronthaul (FH) and the backhaul (BH), [3GPP17b].

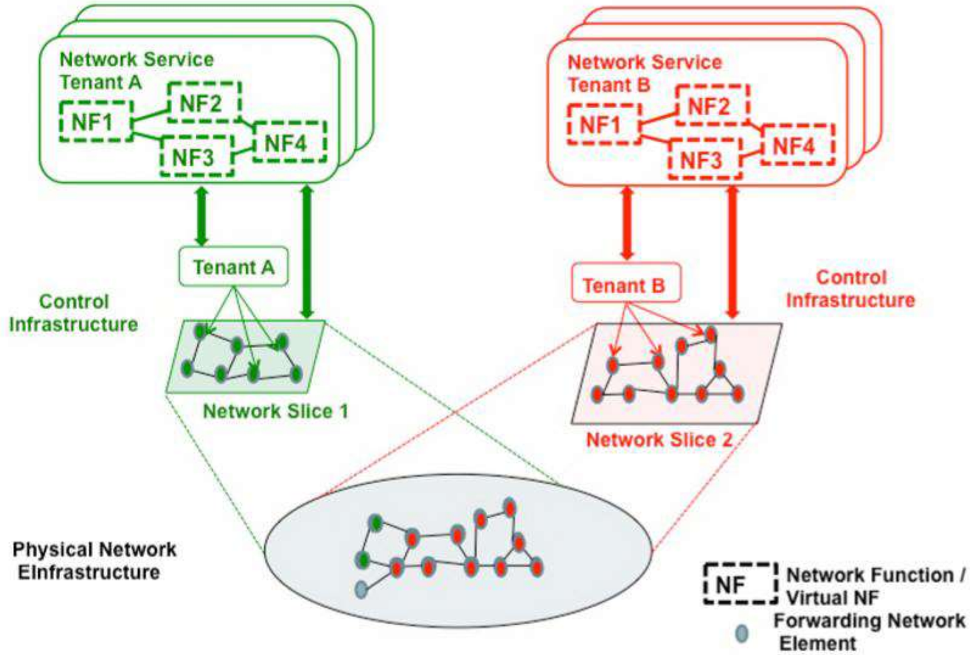

Figure 2.3. Network slicing representation (extracted from [5PPP17]).

To handle multiple slices, the network should have a certain level of automation and orchestration to maintain the correct functionality of the system. So, it is important to emphasise the importance of the life cycle of a slice instantiation that should be made automatically (preparation, instantiation, configuration and activation of the slices, run-time and decommissioning).

To reuse physical and virtual resources between different slices there must be softwarisation and virtualisation of the network using multitasking and multiplexing techniques.

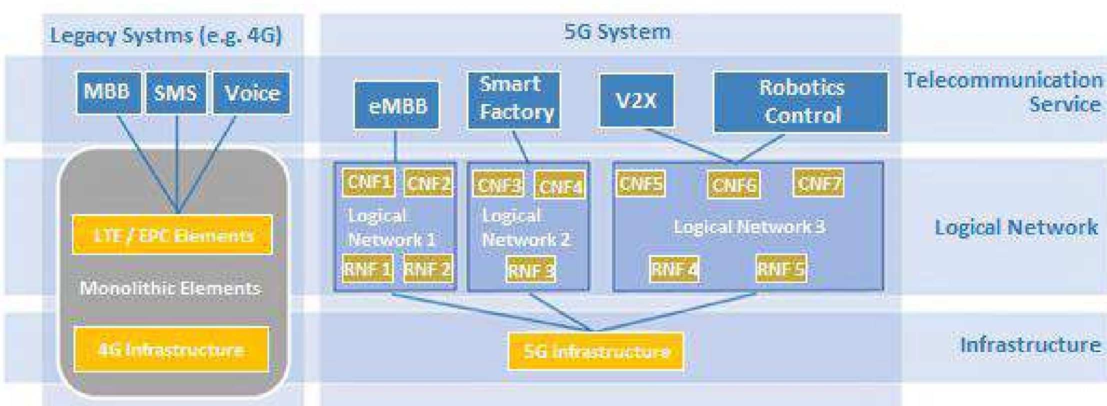

Figure 2.4. Multi-tenancy in legacy networks and slicing-enabled networks (extracted from [5GNO16a]).

The 5G architecture can be divided into the following layers in order to serve all aspects of the network slicing, Figure 2.5:

- **Service Layer:** This layer comprises the decision functions as well as applications and services operated by a tenant, the Business Support Systems (BSSs) and business-level policy.

- **Management and Orchestration Layer:** IT comprises the modules that makes the management of the network, includes the European Telecommunications Standards Institute (ETSI) Network Functional Virtualisation (NFV) Management and Network Orchestration (MANO) functions, and also includes the Virtual Infrastructure Manager (VIM), Virtual Network Function (VNF) Manager and the Network Function Virtualisation Orchestration (NFVO). These modules have the functions to traduce the service descriptions to the resource service allocation passed to the Control Layer and received by the Inter-Slice Broker.
- **Control Layer:** It has three main controllers: Software-Defined Mobile network Control (SDM-C), Software-Defined Mobile network Coordinator (SDM-X) and the Software-Defined Mobile network Orchestrator (SDM-O). These controllers translate the decision commands to the VNFs and PNFs.
- **Data Layer:** It comprises the Virtual Network Functions (VNFs) and the Physical Network Functions (PNFs) that carries the data traffic.

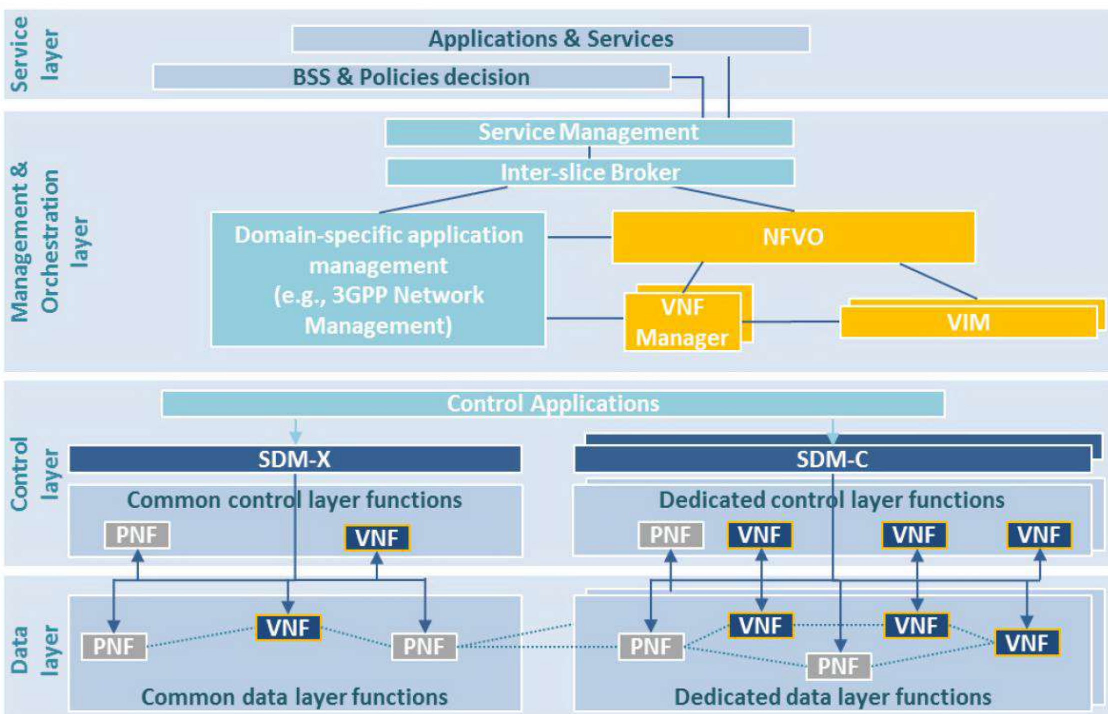

Figure 2.5. Architecture functional layers (extracted from [5PPP17]).

For a better control of the slices, APIs are provided to facilitate this process:

- Network Service Allocation/Modification/De-Allocation API;
- Virtual Infrastructure Allocation/Modification/De-Allocation API;
- Virtual Infrastructure Control with limited control;
- Virtual Infrastructure control API with full control.

To address the proper slices to a network for specific services and their usage a mechanism of control is taken in place, Figure 2.6.

The controllers SDM-C and SDM-X take care of dedicated and shared NFs, while the SDM-O can set up slices and merge them properly at the described multiplexing point respecting QoS/QoE requirements.

So, each slice has an SDM-C, responsible for managing their resources and building the paths to join the network functions considering the requirements by the QoS/QoE Monitoring and Mapping module. The SDM-C may adjust the network slice configuration based on information received by the QoS/QoE reconfiguring some of the VNFs or the data paths. If the requirements cannot be met with these adjustments the SDM-O can perform a slice reshaping e.g. adding more resources to a given slice, or on the other hand if they are not being used, then it shall be removed.

The SDM-O has a complete knowledge of the network managing the resources needed by all slices of all tenants. This enables the SDM-O to perform the required optimal configuration in order to adjust the amount of used resources.

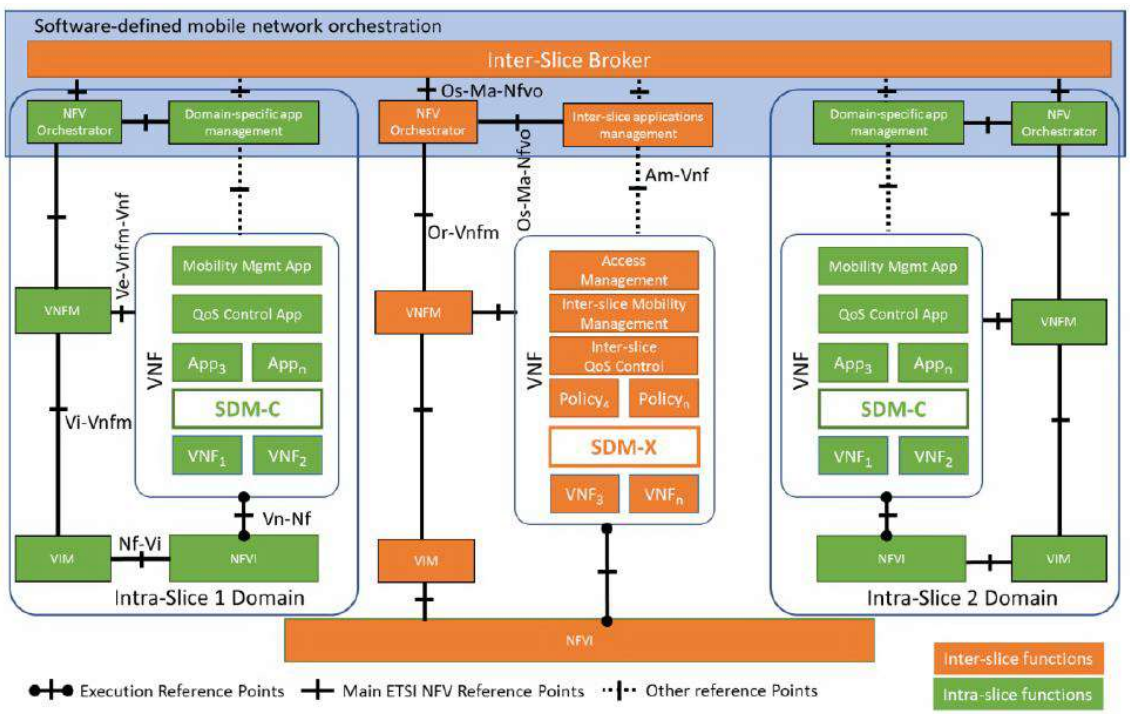

Figure 2.6. Inter and intra slice MANO framework (extracted from [5GNO16b]).

The SDM-C directly interfaces with dedicated NFs and the SDM-X controls shared NFs. This way the SDM-X and the SDM-O makes the inter-slice management. The inter-slice management and orchestration is a key-feature of the 5G architecture, as it supports multi-service and multi-tenancy systems.

Network slicing is a concept that brings more efficiency to the network, with Software Defined Network technology, making the system more autonomous on building the right paths for specific services and applications.

2.1.3 LTE Interconnection

For the improvement of the network it is important that the LTE network still works with the 5G one. This section is based on [3GPP17b]. Figure 2.7 shows how the LTE and 5G networks should operate together.

The modules from the 5G network have already been explained. For LTE one has:

- The Evolved Universal Terrestrial Radio Access (E-UTRAN) is a collection of eNBs connected to the MME via the S1-MME interface. Each eNB is the termination point for all radio related protocols, being responsible for Control Plane functions for monitoring radio resource usage, called Radio Resource Management (RRM).
- Mobility Management Entity (MME). This is the central control element, operating only in the Control Plane as the primary control channel between the UE and the network. It is responsible for the authentication and security of the UE in the network, it manages the subscription profile of the UE, and it deals with mobility issues, always regarding the Control Plane.
- Serving Gateway (SGW). It acts as the mobility anchor in the UP in inter-eNB HOs and provides user data packet routing.
- Packet Data Network (PDN) Gateway (PGW). It establishes the connection between the EPC and external IP networks. Also controls and delivers data over the UP tunnels for UL and DL.
- Policy and Charging Resource Function (PCRF). It provides policy control and flow based charging control decisions. It works together with the Policy and Charging Enforcement Function (PCEF), located in the P-GW, to ensure that the correct Quality of Service (QoS) is provided.
- Home Subscription Server (HSS). It records user subscription data including applicable services and allowable connections and stores the location of the UE within the visited network control node.

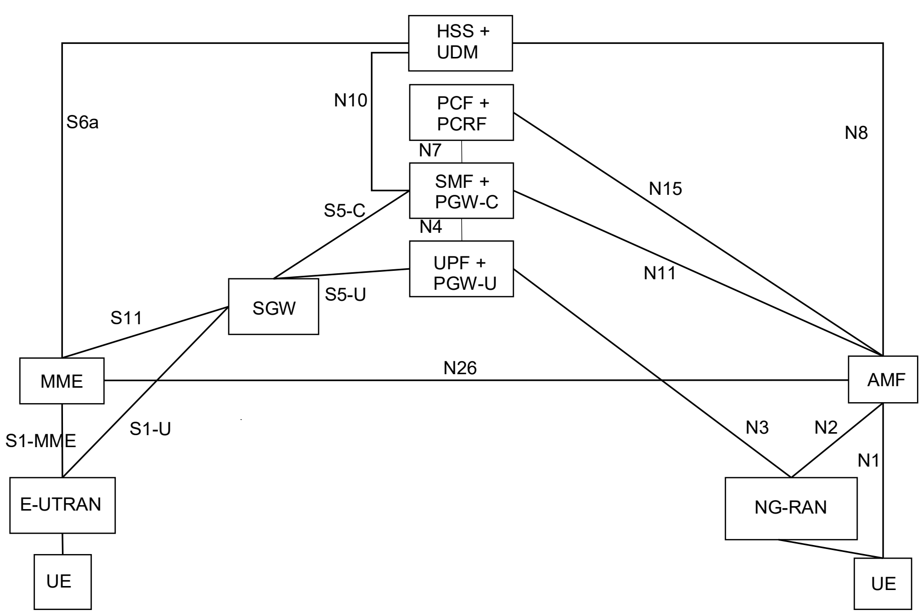

Figure 2.7. LTE and 5G network interconnection (extracted from [3GPP17b]).

2.2 Radio Interface

This section addresses the radio interface of 5G, being based on [3GPP17d], [GWTZ17], [MMMA17] and [3GPP17c].

Officially there is no standardisation at this matter, but there is a lot of aspects that are already decided. This section discusses the relevant areas of the air interface needed to this thesis, which are: spectrum, multiple access, frame structure, coding and modulation, Figure 2.8.

To meet the requirements of the new network and being able to connect more devices, 5G will explore low and high frequencies, meaning that frequencies below and above 6 GHz are going to be used, to have a larger spectrum.

To use the high frequencies spectrum, millimetre waves are used, which have more attenuation thus less range than the lower frequencies. So, the new Radio Access Network is divided between macro and micro cells that handle low and high frequencies respectively, Figure 2.9. Since higher frequencies have a higher attenuation than lower ones, there are more micro cells than macro ones. The bandwidths that are being developed in Europe are the 3.4-3.8 GHz and 26-28 GHz ranges.

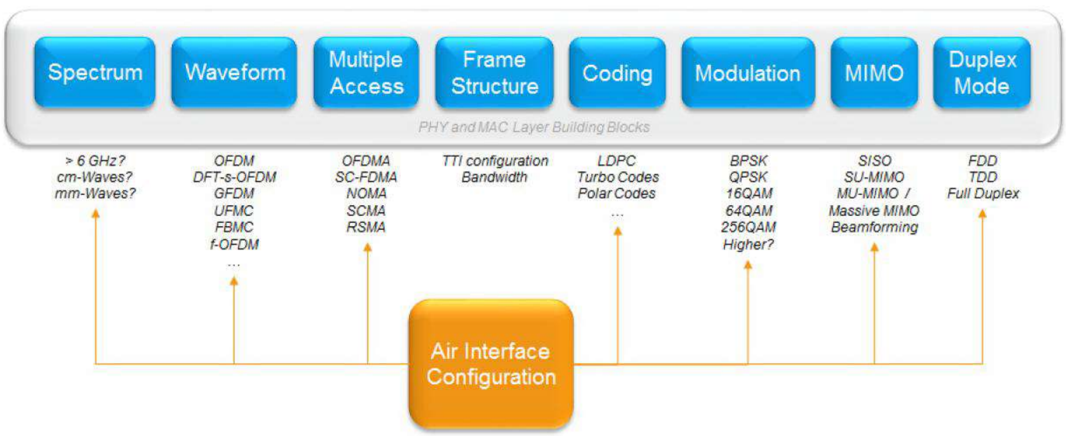

Figure 2.8. 5G Physical and MAC layer building blocks (extracted from [RoSc16]).

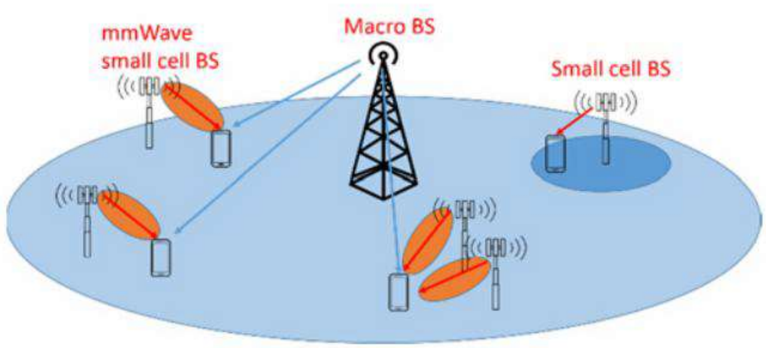

Figure 2.9. Macro and micro cells (extracted from [MMMA17]).

A key feature of the 5G technology is the New Radio (NR) that introduces a new concept for the air interface harmonisation. The NR allows multiple numerologies in the same bandwidth applying multiple subcarrier spaces (SCS). This way, in the same bandwidth one can use different carrier frequencies (Δf) to provide multiple services as shown in Figure 2.10.

The NR supports the multiple OFDM (Orthogonal Frequency Division Multiplexer) numerologies presented in Table 2.1 that can have 5 configurations, and all of them as a normal cyclic prefix (CP), expect configuration 2 that can also handle extend CP. The numerologies follow the reference of $\Delta f_{ref} = 15\ \mathrm{kHz}$ multiplied by a factor of 2^{μ}, with μ being an integer. The sampling time is:

$$T_{s[\mathrm{s}]} = \frac{1}{\Delta f_{\max[\mathrm{Hz}]} \cdot N_f} \tag{2.1}$$

where:

- Δf_{max} is the maximum subcarrier frequency 480 kHz;
- N_f is the maximum number of carrier frequencies which is 4096.

Figure 2.11 illustrates what numerologies should be used at different bandwidths and cell sizes for the latency that is to be achieved.

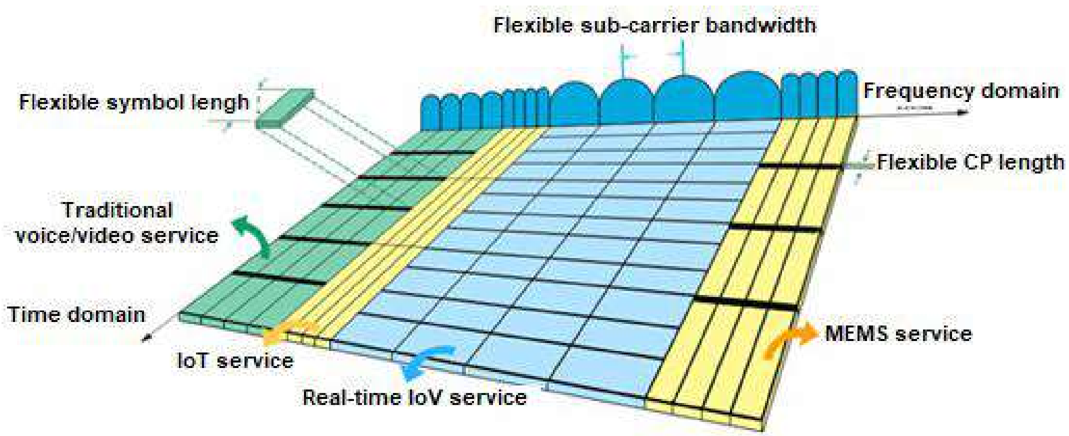

Figure 2.10. Multiple services with different numerologies (extracted from [Dong16]).

Table 2.1. Supported transmission numerologies (adapted from [3GPP17c])

μ	$\Delta f = 2^{\mu} \cdot 15[\mathrm{kHz}]$	Cyclic prefix
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal

The latency intended to be achieved is directly related to the size of the cell, so to achieve very low latencies the connection between user and base station should be with micro ones. As it can be observed in Figure 2.11 at lower bandwidths one useds 3 different SCSs, 15, 30 and 60 kHz that should be used depending on the service provided to the user. For users at high speed, higher SCSs are used, because of the Doppler Effect. For very low latencies connections, the Transmission Time Interval (TTI) needs to be low, thus, higher SCSs are used.

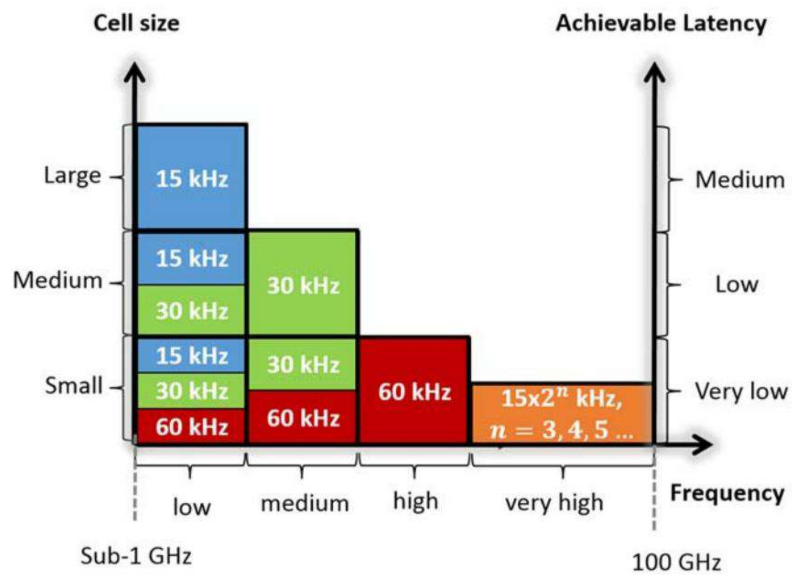

Figure 2.11. Usage of multiple numerologies (extracted from [MMMA17]).

To support multiple numerologies within the same carrier bandwidth, there are two approaches that can be considered: Frequency Division Multiplexer (FDM) and Time Division Multiplexer (TDM). The FDM approach allows more flexibility in scheduling UEs with different numerologies. Though when different ones are used in adjacent frequency resources at the same time, mutual Inter-Numerology Interference (INI) is introduced between them, due to the violation of orthogonality in adjacent subcarriers of different numerologies. On the other hand, in TDM there is no INI since each Transmission Time Interval (TTI) has a single numerology. Therefore, only filtering and/or windowing are required for this approach. The down side of using TDM is that it would restrict the scheduling flexibility of the UEs to the time unit of a TTI, which impacts on the latency of the system.

To overcome the INI problem and respect the resource grid, an offset of $2^n \Delta f_0$ is applied to a certain n numerology. This way the orthogonality is maintained within the same bandwidth.

An example of the frame structure is shown in Figure 2.12 where the agreed specifications state that the Radio Frame keeps being 10 ms so that some services can be compatible with LTE and 5G. It consists of 10 subframes, each one with a duration of 1ms, but for different numerologies the number of slots inside this is one can vary (Tables 2.2 and 2.3). Figure 2.12 shows an example for the numerology with SCS of 15 KHz. The number of OFDM symbols can change, depending on the subcarrier spacing and CP used. For a certain numerology it is specified Table 2.2 and Table 2.3 the number of OFDM symbols per slot (N_{symb}^{slot}), slots per frame ($N_{slot}^{frame,\mu}$) and slots per subframe for a certain cyclic prefix ($N_{slot}^{subframe,\mu}$).

The allocation of the resource grid to the NR is similar to the LTE one, but their physical dimension varies depending on the numerology used. The number of subcarriers per Physical Resource Block

(PRB) is always the same despite the numerology used and it is equal to 12. So, for each numerology there is a resource grid of $N_{RB,x}^{\mu} \cdot N_{sc}^{RB}$ subcarriers and $N_{symb}^{subframe,\mu}$ OFDM symbols. The maximum number of resource blocks, $N_{RB,x}^{max,\mu}$, for a certain numerology for a given link, x, Downlink or Uplink is shown in Table 2.4. Regarding the bandwidths available to transmit information from the BS to the UE, they vary for different numerologies and the allocation of PRB is done by following Table 2.5, where the minimum guard band between each user is given in Table 2.6.

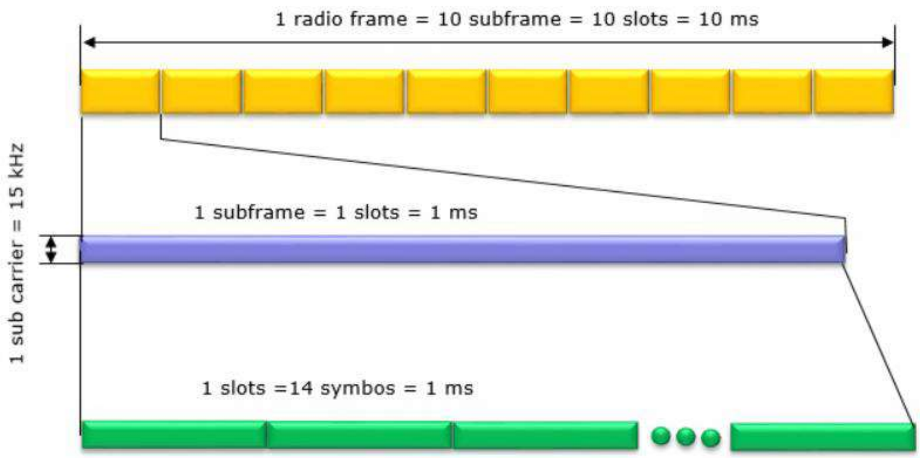

Figure 2.12. Frame Structure of NR (extracted from [Shar17]).

The channel bandwidths are at least 100 MHz wide and can go until 500MHz. To provide a better spectrum efficiency, filtering/windowing techniques are used. The waveform candidates of the radio interface of the 5G technology are CP-OFDM, W-OFDM and f-OFDM. The Out-of-Band Emission (OOBE) is also a factor that increases the INI, so in the presence of mixed numerologies the f-OFDM is a better choice.

Table 2.2.Number of OFDM symbols per slot, slots per frame, and slots per subframe for normal cyclic prefix (adapted from [3GPP17c]).

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16
5	14	320	32

Table 2.3.Number of OFDM symbols per slot, slots per frame, and slots per subframe for extended cyclic prefix (adapted from [3GPP17c]).

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
2	12	40	4

The modulation schemes that are going to be supported are QPSK, 16QAM, 64QAM and 256QAM, with code rates that can range between 1/3 to 8/9. At least a code rate of 8/9 is supported for the 20Gbps decoder information throughput.

Table 2.4.Minimum and maximum number of resource blocks (adapted from [3GPP17c]).

μ	$N_{RB,DL}^{min,\mu}$	$N_{RB,DL}^{max,\mu}$	$N_{RB,UL}^{min,\mu}$	$N_{RB,UL}^{max,\mu}$
0	20	275	20	275
1	20	275	20	275
2	20	275	20	275
3	20	275	20	275
4	20	138	20	138

Table 2.5. Maximum transmission bandwidth configuration N_{RB} (adapted from [3GPP18])

SCS (kHz)	20MHz	50MHz	100MHz
	N_{RB}	N_{RB}	N_{RB}
15	106	270	N/A
30	51	133	273
60	24	65	135

Table 2.6. Minimum guard band in kHz for each UE channel bandwidth and SCS (adapted from [3GPP18])

SCS (kHz)	20MHz	50MHz	100MHz
15	452.5	692.5	N/A
30	805	1045	845
60	1330	1570	1370

2.3 Coverage and Capacity

This section is based on [Alco17] and [Pire15]. It addresses to the analysis of the parameters that affect coverage and capacity which are directly correlated with the data rate throughput, which is influenced by the bandwidth or number of RB instantaneously allocated, channel encoding, number of transmit antennas with MIMO operation, control and signalling overhead, among others.

The estimation of coverage and the evaluation of capacity are important to evaluate the requirements of a certain area according to its geographical parameters, traffic density, frequency used in this zone and bandwidth allocated. To estimate the coverage of a base station, the Signal to Interference plus Noise Ratio level, SINR, at the receiver is used as the measure to calculate the maximum acceptable path loss for a connection. Thus, the SINR together with the path loss of a suitable propagation model, translate the maximum range of a base station the SINR being a key indicator for the coverage of a network, directly relating the throughput reached at a certain cell position.

Planning the capacity of a cell is important to ensure a minimum level of QoS. So, to plan the capacity of a cell, first, it is necessary to know the resources for a certain UE that guarantee a minimum throughput, which is determined by the service that the UE intends. In this way, knowing the size of the cell, i.e. the number of total resources and the throughput for each UE, the total capacity is calculated.

The theoretical throughput for a UE can be obtained as follows, based on [Carr11]. The total throughput is distributed along all UEs connected to the base station. The resources allocated to each user are given by:

$$N_{RB}^{u} = \left\lfloor \frac{N_{RB}}{N_u} \right\rfloor \tag{2.2}$$

where:

- N_{RB}: Total number of resource blocks (RB);
- N_u: Total number of users in the system.

The theoretical throughput for a UE in the downlink DL can be obtained as follows:

$$R_{b,teo[\mathrm{Mbps}]} = \left\lfloor \frac{N_{SC}^{RB} \cdot N_{RB}^{u} \cdot N_{symb}^{SF} \cdot \log_2(m)_{[\mathrm{bits/symbol}]} \cdot N_{streams}}{T_{SF[\mathrm{s}]}} \right\rfloor \tag{2.3}$$

where:

- N_{SC}^{RB}: Number of subcarriers per RB, in 5G it is 12 for all numerologies;
- N_{RB}^{u}: Number of RB per user;
- N_{symb}^{SF}: Number of symbols per sub-frame (14 for normal CP or 12 for extended CP);
- m: Order of modulation;
- $N_{streams}$: Number of streams, in case of MIMO (2x2 MIMO means the number of streams is 2);
- $T_{SF[\mathrm{s}]}$: Sub-frame period, 1ms.

One can see through (2.3) that the theoretical throughput of a user derives directly from parameters such as modulation, MIMO configuration, CP size and number of blocks allocated. However, it should be noted that a user throughput can also be affected by other factors, such as channel overhead by control and synchronisation signals.

Combining (2.2) and (2.3), the total number of users, that the system can serve is:

$$N_u = \left\lfloor \frac{N_{SC}^{RB} \cdot N_{RB} \cdot N_{symb}^{SF} \cdot \log_2(m)_{[\mathrm{bits/symbol}]} \cdot N_{streams}}{T_{SF[\mathrm{s}]} \cdot R_{b,teo[\mathrm{Mbit/s}]}} \right\rfloor \tag{2.4}$$

On the other hand, the total number of users that a cell should cover for a certain radius is:

$$N_{u,cell\,[\mathrm{users}]} = \eta_{[\mathrm{users/km^2}]} \cdot S_{[\mathrm{km^2}]} \tag{2.5}$$

where:

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

The theoretical calculation of cell coverage radius is obtained from the combination of the link budget expression with an adequate environment propagation model for path loss, and can be calculated by:

$$R_{[\mathrm{km}]} = 10^{\frac{P_{t[\mathrm{dBm}]}+G_{t[\mathrm{dBi}]}-P_{r,\min[\mathrm{dBm}]}+G_{r[\mathrm{dBi}]}-L_{p,ref[\mathrm{dB}]}}{10 \cdot a_{pd}}} \tag{2.6}$$

where:

- $P_{t[\mathrm{dBm}]}$: Power fed to the antenna;
- $G_{t[\mathrm{dBi}]}$: Gain of the transmitting antenna;
- $P_{r,\min[\mathrm{dBm}]}$: Power sensitivity at the receiver antenna;
- $G_{r[\mathrm{dBi}]}$: Gain of the receiving antenna;
- $L_{p,ref[\mathrm{dB}]}$: Reference path loss;
- a_{pd}: Average power decay.

Interference may cause degradation of the received signal and consequently cause throughput reduction. In this way the interference reduces the capacity of the network and makes the throughput received by the users not enough for the services wanted, especially in cell-edge users. Therefore, the increase in interference causes degradation of the cell coverage, reducing its radius and data rates. Transmission speeds are larger for higher SINR, as well as the modulation order. Low modulation orders are less susceptible to transmission errors, however, they reach lower speeds. So, larger modulation orders are used to achieve large velocities as can be seen in Figure 2.13. The code rate is used according to the channel quality. A high code rate is used for a high SINR, whereas for a low-quality channel a low code rate is used.

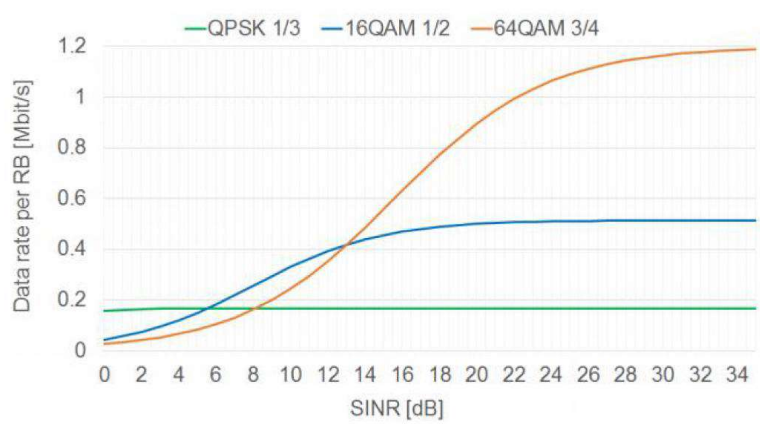

Figure 2.13. Relation between the SINR and Throughput per RB in DL, for different modulation schemes and coding rates (extracted from [Pire15]).

2.4 Services and Applications

The 5G network enables new services, this section being based on [IMTV15] and [Dong16]. They can be categorised in 3 categories: enhanced Mobile Broadband (eMBB), Massive Machine Type

Communication (mMTC) and Ultra-reliable and Low Latency Communications (UrLLC). Figure 2.14 shows the general view of these services: the eMBB category summarises the services provided through internet access on mobile devices, like ordinary apps for smartphones or a simple search on the web, the mMTC category enables the connection of multiple devices providing services for the Internet of Things (IoT) as example or for implementing some smart city technologies, while the UrLLC allows services with low latency like augmented reality, self-driving cars, etc.

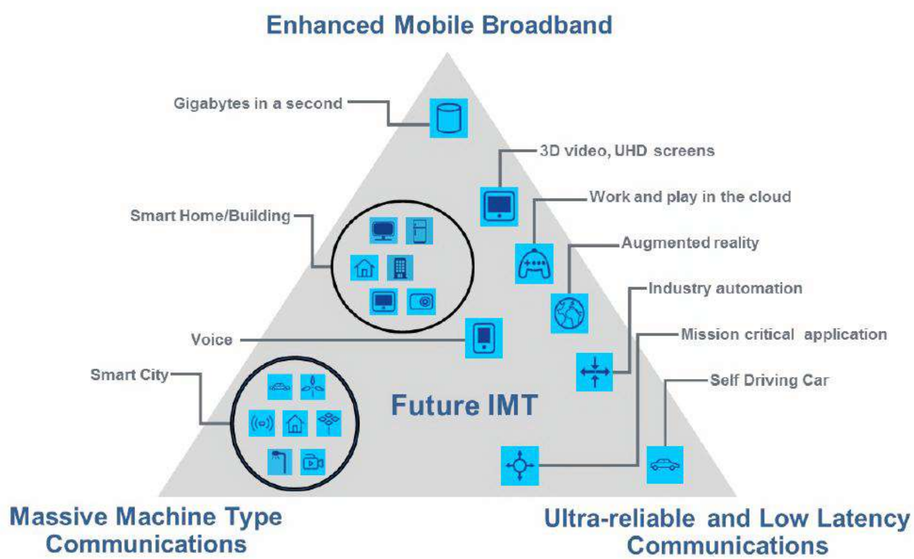

Figure 2.14. Services categories for 5G (extracted from [IMTV15]).

The different services imply requirements for their respective performance. For each category the importance and priority of each parameter is represented in Figure 2.15, where in mMTC, the main aspect is Connection Density since it wants to connect multiple devices in networks like IoT, and the Network Energy Efficiency parameter is also important since the batteries of the devices need to be longer. The UrLLC provides priority to the Latency and Mobility parameter, enabling faster connections between devices with high speed. The eMBB is the most complete category giving high importance to the general of aspects providing good coverage, capacity and throughput to most of the devices.

5th generation networks bring a few improvements of the 4th one, a brief description of their differences being presented in Figure 2.16, where IMT-2020 represents the 5G network and IMT-Advanced the LTE one. One can see that the peak data rates are much higher in the 5th generation than in the 4th one, being 20 Gbit/s against 1 Gbit/s. Even the user experienced data rate is 10 times higher. The spectrum efficiency is 3 times better than the LTE one. As for the mobility of the UE, LTE supports communications up to 350 km/h while 5G can go up to 500 km/h. Regarding latency, LTE can have a minimum of 10 ms, while 5G enables new services going down to 1 ms. It also brings advantages concerning device density, since it can handle 10 times more devices per km^2 and as for energy efficiency it is 100 times better than LTE.

The services used in the 5G network have different transmission rates depending on their purpose. In Table 2.7 these services are broken down, where voice and music services require only a few kbps for minimal QoS, while streaming, web browsing and file transfer services require data rates up to Mbps. These data rates influence the quality of service. Voice services for example only require 8 to 64 kbps and music services need 128 to 320 kbps, [AnJa15].

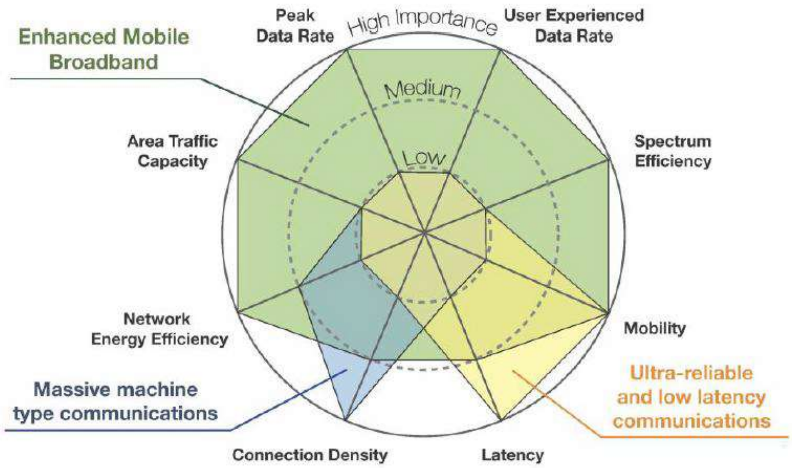

Figure 2.15. Importance of key performance indicator for each category of 5G applications (extracted from [IMTV15]).

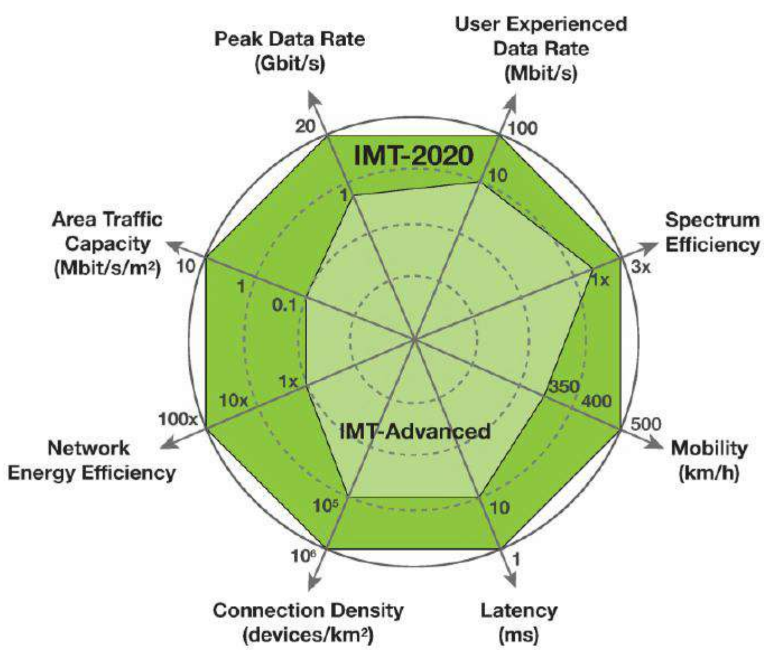

Figure 2.16. Comparison of Key Performance Indicators for LTE (IMT-Advanced) and 5G (IMT-2020) (extracted from [IMTV15]).

As for streaming services, they need higher transmission speeds in order to ensure better quality, so while watching videos on the phone with a minimum QoS requires 2.5 Mbps, watching HD videos requires 5 Mbps and Ultra HD requires 25 Mbps, [Netf18]. Services such as Web Browsing, FTP, Email and P2P do not require any specific QoS parameters because their required transmission rate fluctuates greatly depending on their content. For virtual (VR) and augmented reality (AR), according to [Mush17] and [Qual17] the transmission rates vary between 25 and 600 Mbps, with this minimum value the image quality is low and the maximum value is achieved retinal quality.

Table 2.7. Services characteristics (adapted from [Alco17])

Service	Service Class	Minimum Throughput [Mbps]	Maximum Throughput [Mbps]
Chat	Background	0.064	0.384
EMAIL	Background	1	-
VoIP	Conversational	0.032	0.064
FTP	Interactive	1	-
P2P	Interactive	1	-
Web Browsing	Interactive	1	-
Streaming	Streaming	1	25
VR & AR	Streaming	25	600

2.5 State of the Art

This section presents the work performed by other authors similar to the dimensioning of coverage and capacity of 5G networks. For each project one explaines their methodologies, conclusions and results obtained with their respective simulations.

The Metis European project, [METI17], evaluates the harmonisation interface for radio access in 5G networks. This group has developed two projects related to the 5G network. The second one, METIS-II, develops the overall 5G radio access network design and provides the technical enablers needed for an efficient integration and use of the various 5G technologies and components currently developed. METIS-II provides the 5G collaboration framework within 5G-PPP for a common evaluation of 5G radio access network concepts. To this end, they made a simulation to evaluate the impact of different waveforms and other parameters to provide multiple services. These multiple services vary between the key ones studied in the 5G deployment, like mMTC, uMTC and eMBB. The result of this project is a simulation for different scenarios using macro and micro cells to provide the 5G services in an urban environment.

The mmMagic group, [MMMA17], is part of one of the 5G-PPP groups, studies the use of millimetre waves for implementation on communication networks. It studies the frequency band 6-100 GHz, providing important aspects about their feasibility and technical implementation. This project also provides major enhancements, e.g. regarding ground reflection and blockage effects, spatial consistency, and outside to inside penetration loss modelling. They made simulations and outdoor experiences (28 GHz, 500MHz bandwidth, CP-OFDM and DFT-OFDM) to prove the concept and what aspects should be worked on.

5GTN, [5GTN17], is a Finnish research group based on the University of Oulu. They provide a 5G test network to experiment different services that is meant to be used on the next generation telecommunication network. To this purpose, they provide state of the art equipment to test 5G services mainly on the IoT kind. This project focus on the use of millimetre waves to cover a certain area, implementing micro cells. 5GTN is testing multiple radio access techniques to measure the QoS of the multiple services that 5G networks will provide. They also provide data analytics infrastructure to best analyse results.

MiWEBA, [MiWE17], is a Dutch research group that studies the use of millimetre waves to use in Access Radio, Fronthaul and Backhaul. This project has made tests in order to implement millimetre waves in different scenarios. On the subject of this thesis, this group has analysed the use of micro cells to implement the radio access at dense areas being indoors or outdoors. This way, they are capable of increasing capacity of the network by 1000 times.

Fantastic 5G, [FA5G17], is a project that studies the flexible air interface for scalable service delivery within wireless communication networks 5G. They made simulations to contribute to the standardisation of 5G requirements, providing results of the Key Indicators that need to be achieved to improve capacity, reliability, latency and efficiency of the new network. This project only studies the spectrum below 6 GHz and uses as reference the E-UTRAN of the LTE network for the general simulations, e.g. the study of interference, capacity and coverage.

In the Sungkyunkwan University in South Korea, [KSOP14], a group of researchers did a project that analyses the capacity and coverage of millimetre waves in the 27 GHz spectrum. They build a 3D model of the city of Daejeon with an area of 1 km^2. They simulate in the language of C++ the UE experience and considering a certain minimum SINR, they made a model for the system capacity and coverage. These results impact mainly on the antenna structure level, contributing with information regarding the architecture and structure of the antennas for the 5G network on high frequency bands.

At the Polytechnic University of New York, [MDZA16], a group of researchers has done a project that studies the implementation of millimetre waves at 28 GHz in the 5G network. To study their impact, they used an open source software, NS-3, which simulates the parameters of the 5G network with a bandwidth of 1 GHz. The results allow to compare the quality of the signal in LoS and in NLoS comparing the intensity of the SINR and the value of throughput.

Qualcomm Network, [Qual18], simulates a non-standalone 5G NR network in Frankfurt, Germany. They put together a network combining macro and small cell base stations with the new 5G NR cell sites colocated with existing LTE ones. The simulation includes the modulation of radio frequencies capabilities and the use of massive MIMO utilising up to 256 antennas. To simulate the propagation losses between the base stations and the devices, a detailed 3D urban macro cell and micro cell models were used, to accurately depict the real-world performance like path loss and shadowing. This simulation operated on a 100 MHz bandwidth at a frequency band of 3.5 GHz underlying on a Gigabit LTE network. The environment of the simulation counted with 13000 devices where half of them were indoors and the rest were outdoors. By measuring some of the KPIs of the network, this study concludes that the median burst rate of 4G LTE devices is twice using an LTE plus 5G NR network instead of an LTE one alone. Also, the downlink capacity of the cell increased 4.8 times considering new services like downloading a High Definition (HD) movie, 360-degree video streaming and mobile apps (social network feeds).

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 and explanation of the models used in this thesis along with its mathematical formulation.

3.1.1 Dimensioning Process

The network dimensioning process consists of analysing the necessary resources to satisfy the minimum requirements of the services that are intended to be provided in a certain area. In this way, the base station coverage area and respective capacity are determined with this process, so that the quality of the service is guaranteed. Thus, network dimensioning must consider various factors that influences the traffic load that must be supported and distribute the resources accordingly. This dimensioning process should not only be done to provide efficient services but should also be performed to maximise the combination of all requirements to optimise the network in terms of cost and efficiency.

The execution of the main phases of the network dimensioning can be divided into two planes: coverage- and capacity-plan. Before these plans are executed, the necessary inputs are obtained for the dimensioning and then these two plans are sequentially executed, obtaining at last the desired outputs. The execution of these phases is indicated in Figure 3.1.

First, the inputs used by the dimensioning process are defined. Among them, there are the inputs of the user, the network and the scenario in question. These inputs are specified in detail in Section 3.1.2.

As for the dimensioning process, the first approach is to determine the coverage planning limit, i.e. to calculate the maximum radius that the cell can achieve in a given scenario to obtain a link between the BS and the UE, even if the minimum service requirements are not meet. Thus, the site coverage area is determined, which is used in the next phase, in the capacity plan, which begins by the population density calculation.

In the next phase, the possibility of serving the desired services with the minimum requirements inside the site, using the base station resources is analysed. For this analysis a specific profile is used for each user. If the coverage plan respects the limits imposed by the network and the users then the outputs are extracted according to the coverage plan, otherwise a second approach is used. The outputs are defined in more detail in Section 3.1.2.

In a second approach, since the coverage plan does not respect the limits imposed, a capacity plan is used. This plan considers the total traffic load imposed by the users and adjusts the size of the cell according to the available resources. The coverage and capacity plans are explained in the following Sections 3.1.3 and 3.1.4, respectively.

In this thesis, the study of a non-standalone network is done, therefore, the developed model intends to verify if the already LTE network allows to evolve to a 5G network using the same positioning of the base stations. Thus, this model analyses the use of the 3.5 GHz frequency in DL and the frequencies

1800 MHz and 800 MHz for UL. The use of different frequencies is due to the optimization of the cost-efficiency of the network, since UL achieves a lower throughput compared to DL for the same distance.

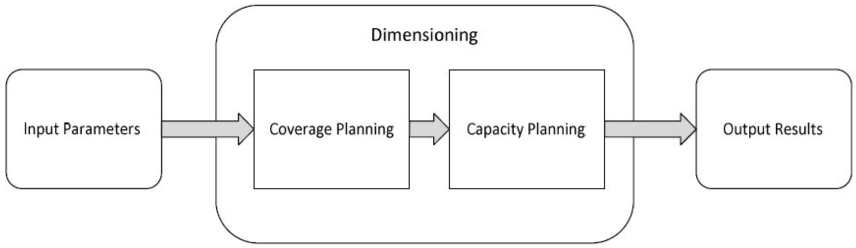

Figure 3.1. Model dimensioning (extracted from [Alco17]).

3.1.2 Inputs and Outputs of 5G Dimensioning

The input parameters of the dimensioning process of a 5G network are given by the user, scenario and network. In network dimensioning there are many parameters that can be grouped into groups that affect the quality, coverage, and capacity of the cell. However, these groups are correlated with each other, and thus, one parameter can have impact on more than one group in an indirect way.

In quality, the minimum throughput achieved at cell edge in DL and UL is the parameter that defines the minimum quality level. With this parameter the required SINR is computed, which in turn affects the coverage of the cell and it is also the reference of the investment by an operator to offer a minimum service.

For coverage, Radio Link Budget parameters play a key role such as transmitter power, number/type of antennas and numerology used. In the LTE network, a single numerology is available, while in the 5G network there is the possibility of using others. Also included in this group are the propagation models along with their respective parameters with the conventional gains and losses of the system. Some margins considered in the system also influence the coverage of a site, such as the handover margin and the probability of a user being indoor or outdoor.

In capacity, the inputs are the number of subscribers, the services provided, the amount of use by each user and the amount of available bandwidth.

The main dimension output parameter is the radius of the cell (3.8) in which the input parameters are satisfied. In addition to this parameter other indicators can also be computed from the dimensioning process, like the number of served users (3.11), the average traffic inside the cell (3.29) and the percentage of use of each service (3.30).

3.1.3 Coverage Planning

The coverage plan gives an assessment of the maximum area covered by a BS. Therefore, the maximum distance in DL and UL, for which a connection between the UE and the BS is established, according to the minimum quality parameter for this simulation is calculated. In Section 3.1.2, the quality of the connection is defined, and it must guarantee at least a certain throughput. In order to determine the maximum coverage area in both DL and UL, the coverage plan follows a sequence of steps summarised in Figure 3.2.

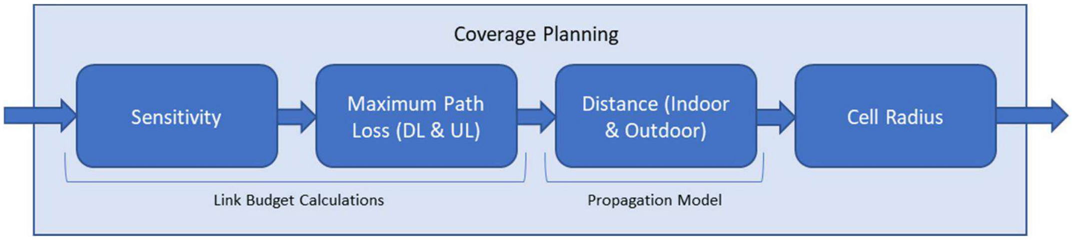

Figure 3.2. Coverage planning workflow

The first step is to process the Link Budget parameters, in which all the gains and losses of the connection between the transmitter and the receiver are defined. In order to compute the maximum path loss of the link, whether is it downlink or uplink, the sensitivity of the receiver considering a connection between the UE at cell edge and BS needs to be calculated. This sensitivity varies mainly in the scope of the study of this thesis with the reference throughput obtainable at cell edge or with the RB bandwidth. The quality parameter enters in this process, so that the minimum received power represents a sufficient SINR to reach the minimum quality requirement. This requirement represents the quality level of 5G services. Thus, the sensitivity is computed by the following expression:

$$P_{Rx,min_{[\mathrm{dBm}]}} = -174 + 10 \cdot \log_{10}\left(B_{RB_{[\mathrm{Hz}]}}\right) + F_{N_{[\mathrm{dB}]}} + \gamma_{[\mathrm{dB}]} \tag{3.1}$$

where:

- B_{RB}: bandwidth per RB, which depends on the SCS;
- F_N: noise figure of gNB receiver;
- γ: SINR requirement for the UL or DL traffic channel.

The transmission power is given by the system along with the gains of both antennas, transmitter and receptor. So, having all gains and powers of the link, to determine the maximum distance in the next phase, with the Link Budget the maximum path loss that each link in DL and UL can have is calculated with (3.2). According to [Corr16], the power available at the receiving antenna can be expressed by:

$$P_{r_{[\mathrm{dBm}]}} = P_{t_{[\mathrm{dBm}]}} + G_{t_{[\mathrm{dBi}]}} + G_{r_{[\mathrm{dBi}]}} - L_{p,total_{[\mathrm{dB}]}} \tag{3.2}$$

where:

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

The antenna gains of the BS depend essentially on the antenna type and the number of sectors, while the UE one depends on the type of device. The expressions for the power transmitted in DL and UL can are (3.3) and (3.4) respectively.

$$P^{DL}_{t[\mathrm{dBm}]} = P_{Tx[\mathrm{dBm}]} - L_{c[\mathrm{dB}]} \tag{3.3}$$

where:

- P^{DL}_t: power fed to the antenna in the DL;
- P_{Tx}: transmitter output power;
- L_c: losses in the cable between the transmitter and the antenna.

$$P^{UL}_{t[\mathrm{dBm}]} = P_{Tx[\mathrm{dBm}]} - L_{u[\mathrm{dB}]} \tag{3.4}$$

where:

- P^{UL}_t: power fed to the antenna in the UL;
- L_u: losses due to the user's body.

For the losses due to the user's body, the services being used need to be considered. If the service being used is voice, then head attenuation is considered, while for other services like data, where the user is using the phone in their hand, the attenuation considered must be only from their hand.

The power at the receiver in DL and UL can be expressed in (3.5) and (3.6) respectively.

$$P^{DL}_{Rx[\mathrm{dBm}]} = P_{r[\mathrm{dBm}]} - L_{u[\mathrm{dB}]} \tag{3.5}$$

where:

P^{DL}_{Rx}: receiver input power at DL.

$$P^{UL}_{Rx[\mathrm{dBm}]} = P_{r[\mathrm{dBm}]} - L_{c[\mathrm{dB}]} \tag{3.6}$$

where:

- P^{UL}_{Rx}: receiver input power at UL.

From the equations above, and taking considerations with interference and TMA gain, the radio link budget equation is expressed by:

$$\begin{aligned} L_{p,max[\mathrm{dB}]} = {} & P_{Tx[\mathrm{dBm}]} - L_{t[\mathrm{dB}]} - P_{Rx,min[\mathrm{dBm}]} - L_{r[\mathrm{dB}]} + G_{t[\mathrm{dBi}]} + G_{r[\mathrm{dBi}]} - I_{m[\mathrm{dB}]} + G_{Tx[\mathrm{dB}]} \\ & + G_{TMA[\mathrm{dB}]} \end{aligned} \tag{3.7}$$

where:

- L_t: losses due to the body of the user in UL ($L_t = L_u$) and from the cables in DL ($L_t = L_c$);
- L_r: losses due to the body of the user in DL ($L_t = L_u$) and from the cables in UL ($L_t = L_c$);
- 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).

The new 5G radio can work with different numerologies, so coverage dimensioning varies depending on the SCS used. In the Link Budget process this parameter directly influences the sensitivity of the receiver (3.1), since the bandwidth of each RB ($B_{RB_{[\mathrm{Hz}]}}$) changes. The greater the numerology, as indicated in Table 2.1, the bandwidth of each RB increases, also increasing the value of the power received. Using a higher numerology slightly decreases the SNR obtained for the same distance with a smaller numerology, however the throughput doubles, thus, achieving higher quality requirements. In this way, with the minimum quality requirements defined, there is an associated coverage plan for each numerology.

In the second phase, once the maximum path loss of the DL and UL connections has been determined, along with the appropriate propagation model, the maximum distance is calculated. For both connections there are different frequencies bands, though, for the 800, 1800 and 3500 MHz bands, the WINNER Plus propagation model is used, which is valid for frequencies between 0.5 GHz and 6 GHz; the distance is computed with (A.4) given the maximum path loss, the model being detailed in Annex A. For each connection two distances are calculated, one for outdoor users and another for those who are indoor.

Finally, in the last phase of the coverage plan, the maximum area covered in each connection is calculated through the distances computed in the previous phase. For each connection, the radius of the cell is defined by the average of the indoor and outdoor distances. For the urban scenario it is considered that 80% of users are indoor and only 20% are outdoors, thus, the cell radius for each DL or UL is given by (3.8).

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, which is 80%;
- $\overline{r_{indoor}}$: maximum indoor radius;
- $p_{out_{[\%]}}$: percentage of outdoor user, which is 20%;
- $\overline{r_{outdoor}}$: maximum outdoor radius.

To represent the coverage area of a cell, one can use a circular representation or a hexagonal one. Both are acceptable designs, and the circular one shows a simple approach where there are areas where there will be overlaps or uncovered gaps, while the hexagonal one fits precisely with the coverage zone of other sites. The area of a cell depends on the configuration of each site, and for a tri-sectorised site, the area is given by:

$$A_{c_{[\mathrm{km}^2]}} = \frac{3}{2} \cdot \sqrt{3} \cdot \overline{r_{cell_{[\mathrm{km}]}}}^2 \tag{3.9}$$

3.1.4 Capacity Planning

After calculating the coverage of a certain cell, an analysis is made of its capacity. If this analysis represents positive results, no changes are made to the initial plan. Otherwise, the radius of the cell is reduced to reach the required capacity levels. After calculating the cell range, the number of users within each cell can be calculated with the following expression:

$$N_{u,cell_{[\text{users}]}} = \left\lceil \eta_{[\text{users/km}^2]} \cdot A_{c_{[\text{km}^2]}} \right\rceil \tag{3.10}$$

where:

- η: user density in the target area;

The network dimensioning process is based on a uniform distribution of users within the coverage area. In this way, the number of users for each modulation corresponds to a percentage of the total number of users calculated in (3.11). The distribution is made by the following expression:

$$N^M_{u,cell_{[\text{users}]}} = \sum_M N^M_{u_{[\text{users}]}} \tag{3.11}$$

where:

- M: are the modulations served in the cell: 4, 16, 64 and 256 QAM;
- N_u^M: is the number of users served by the modulation M given by (3.12), (3.13), (3.14) and (3.15).

$$N^4_{u,cell} = \left\lfloor \frac{R_Q^2 - R_{16}^2}{R_Q^2} \cdot N_{u,cell} \right\rfloor \tag{3.12}$$

where:

- R_Q: cell QPSK radius;
- R_{16}: cell 16-QAM radius.

$$N^{16}_{u,cell} = \left\lfloor \frac{R_{16}^2 - R_{64}^2}{R_Q^2} \cdot N_{u,cell} \right\rfloor \tag{3.13}$$

where:

- R_{64}: cell 64-QAM radius.

$$N^{64}_{u,cell} = \left\lfloor \frac{R_{64}^2 - R_{256}^2}{R_Q^2} \cdot N_{u,cell} \right\rfloor \tag{3.14}$$

where:

- R_{256}: cell 256-QAM radius.

$$N^{256}_{u,cell} = \left\lfloor \frac{R_{256}^2}{R_Q^2} \cdot N_{u,cell} \right\rfloor \tag{3.15}$$

Once users are distributed along the coverage area of the cell for each modulation, the realistic approach would be to assign a specific SNR value to each user within a certain modulation area, based on his position, meaning the user could be close to the center of the BS or far away, or one could be indoor or outdoor. Though, there is no tool or software available to simulate this kind of SNR values, so usually an approach to this problem is to simulate a random SNR value for each user and to distribute them along the cell, and then, run the simulation multiple times to get an average value of the outputs of the simulator. However, since the user distribution is uniform along the cell, this approach could lead to an average value that does not represent the reality, leading to mismatch results. In order to get more controllable results, one considers the SNR value of all users within the same modulation equal, and this value is the average SNR obtainable with one RB at the beginning and ending of the modulation radius. In this way, the throughput served to a user for each modulation is also the average of the throughput achievable with one RB at the beginning and ending of the modulation radius. Since there is no tool that for a certain geographic area, simulates the main spots where it is most probable for a user to use mobile communications, this is an approach that allows to compute average results of what could happen in a certain geographic area taking into considerations main inputs, like urban setting, user density, type of service usage, etc.

The borders of each modulation are stablished when with an inferior modulation is possible to achieve a better throughput, meaning, there is an SNR value, where the throughput of two adjacent modulation are the same, this is the point where the border of these modulations is drawn, Figure 3.3. For each modulation there is an expression that relates the SNR with the corresponding throughput.

To relate the SINR to the throughput, expressions were obtained for the QPSK, 16-, 64- and 256-QAM modulations. The expressions for the QPSK, 16- and 64-QAM modulations were obtained based on [Alco17], which result from the interpolation and extrapolation of the experimental measurements of several manufactures found in [3GPP11]. To obtain an expression for each of the modulations, the logistic function or sigmoid function was used to interpolate the results. The code rate assigned to each of the modulations is the average 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 note that for these modulations the channel mode considered is EPA5.

As for the 256-QAM modulation, an expression was obtained based on [LLPR14]. This study reports that the 256-QAM modulation in its saturation zone has a gain of 23.1% compared to the 64-QAM one, when 0% of impairments are considered in both the receiver and the transmitter.

Also, in [SKYW17] a theoretical comparison of the peak data rates of the modulations used in 5G is made. Within which, the relationship between 64-QAM and 256-QAM modulation is 4/3. This theoretical comparison validates the experimental results obtained in [LLPR14], having a difference of less than 10%.

Thus, to obtain an expression of the data rate against SINR, the data extracted from [LLPR14] are used. To maintain the consistency between expressions, the 256-QAM one was extrapolated from the 64-QAM obtained in [Alco17], with a gain of 23.1% compared to this one. In this modulation the channel model EPA10 is considered and that the code rate used varies from 0.70 to 0.94.

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

$$R_{b[bps]} = \frac{2.34201 \cdot 10^6}{14.0051 + e^{-0.577897 \cdot \rho_{IN}}} \tag{3.16}$$

$$\rho_{IN[dB]} = -\frac{1}{0.577897} \cdot \ln\left(\frac{2.34201 \cdot 10^6}{R_{b[bps]}} - 14.0051\right) \tag{3.17}$$

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

$$R_{b[bps]} = \frac{47613.1}{0.0926275 + e^{-0.295838 \cdot \rho_{IN}}} \tag{3.18}$$

$$\rho_{IN[dB]} = -\frac{1}{0.295838} \cdot \ln\left(\frac{47613.1}{R_{b[bps]}} - 0.0926275\right) \tag{3.19}$$

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

$$R_{b[bps]} = \frac{26405.8}{0.0220186 + e^{-0.24491 \cdot \rho_{IN}}} \tag{3.20}$$

$$\rho_{IN[dB]} = -\frac{1}{0.24491} \cdot \ln\left(\frac{26405.8}{R_{b[bps]}} - 0.0220186\right) \tag{3.21}$$

The expressions for the extrapolation of the 256-QAM considering MIMO 2x2, throughput per RB and the corresponding SINR can be given by:

$$R_{b[bps]} = \frac{26407.1}{0.0178868 + e^{-0.198952 \cdot \rho_{IN}}} \tag{3.22}$$

$$\rho_{IN[dB]} = -\frac{1}{0.198952} \cdot \ln\left(\frac{26407.1}{R_{b[bps]}} - 0.0178868\right) \tag{3.23}$$

For the Coverage Planning, a general formula has to be computed comprising the best modulation for each ρ_{IN}:

$$R_{b[bps]} = \begin{cases} \dfrac{2.34201 \cdot 10^6}{14.0051 + e^{-0.577897 \cdot \rho_{IN[dB]}}}, & -10 < \rho_{IN} \leq 5.56 \\ \dfrac{47613.1}{0.0926275 + e^{-0.295838 \cdot \rho_{IN[dB]}}}, & 5.56 < \rho_{IN} \leq 13.03 \\ \dfrac{26405.8}{0.0220186 + e^{-0.24491 \cdot \rho_{IN[dB]}}}, & 13.03 < \rho_{IN} \leq 25.75 \\ \dfrac{26407.1}{0.0178868 + e^{-0.198952 \cdot \rho_{IN[dB]}}}, & 25.75 < \rho_{IN} \end{cases} \tag{3.24}$$

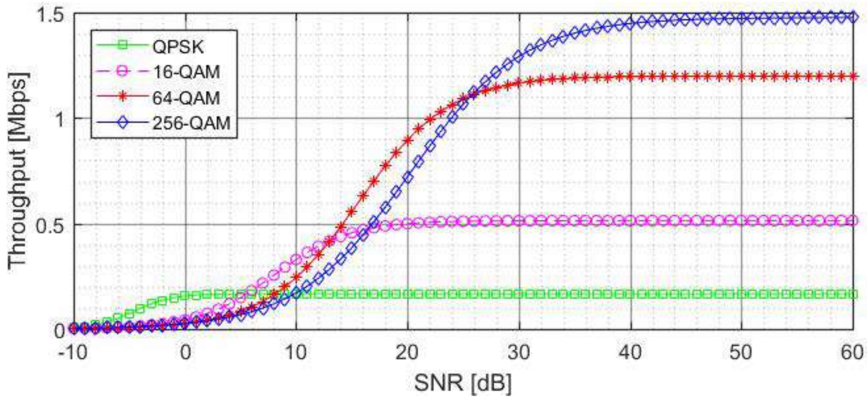

Figure 3.3. Throughput in function of the SNR per RB for a SCS of 15kHz.

User traffic demands, and their respective trend are important factors affecting capacity requirements. The distribution of traffic through the cells is not uniform, so there are cells in which traffic demand is lower than in others. And there are also peaks of the day when the demand for certain services are much higher than the rest of the day. These factors are taken into account when estimating the number of users that a single gNB can handle and also what is the average traffic load that it can handle.

This way, different types of traffic are important to be aware of, i.e. the various services that can be used and their parameters, as well as the number of active users for a specific service. Information about these variables can be estimated according to the fashions of certain services. Thus, three different types of traffic are considered: Residential, Office and Mixed. As such, a profile is drawn for each user and this is considered to estimate the maximum permissible network load. In this way, according to the profiles of the three types of traffic, the total network load is determined. The amount of radio resources to support estimated traffic is then estimated.

The available bandwidth is important for the capacity plan because the capacity of the BS is directly related, i.e. the higher the bandwidth the higher the traffic capacity that is supported. Thus, to evaluate the capacity of each band, it is important to understand the average number of RBs required by each user for a specific service.

To support a certain service on a base station, it is necessary to know the amount of resources for a given service, to satisfy the users with an average throughput. Given the profile of a user, the average throughput of a certain service is characterised, dividing by the average throughput that a single RB can provide for a certain modulation, the number of RBs allocated in a BS for this user is determined:

$$\overline{N_{RB,user,s}} = \left\lceil \frac{\overline{R_{b,user,s}}_{[\mathrm{Mbps}]}}{\overline{R_{b,RB}^{M}}_{[\mathrm{Mbps}]}} \right\rceil \tag{3.25}$$

where:

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

As the average throughput for each service and user are different, the total number of RBs for a modulation is:

$$\overline{N_{RB}^{M}} = \left\lceil \sum_{service} \overline{N_{RB,user,s}} \cdot N_{u,cell}^{M} \cdot P_{u,s_{[\%]}} \right\rceil \tag{3.26}$$

where:

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

Lastly, the total number of RB in a single cell can be obtained by:

$$\overline{N_{RB,required}^{M}} = \sum_{M} \overline{N_{RB}^{M}} \tag{3.27}$$

where:

- $\overline{N_{RB}^{M}}$: number of RBs required in modulation M;

With the variable $\overline{N_{RB,required}}$, it is possible to determine if the system is coverage- or capacity-limited. If $\overline{N_{RB,required}}$ is bigger than the total number of RBs available in a single cell, the system is capacity-limited, and the average throughput is decreased, meaning that each user will have less resources available. On the opposite, the system is coverage-limited and in this case, there is no need to change the resources of the BS for QoS purposes. On the other hand, from an economical point of view the resources might be reduced.

To summarise the overload of a cell, it can be broadly defined with the expression (3.28), where the required amount of resources to satisfy the requested traffic is divided by the total number of resources available in a cell. If this value is greater than 100 %, the existence of overload is indicated, on the other hand, if the value is less than 100 % then there is no overload, thus, the load ratio a cell is determined as follows:

$$\eta_{cell[\%]} = \frac{\overline{N_{RB,required}}}{N_{RB,cell}} \cdot 100 \tag{3.28}$$

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.

The following expression indicates the average consumption of all users in all services, meaning, the total average throughput of a cell can be obtained by:

$$\overline{R_{b,cell_{[\mathrm{Mbps}]}}} = \sum_{service} \overline{R_{b,user,s_{[\mathrm{Mbps}]}}} \cdot N_{u,s_{[\mathrm{users}]}} \tag{3.29}$$

where:

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

To detail the information on the traffic of a single cell, the percentage of traffic for each service with the following expression can be indicated:

$$p_{traffic,s_{[\%]}} = \frac{\overline{R_{b,user,s}} \cdot N_{u,s} \cdot \eta_{cell}}{\overline{R_{b,cell_{[\mathrm{Mbps}]}}}} \tag{3.30}$$

The percentage of active served users is given as follows:

$$\eta_{u,cell_{[\%]}} = \frac{N_{u,cell_{[\mathrm{users}]}}}{N^{M}_{u,cell_{[\mathrm{users}]}}} \tag{3.31}$$

where:

- $N_{u,cell}$: number of active users in the cell.

When the cell is overloaded, and every user is served by the minimum QoS in all services provided, users start being removed. Therefore, the number of active users' decreases being different from the total number of users that can be initially served.

The workflow of the capacity planning algorithm is described in Figure 3.4, where one can observe that once the users of the cell have been generated according to their traffic model, a comparison is made between the resources needed to satisfy the requirements of all users and the maximum resources available in the cell. If no more resources are needed, the simulator follows directly to the output of the network indicators, however, on the opposite, a two cell adjustment processes are performed. The first one, Cell Load Adjustment, reduces users' QoS and removes the ones needed to meet the resource limits imposed by the cell, in the second process, Cell Radius Calculation, the new radius of the cell is determined if users have been removed for lack of sufficient capacity.

In the Cell Load Adjustment process, a complex algorithm is followed to fit the cell correctly with her capacity limitation. This algorithm is summarised in Figure 3.5, in which the cell adjustment begins by being done at the edge, because the edge of the cell is served with the QPSK modulation, which results in a larger area covered compared to the other modulations served in the cell. In this way, this modulation covers a large percentage of users and consumes many resources, since this modulation is the one with a lower maximum throughput. In order to impose a maximum utilised resource rate by the edge of the cell or a maximum throughput, then the load adjustment is done if there is Cell Edge Overload:

$$\eta_{cell\ edge} = \frac{R_{b,cell\ edge_{[\mathrm{Mbps}]}}}{\overline{R_{b,required_{[\mathrm{Mbps}]}}}} \tag{3.32}$$

where:

- $R_{b,cell\ edge_{[\mathrm{Mbps}]}}$: total throughput available at cell edge;
- $\overline{R_{b,required_{[\mathrm{Mbps}]}}}$: total average throughput given by (3.29), but applied only to cell edge users.

If this parameter is less than 1 then, the algorithm continues to adjust the traffic of the edge of the cell, otherwise as the algorithm in the Figure 3.5 indicates, if there is still overload of the total load of the cell, the global traffic adjustment that involves all users of the modulations used is made.

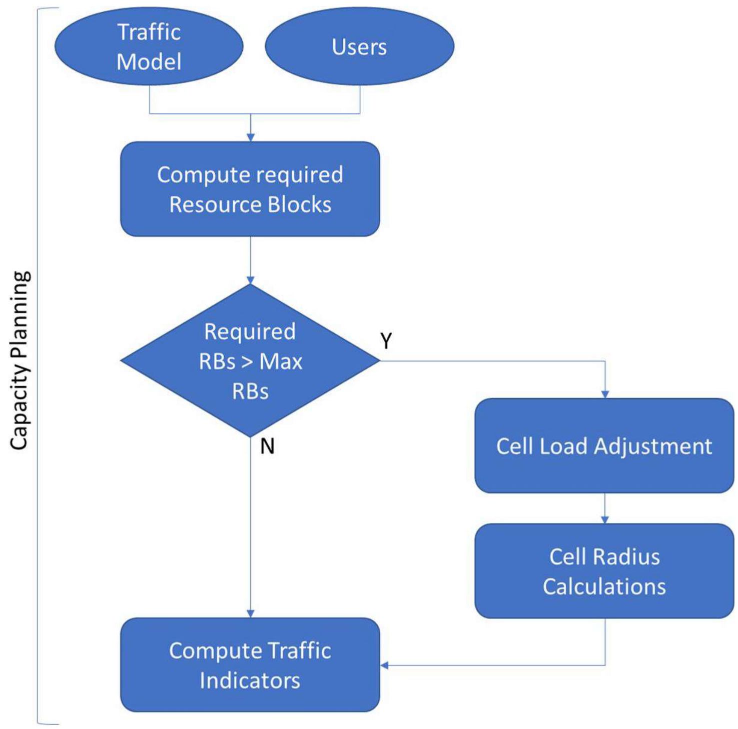

Figure 3.4. Workflow of the capacity planning

The load adjustment done individually or at the edge of the cell or in its overall follows the same algorithm summarised in the Figure 3.6, the difference being only the users concerned. The load adjustment algorithm then starts to check in the overload condition if the users are all consuming the minimum throughput of the respective service. If there are users whose QoS is not minimum, the reduction method is applied to the same, according to the priorities of the respective services indicated in Table 4.2.

Therefore, by first reducing service traffic with a higher priority, reducing a user's QoS is done by removing one RB from the resources previously allocated by the user. If the throughput now obtainable, $R_{b,new_{[\mathrm{Mbps}]}}$ is greater than the minimum service throughput, $R_{b,min_{[\mathrm{Mbps}]}}$, the number of resources allocated to this user and their throughput are updated. This process is repeated for the same service until there is no overload or all users of this service are using the minimum QoS. In this case the same method is applied to the following services. When $R_{b,new_{[\mathrm{Mbps}]}}$ is less than $R_{b,min_{[\mathrm{Mbps}]}}$ of the service, the resources allocated by the user are not reduced, but the ones assigned to this user have the least QoS status since they cannot be further reduced.

When there is still overload, but all users are using the minimum QoS, the ones with the most resources allocated begin to be removed according to the order of priority of the services and also in the order of the modulation, first removing those farthest from the center of the cell. In both processes of user removal and load adjustment, whenever a user is upgraded, the overload condition is checked.

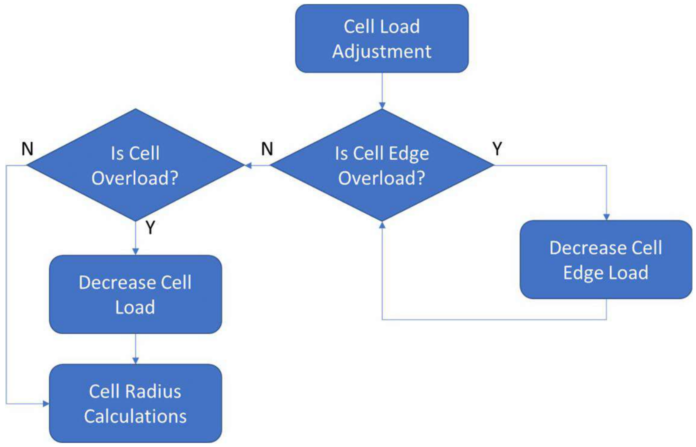

Figure 3.5. Workflow of Cell Load Adjustment

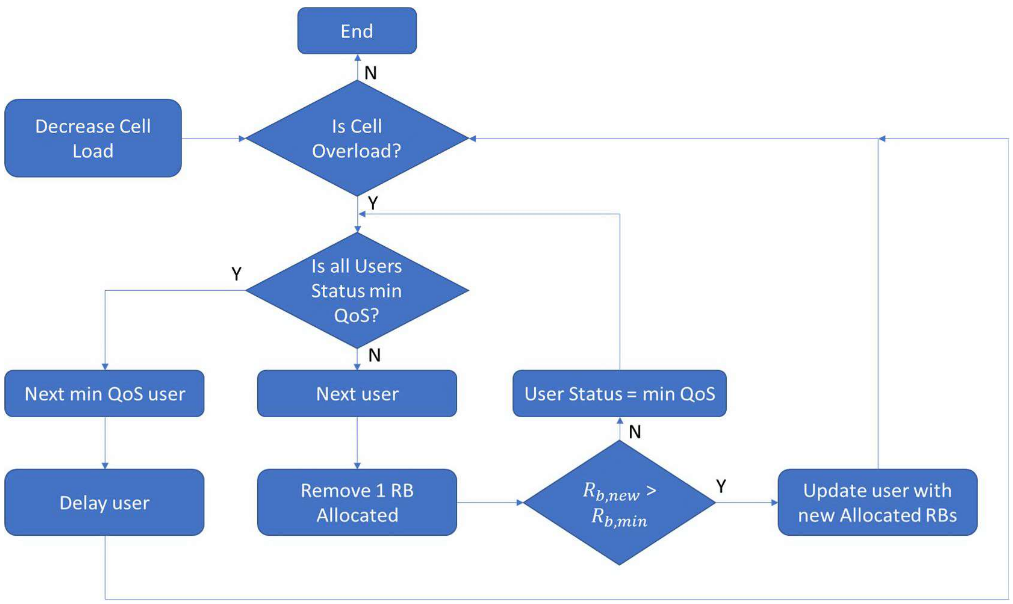

Figure 3.6. Load Adjustment Algorithm

For the allocation of resources of voice services, the process is different since for this type of services a very low throughput is required compared to the one that is offered to it. In QPSK modulation the maximum throughput offered is approximately 200 kbps whereas these services consume only about 22 kbps. In addition, the allocation of resources for this type of service does not need to be done at all time slots, meaning, at each 1 ms, but every 20 ms. This way several users of this service can be served by the same RB. To have this criterion in mind, in the simulator, the allocation of resources to a user of this service is divided by a scale factor:

$$F_s = \frac{R_{b,offered,s_{[\text{Mbps}]}}}{R_{b,target,s_{[\text{Mbps}]}}} \tag{3.33}$$

where:

- $R_{b,offered,s_{[\mathrm{Mbps}]}}$: offered throughput for a given service s;
- $R_{b,target,s_{[\mathrm{Mbps}]}}$: target throughput associated with service s.

3.2 Model Implementation

A simulator was developed to implement the models described in Section 3.1. This simulator was made based on previous works like [Alco17] and [Guit16]. Although the ideas are based on these previous works, the simulator was programmed from scratch using only the free tool Microsoft Visual Studio 2017. This tool allows the use of several programming languages; however, this simulator is entirely programmed with the object-oriented language C #. It is important to emphasise that the proper use of this simulator only allows to take a photograph of the network at a given moment. Therefore, the final results come from the analysis of the network at a specific time, which can be defined by the user of the simulator by changing the input parameters.

In Figure 3.7 the workflow of the simulator and its implementation are represented. The implementation of this simulator also aims to be continued in subsequent theses or that some parts are reusable for other projects. In this way the various processes are distributed in several packages that can be individually imported for external projects. The packages are represented with orange rectangles, in blue are their classes, finally with gray rectangles are the functions that make of the respective classes and that are essential for the understanding of the workflow of the simulator. Each class has a white rectangle inside that has a brief summary of what it does or what it contains.

The only module that the user has access to is the class Input.cs where all parameters are placed for the operation of the simulator. In this class, the parameters of the environment where the base station is located are inserted, which will influence the propagation model used, the traffic model and the parameters that are used in the coverage and capacity plans, such as the 5G NR configuration, the indoor/outdoor user margins, resource rate at the edge of the cell, etc.

Then the parameters of the class Input.cs are inserted in the class Dimensioning.cs. This class is the orchestrator of the network dimensioning, which is where capacity and coverage plans are executed. Therefore, at the beginning of the dimensioning, a base station, Gnb.cs, is created, which is a simulator object that contains all the information acquired by the coverage and capacity plans.

This information can be for example the radius of the cell, the number of users covered, or the traffic used in each of the services and in each modulation. This information is then used as indicators of cell traffic. Then the coverage plan is executed in the CoveragePlanning.cs class where the model detailed in Section 3.1.3 is applied. Within this class are also used the classes LinkBudget.cs where are the expressions of the coverage plan and classes PropagationModels, which contain the appropriate propagation models, to calculate the maximum distance of the modulations served in the cell. These propagation models are in Annex A. In the process of LinkBudget.cs the SINR expressions are also used as a function of the detailed throughput in the class SINRvsRb.cs contained in the packet

SINRvsThroughput. These expressions are listed in the coverage plan section. For reasons of programming, the class cannot have the same name as the package.

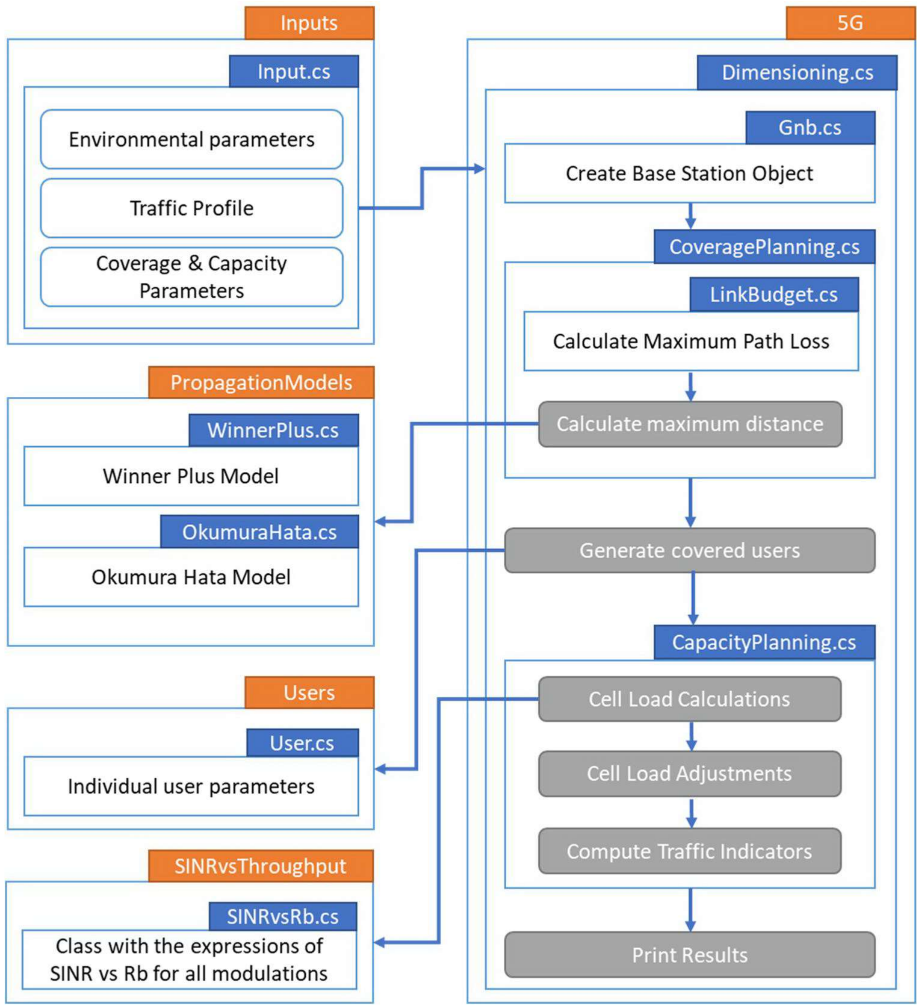

Figure 3.7. Simulator Workflow

Once the cell coverage has already been calculated, one follows the generation of user objects generated with the class User.cs according to the traffic model entered in Input.cs and the total number of users covered. In this object is contained the information about the individual status of the user, i.e., what level of QoS is consuming, one's position in the cell and service.

Then the capacity plan developed in the class CapacityPlanning.cs is executed, where the resources used by the users and those in the cell are computed. In this process the algorithms and methods detailed in Section 3.1.4 are applied, with due reductions if necessary.

Finally, the cell dimensioning is finished, and the desired outputs are made with the results to a .CSV file where they can be further analysed in the Microsoft Office Excel tool.

In order for the scaling rules of the simulator implementation to be respected, the classes corresponding to the dimensioning of a 5G network are contained in the 5G package, which are: Dimensioning.cs, CoveragePlanning.cs, CapacityPlanning.cs, Gnb.cs and LinkBudget.cs.

3.3 Model Assessment

In order to validate the correct functioning of the simulator, it was submitted to a series of tests before the analysis of results. Since the simulator can be divided into two major processes, coverage and capacity planning, the assessment was also divided into two parts. The first was to evaluate the coverage plan and verify its correct functioning, whose evaluation tests are detailed in Table 3.1. In the second part of the evaluation, was the capacity plan with the tests in Table 3.2 However, in addition to these two large processes, the various modules used in the simulator were individually tested, observing the intermediate values of the variables and checking their theoretical coherence.

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

Tests	Validation
1	Check if an error message is shown after all input parameters are inserted
2	Validation of the budget link and propagation models following the procedures manually together with a scientific calculator and comparing the final and intermediate results with those of the simulator.
3	Validation of the simulator functions together with Matlab.
4	Verify if the cell radius is decreasing with the increase of modulation order.
5	Verify if the cell radius is decreasing with the increase of frequency band.
6	Verify if the cell radius decreases with the increase of numerology.
7	Verify if the total number of users increase with the increase of cell radius.
8	Check if the output file with the coverage outputs results, exists in the desired Directory location.

To ascertain the theoretical consistency of the intermediate results, these values were compared not only with previous work in the same context, but also with the measurements of the authors of the propagation models used. In Figure 3.8 the graphs of the cell radius as a function of frequency are plotted for the Okumura-Hata and WINNER Plus propagation models; while Winner Plus is valid for the entire spectrum (0.45-6 GHz), Okumura-Hata is only valid for 0.5 - 2 GHz. These two models of propagation are shown to be consistent since frequency of 2 GHz the cell radius samples are very close. In addition, the distance obtained is related to the maximum Path Loss entered in the propagation model. After analysing the path loss values obtained by the simulator with MathLab, its veracity was verified comparing them with the values obtained by the authors of the Winner Plus propagation model, for urban environments similar to the scope of study of this thesis. For the capacity plan, Table 3.2 discriminates the series of tests made to verify its correct functioning.

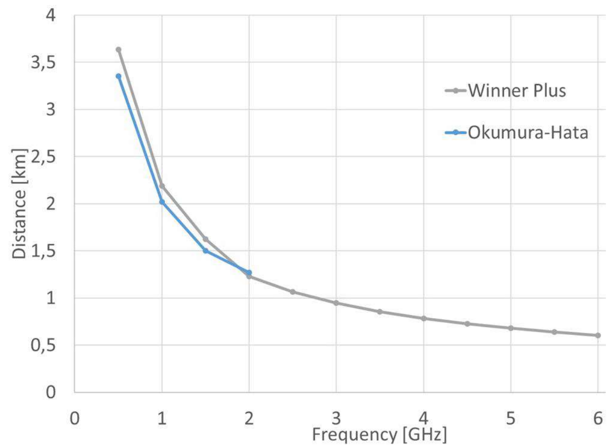

Figure 3.8. Distance in function of the frequency for multiple propagation models.

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

Tests	Validation
1	Check if an error message is shown after all input parameters are inserted
2	Validation of the number of RBs allocated to a user for a specific service using a scientific calculator machine to confirm with the values obtained in the simulator.
3	Verify that the number of active and covered users is equal when the total number of required resources is less than the maximum of the cell.
4	Verify that the percentage of active users decreases when the total number of resources required is greater than the maximum of the cell.
5	Verify that the percentage of active users decreases with increasing user density.
6	Verify that the percentage of active users decreases with increasing user density.
7	Check if the output file with the capacity outputs results, exists in the desired Directory location.

Several graphs of the network indicators were taken to ascertain the consistency of the capacity plan. With the algorithms and models previously described it is expected that with the increase of covered users the load of the cell will increase. This effect is represented in Figure 3.9 where the saturation of the cell is verified when the density of users reaches approximately 120 users/km^2.

This cell saturation means that all covered users cannot be served and thus the percentage of served users decreases. Figure 3.10, allows to verify that this percentage begins to decrease also approximately at 120 users / km^2. When the cell is in the saturation zone, the adjustment of its load begins at the edge, which results in a sharp decrease at the beginning of its dimensioning. Once the reference value for the throughput at the end of the cell has been reached, the QoS of the remaining users begins to be reduced, with the percentage of users served being stagnant in the face of increasing density. This effect occurs between 140 and 300 users / km^2. As soon as all users are consuming the minimum QoS, cell adjustment starts again to remove users result again in decreasing the percentage of users served, but this time not so accentuated.

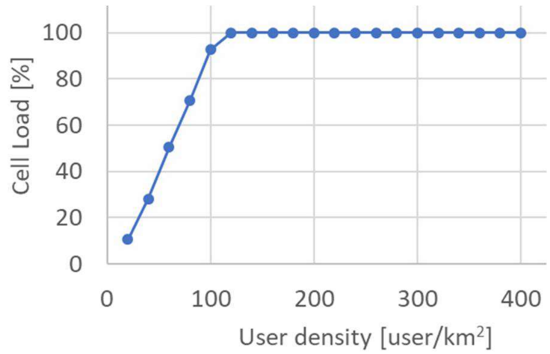

Figure 3.9. Cell Load in function of the user density.

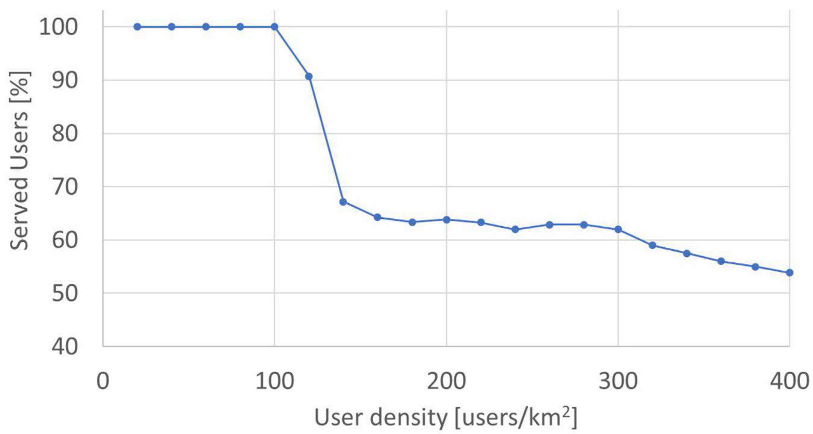

Figure 3.10. Served users in function of the user density.

The effect of user adjustment served against user density is also visible in the maximum radius of the cell shown in Figure 3.11, where the respective decrease occurs in the same zones as in the graph of Figure 3.10. This shows the consistency of the capacity plan.

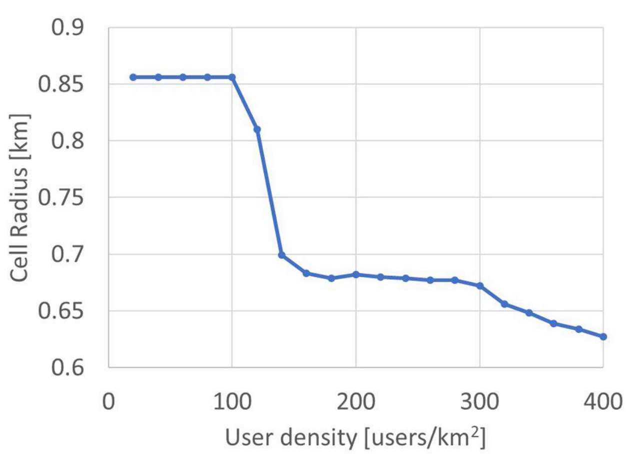

Figure 3.11. Cell radius in function of user density.

The percentage of users per service is represented in Figure 3.12 in which the correct functioning of the model can be observed. The percentage of users of the highest priority services is the first to be reduced by what works according to the algorithms detailed in Section 3.1.4.

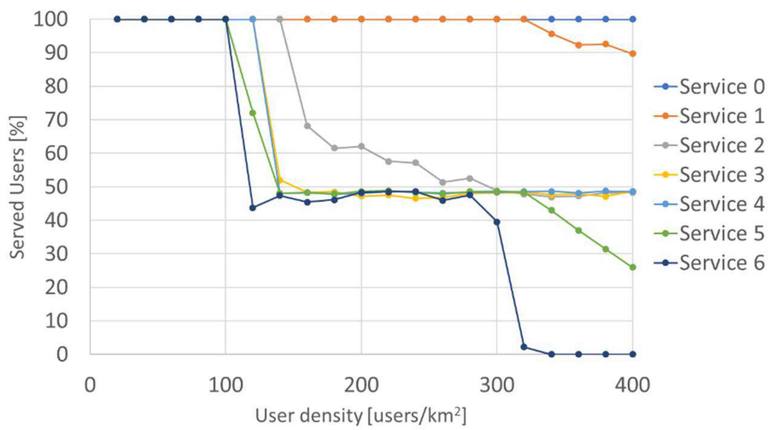

Figure 3.12. Served users in function of user density for multiple services.

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 metropolitan area of Lisbon is the reference scenario, which according to Figure 4.1, is divided into several municipalities. These municipalities are considered as urban areas, however, each of them has its own configuration. This configuration can be defined by the population density, the traffic profile or its geographical characteristics and height of the buildings. In this way, they all have different capacity and coverage requirements. The simulator is not restricted only to the city of Lisbon, several types of urban cities can be simulated according to the definition of the initial parameters of the simulator. In the metropolitan area of Lisbon there are municipalities with very different characteristics, some of which are similar to other cities. Thus, the simulator is used to make the analysis of several ones that can simulate the development of the 5G network in other cities.

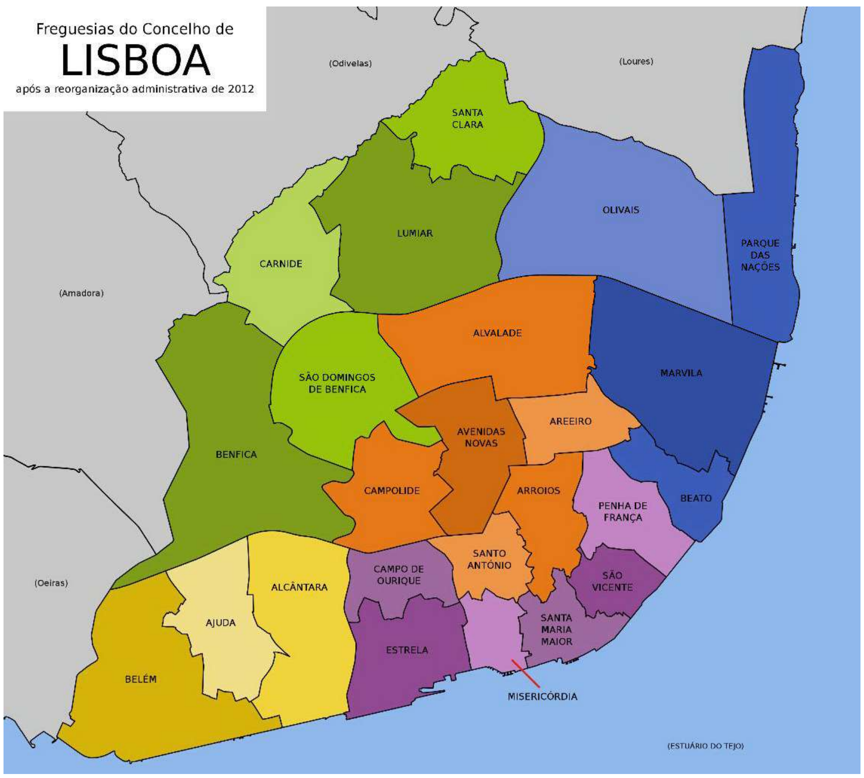

Figure 4.1. Map of the municipalities of Lisbon (extracted from [CMLi18])

Population density is one of the parameters that differentiates each municipality in the metropolitan area of Lisbon and it takes the values represented in Figure 4.2. The population density was computed by dividing the total population of a municipality obtained in [PorS18] by the respective area obtained in [TerrP18]. The population density of a municipality serves only as an initial indicator for estimating the number of users. The ratio of penetration and utilisation is multiplied by this indicator to perform the capacity calculations. The penetration ratio indicates the percentage of users who have a smartphone with data internet access, while the utilisation ratio indicates the percentage of those users who are using it. These ratios have to be accounted when dealing with user density of each municipality, though, the user density value used in the simulator is the active covered users. This ratio has a low value due to the fact that in indoor environments most of the users use the Wi-Fi network available in the building.

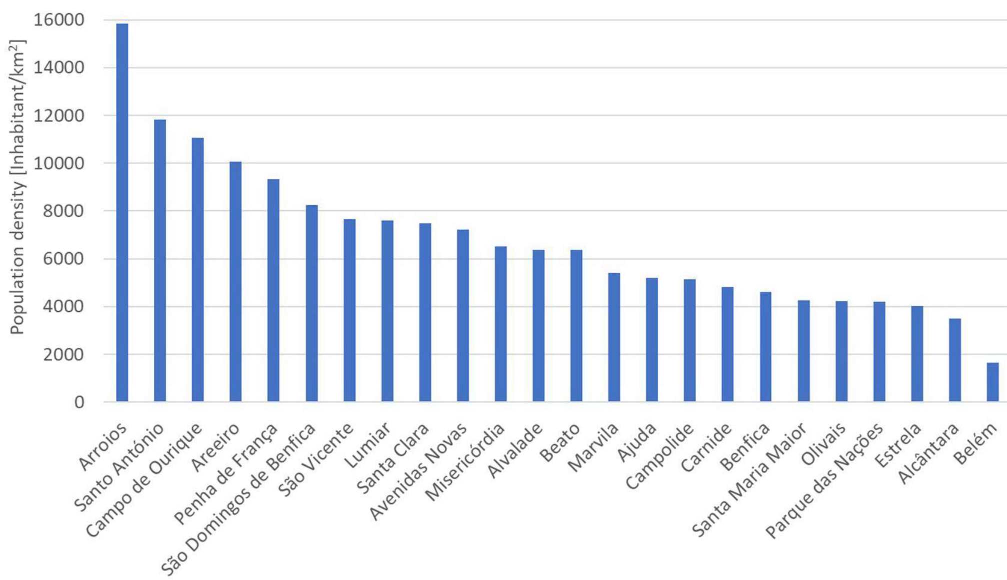

Figure 4.2. User density of Lisbon Municipalities.

The number of users to study in a certain region is due not only to population density, penetration ratio and usage, but also distinguished by the environment in which they are. Users can be in indoor or outdoor, and, in reality, the majority of users who use mobile data are indoors. The margins considered in the simulator for the dimensioning of coverage and capacity are detailed in Table 4.1.

Table 4.1. Margins description.

Parameter Description	**Value**
Reference throughput [Mbps]	5
Outdoor coverage probability [%]	90
Indoor coverage probability [%]	90
Outdoor users [%]	20
Indoor users [%]	80
Handover percentage [%]	5
Cell load [%]	75

A traffic model is applied to the covered users. This model includes the services used by the users with their respective throughputs and the percentage of use of each of them. Nowadays, social networks and video applications are the applications most consumed by our society. The growth of these applications is positive and therefore, in the next generations of mobile communications, the percentage of use of these services will tend to increase. Social networks are included in the Web Browsing service and the video applications in Video Streaming. The traffic model is described in Table 4.2 where the throughputs of each of the services are discriminated as well as the priority of each one. The percentage of use of these services also varies according to the user scenario.

Table 4.2. Services definition (adapted from [Guit16]).

Service		**Service Class**	**Throughput [Mbps]**			**Service Mix [%]**	**Priority**
			Min.	**Avg.**	**Max.**		
VoLTE		Conversational	0.005	0.023	0.064	22	1
Video	Calling	Conversational	0.064	0.384	2.048	8	2
	Streaming	Streaming	0.5	2.5	25	28	3
Music Streaming		Streaming	0.016	0.064	0.320	20	4
Web Browsing		Interactive	0.031	0.5	5	10	5
File Sharing		Interactive	0.384	1.024	2.5	8	6
E-mail		Background	0.010	0.1	1	4	7

The amount of services considered for Downlink and Uplink is different, therefore, two profiles were used. For the DL connection 7 types of services are considered described in Table 4.2, while for the UL only four are considered: voice, video calling, file sharing and email.

For the reference scenario, propagation models are used in order to determine the coverage area. The used propagation models are the Winner Plus, which covers all study frequencies (800, 1800 and 3500 MHz) and Okumura-Hata for comparison purposes, but this one is only valid for frequencies between 0.5 and 2 GHz. The parameters used in these propagation models are shown in Table 4.3.

The maximum radius obtained with propagation models depends on the maximum path loss obtained with the Link Budget. The parameters used are detailed in Table 4.4 where the values of losses and gains are used. These values are based on [Alco17] and serve as reference to verify the correct operation of the simulator. The frequency bands under study for both UL and DL:

- 3500 MHz This frequency band is the one defined by 3GPP for 5G deployment;
- 1800 MHz and 800 MHz: These frequency bands serve to aid the coverage and capacity of the 3500 MHz band.

Table 4.3. Environment parameters definition.

Parameter Description	Value
Environment	Urban
Height of the BS antennas [m]	25
Height of the Buildings [m]	21
UE height [m]	1.2

Table 4.4. Link Budget parameters definition.

Parameter Description	Value		
Frequency Bands [MHz]	800	1800	3500
Maximum Bandwidth [MHz]	20	20	100
DL transmission power [dBm]	42		
BS maximum antenna gain [dBi]	17.8		
Modulations	QPSK, 16QAM, 64QAM, 256QAM		
UE antenna gain [dBi]	0		
UE losses [dB]	1		
Cable losses [dB]	2		
Noise figure [dB]	5 (UL) / 8 (DL)		
Diversity gain [dB]	3		
Interference margin [dB]	3		
TMA gain [dB]	2		
MIMO order [dB]	2		

In the process of obtaining the maximum path loss it is necessary to take into account the penetration of the signal in indoor environments. In this way, average attenuation is taken into account according to

Table 4.5 in which the Standard Deviation is explicit by the appropriate propagation model, but the average value is given by [Corr16]. This attenuation is calculated using a statistical approach for the slow fading margin, i.e. Log-Normal Distribution, given a certain probability of specific coverage.

Table 4.5. Indoor Mean Attenuation for each frequency band (adapted from [Corr16])

Frequency Band [MHz]	Average [dB]
800	2.6
1800	10.2
3500	11.7

In the dimensioning process, the indoor and outdoor scenarios are taken into account, and the user percentages are 80 % and 20 %, respectively. These percentages come from the fact that users are currently consuming more data when they are standing in the office or at home. Thus, the path loss for the indoor users will be larger and therefore their distance from the coverage against the distance outdoors will consequently be smaller.

Another important parameter in the dimensioning that is introduced in the new 5G radio is numerology. In 5G one can several numerologies, when using the same bandwidth, this is the reason why the maximum number of blocks of resources available in the cell varies. The numerologies studied are detailed in Table 2.5 together with their respective bandwidths. Finally, the simulator input and output parameters are represented in Figure 4.3.

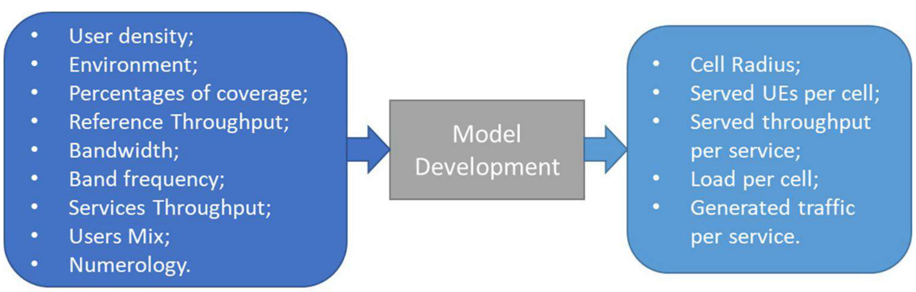

Figure 4.3. Model generalisation.

4.2 Downlink Analysis

4.2.1 Analysis of Number of Users

For a first approach a study is made on the variation of active users in the cell. The goal is to analyse how many active users a cell can handle until all its resources are being used. In this way the variation of the density of users varies between 10 and 90 inhabitants per km^2 that is enough to verify the saturation of the cell in all numerologies.

Since 5G has the option of using different numerologies, it is important to analyse how the cell behaves using each one of them. In theory, using a numerology immediately above means that it is possible to achieve the double throughput of the previous numerology. However, when applying the traffic profile to the covered users, it is not always necessary to double the capacity per RB, so a user can be served. For example, in services with a low throughput in which 1 RB of numerology 15 SCS is sufficient to serve it, with a numerology of 30 SCS would continue to be used 1 RB. In the case of services with high throughputs, such as video streaming, when using a higher numerology, in some cases depending on the modulation used, half the resources that would be needed with smaller numerology are required. Thus, the cell has a greater capacity the greater the numerology used and thus serve more users as can be seen in Figure 4.4. However, for the reference scenario there is no double of capacity with the increase in numerology, since services benefiting from this effect are not used in majority.

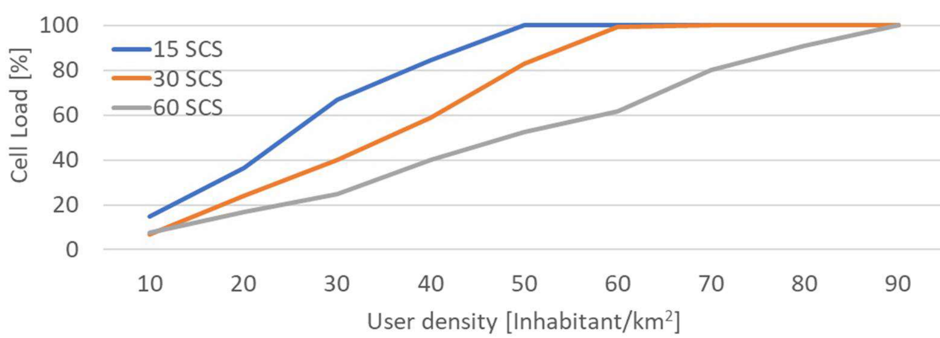

Figure 4.4. Cell Load in function of the user density.

Although the cell gets saturated, the percentage of served users remains intact, since the resource allocation algorithm begins to decrease the allocation of RBs to users who are consuming a lot, reducing the quality of QoS, but continuing to serve other users.

The reduction of RBs allocated to users happens when the cell goes into saturation, that is, the allocation of resources exceeds a certain threshold imposed by the operator. In this way, the users with better QoS are reduced to the minimum throughput reference of the respective service, but the percentage of active users against the covered users remains intact. Only when all users are enjoying the minimum quality of service will users be removed until the cell load stops exceeding the threshold level.

As for the radius of the cell, it also remains constant even after the cell usage percentage enters the saturation zone due to reduced quality of service. So, the cell radius decreases when active users start to be removed. Figure 4.5 shows the cell radius obtained when considering a saturation level of 75% of the cell load.

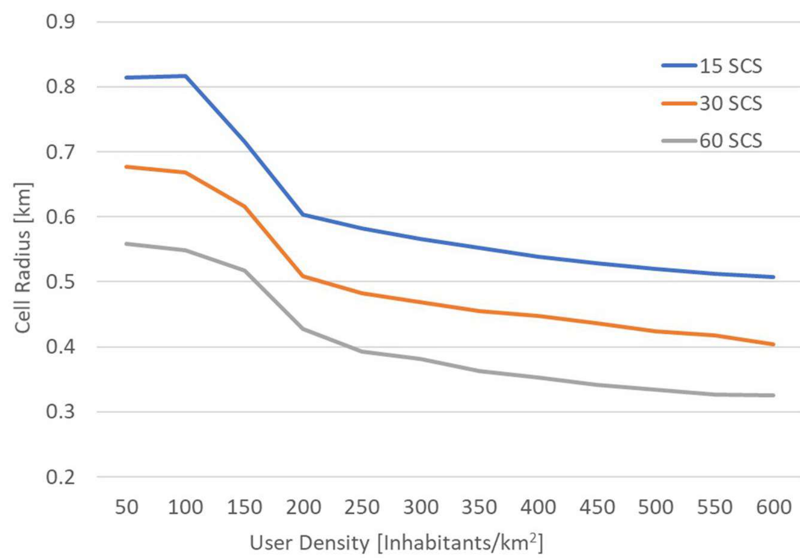

Figure 4.5. Cell radius in function of user density for a cell load of 75%.

4.2.2 Bandwidth and Frequency Band Analysis

In this section, one analyses the variation of bandwidth and frequency band in downlink for the ones allowed by 3GPP. With this is mind, only the bandwidths of 50 MHz and 100 MHz are studied in the frequency band of 3500 MHz.

The analysis of the variation of active cell users in Section 4.2.1 shows that the best value to study the various configurations is 30 users/km^2, because the cell is not saturated, with the cell load being 67% which is slightly below the 75% benchmark.

Regarding the cell radius, there is no difference with bandwidth variation, since only the sensitivity of a single RB in the UE is considered to calculate the maximum radius. Thus, the average noise varies only with the bandwidth of an RB, that the larger it is, the greater the noise, the greater the sensitivity and consequently the radius of the cell decreases. In this way, the cell radius is reduced with the increase of the numerology used and not with the bandwidth itself. Therefore, for the same numerology, the cell radius is the same for both the 50 MHz and 100 MHz bandwidths.

For the same numerology, when the bandwidth is doubled, the number of available RBs also doubles. So, in theory the cell capacity is larger and supports twice as many active users. Figure 4.6 shows that in the same numerology the cell load percentage is reduced by approximately half when the 100 MHz bandwidth is used instead of 50 MHz. This reduction is not exactly half due to the approximations made over the such as the number of users covered, RBs used by each UE and distribution of users by their respective services. For the configuration of 15 SCS in the bandwidth of 100 MHz, it is not defined by 3GPP, so it is not considered.

The analysed reference scenario is situated in the active zone of the cell, and thus, since all covered users are served on both bandwidths, the total traffic generated is equal. In Figure 4.7 this effect of the traffic generated according to the bandwidth used is visible and that with the numerology increase it is reduced due to the existence of less users once the coverage radius decreases. The reduction of Cell Load as the numerology increases is also observed in Figure 4.6.

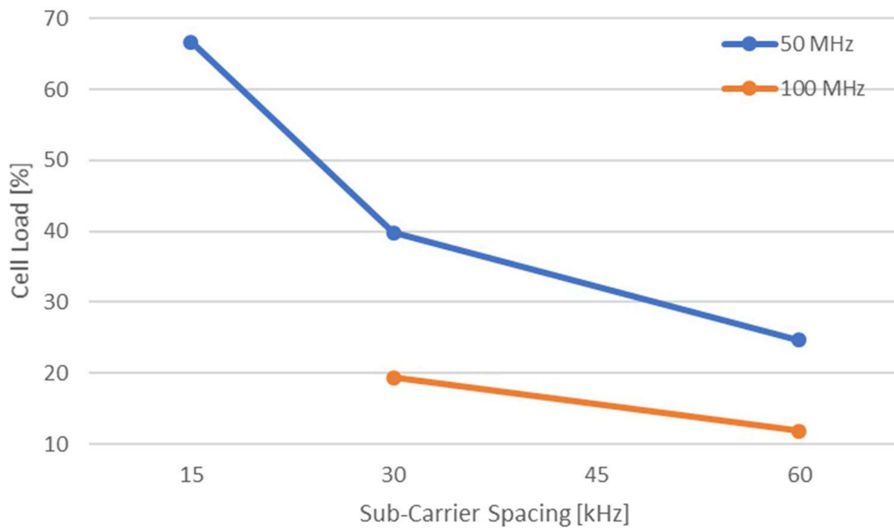

Figure 4.6. Cell Load in function of the numerology for different Bandwidths.

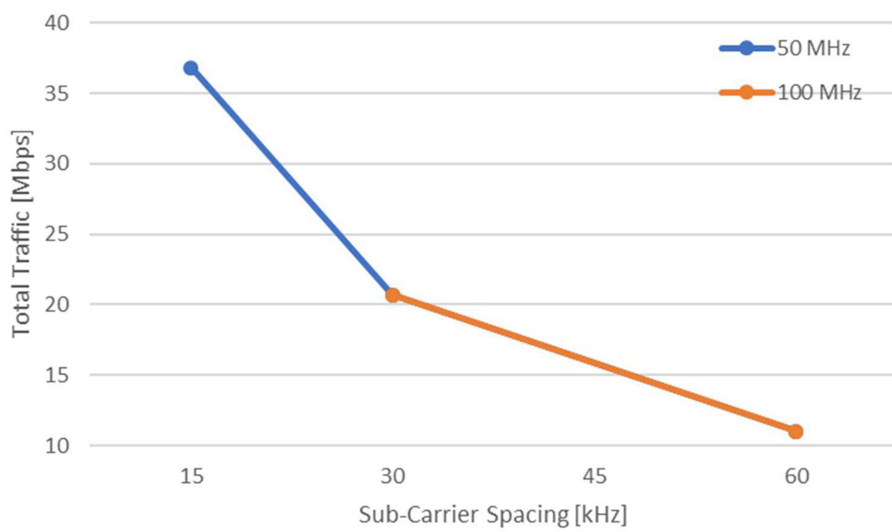

Figure 4.7. Total Traffic generated in function of the numerology for different bandwidths.

4.2.3 Impact of Reference Throughput Analysis

In this section we analyse the reference of a certain throughput for the traffic generated at the edge of the cell. A brief analysis before any simulation is sufficient to realise what are the advantages and disadvantages in each of the bandwidths by increasing or reducing this reference. Figure 4.8 shows that to use a 10% resource allocation ratio with 30 SCS numerology, for the 50 MHz bandwidth only about 5 Mbps is allowed and for the bandwidth of 100 MHz are attainable 10 Mbps. That is, by doubling the bandwidth, the attainable throughput is also doubled. However, if the reasoning is reversed, in order to be able to use 10 Mbps in the 100 MHz bandwidth, at least 10% of the RBs available in the cell are required.

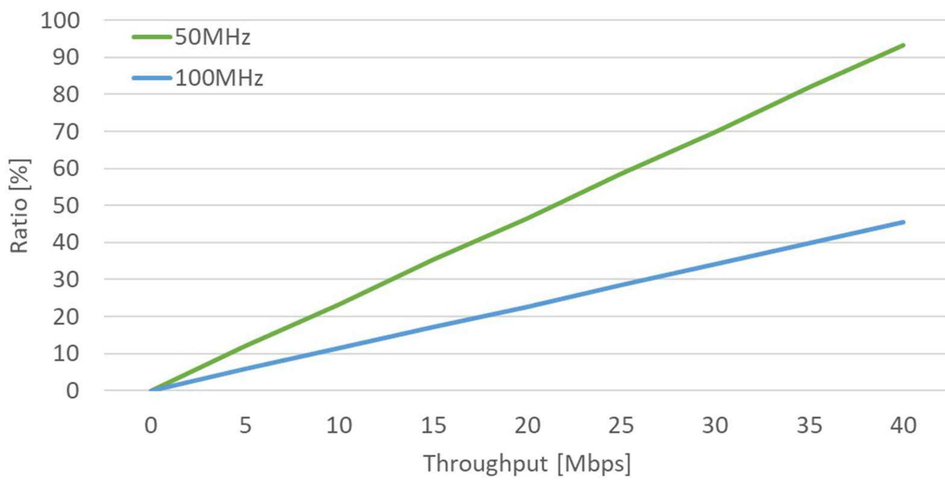

Figure 4.8. Cell edge ratio in function of the reference throughput for different bandwidths.

Although this graph is applied only to the numerology of 30 SCS, with Figure 4.9 it is verified that with another one immediately above or below, the difference is not considerable being it a maximum of 4.5 %.

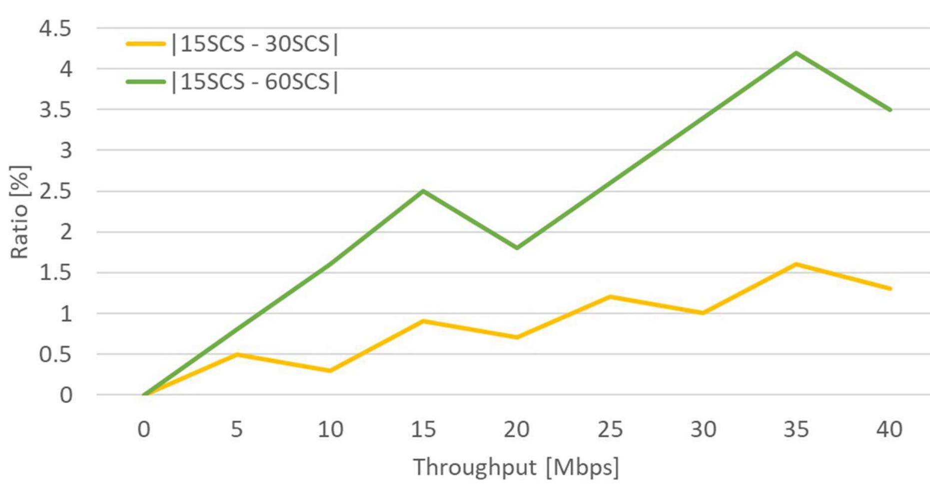

Figure 4.9. Ratio difference for multiple numerologies.

In reality when users are evenly distributed throughout the cell and coverage planning is done, approximately 30 % of users are at the cell edge, since with QPSK modulation it is possible to serve users with low SINR. What it means after the traffic profile is applied to the entire cell, about 30 % available RBs will be allocated to the cell edge. Even if the cell is saturated after all users are set to a minimum QoS, the removal of users made according to the priority of the services begins at the end of the cell. Only in this case the percentage of resource allocation at the cell end could be less than 30%, but still well above the 10% benchmark.

The only way to impose this limit on the cell edge is to use the algorithm described in Figure 3.5, where the users at the edge of the cell start to be removed until the threshold traffic is reached. This algorithm has some advantages in that the RBs in the QPSK modulation have a low maximum throughput compared to the other modulations, and thus require more RBs. This way the users who require more resources are the ones that are at the edge of the cell, thus when removed first make cell resource management more efficient.

4.2.4 Traffic Profile Analysis

For the analysis of the traffic profiles, the percentage of users in a given environment, the percentage of use of the services and the throughput of the services is varied. In order to analyse the environment in which users are located, two scenarios are considered: the reference scenario, where all users are in a residential environment and another, where it is considered a mixture between residential and business environments and a mixture of the two (ROM). This last scenario is due to the fact that in reality when taking a snapshot of the network traffic, there is a percentage of users in each of the environments. Table 4.6 shows the percentages used in each of these scenarios. The distribution of users against their environment is made according to [Guit16].

Table 4.6. Environment scenarios (adapted from [Guit16]).

User Profile	**Scenario [%]**	
	Reference	**ROM**
Residential	100	60
Office	0	30
Mix	0	10

For each of these environments' users have an adequate traffic profile by varying the percentages of each of the services. In Table 4.7 it is possible to verify the percentages of each of the services according to the environment, whereas in residential the most used service is video streaming with 28% and in business medium is Web Browsing with 30%. These values were adapted from previous theses also on analysis of mobile communications in urban environments.

In 5G it is expected that some throughputs of certain services will be greater such as Video Calling and Video Streaming, in this way are analysed two scenarios in which the average and maximum throughputs of Table 4.2 are used.

Table 4.7. Services percentage distribution for multiple environments in Downlink (adapted from [Guit16]).

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

When using the average throughputs, through Figure 4.10 it is possible to verify that the cell for both scenarios, Reference and ROM, does not reach saturation. For the same numerology the impact of the ROM scenario on the Reference scenario causes a reduction in the cell load of approximately half. This effect is due to the fact that, in a residential environment, the Video Streaming service is the one that needs the most resources. Thus, since the ROM scenario is the closest to reality, this reinforces that in the analysis done to the number of users, this study was done considering the worst-case scenario and that in fact it is possible for the same percentage of cell usage, to serve twice as many users.

With the variation of numerology, it is remarkable that the numerology of 30 SCS reduces the percentage of use of the cell. This is because by doubling the bandwidth of one RB, the capacity of the same also doubles, so it is possible to serve users with only one RB whereas with the numerology of 15 SCS it might be necessary two RB. The percentage of use of the cell is also reduced since the coverage radius is also smaller and therefore the number of users is also lower. However, with the numerology 60 SCS, this effect is no longer so pronounced since the previous numerology already covers a large part of the services with only one RB, except some as the Video Streaming. For the ROM scenario, the use of a numerology of 60 SCS instead of 30 SCS has no benefits due to this effect.

The effect explained above is also notable noting the total cell traffic, Figure 4.11 where cell behavior according to numerology and scenario is the same as in Figure 4.10. Nevertheless, the obtained results allow to compare the traffic with the LTE technology and to realise that the reference scenario is in coherence with the theoretical prediction. According to [ViQR10], the total traffic expected in an LTE cell for the same conditions but with a bandwidth of 20 MHz is about 20 Mbps. Thus, using a reference bandwidth of 50 MHz, which is slightly more than double, it is acceptable that the reference scenario also has twice the traffic.

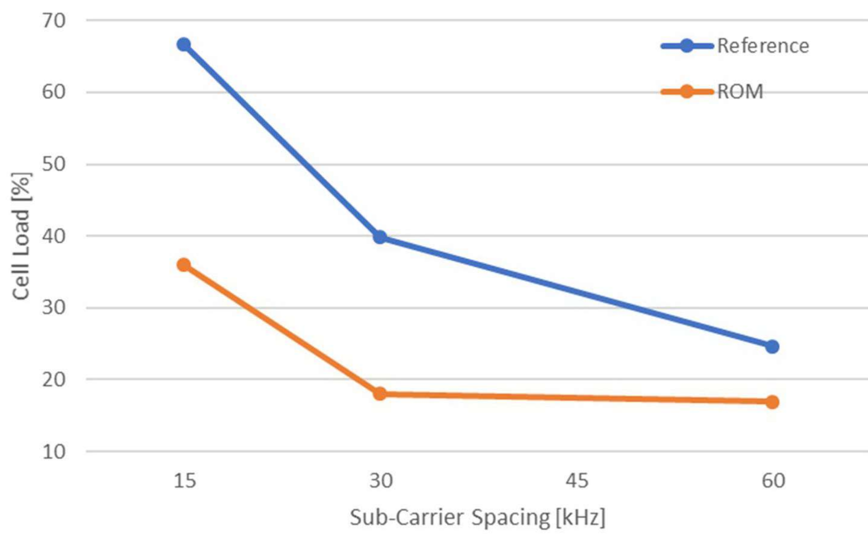

Figure 4.10. Cell load in function of the numerology for multiple environments with services in average throughput.

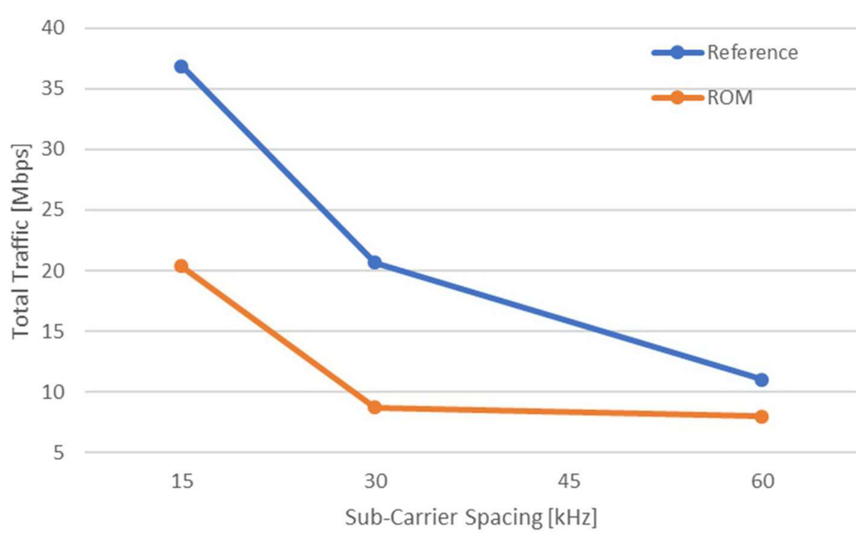

Figure 4.11. Total traffic in function of the numerology for multiple environments with services in average throughput.

When maximum throughputs are used, for both the Reference and ROM scenarios, the cell is in saturation, that is, its utilisation is approximately 75%. Since it is in saturation one cannot complete any benefit using one of the scenarios. Even with the variation of numerology, the cell usage is slightly different only due to the rounding done on the model thus having no meaning with value.

In a hypothetical scenario where there is a greater concentration of the use of video services the percentages are distributed as in Table 4.8:

Table 4.8. Services percentage distribution for multiple environments in Downlink for a video centric approach (adapted from [Guit16]).

Service		**Scenario [%]**		
		Video Centric		
		Residential	**Office**	**Mixed**
VoLTE		5	20	12
Video	Calling	8	10	9
	Streaming	40	20	30
Music Streaming		9	10	10
Web Browsing		24	30	27
File Sharing		9	5	7
E-mail		5	5	5

Now with average throughputs, but with a higher video concentration, ROM continues to have a smaller impact on the cell load. With the increase in numerology, from 30 SCS to 60 SCS, there is already a reduction in the cell load, contrary to what happened in the reference scenario. The forms of the Cell Load and Total traffic graphs have the same as those of Figures 4.10 and 4.11 respectively as such only the gains are shown when using the new video centric scenario in Figure 4.12. It is concluded with this figure that when using a scenario centered on the video services, there is a gain of approximately 1.5 in both the cell load and in the total traffic for the numerology of 15 SCS. For the ROM scenario the gain of the SCS numerals 30 and 60 ranges between 2 and 1.3 respectively because while services with a higher throughput are benefited by a higher numerology, there are services that do not require it and therefore the gain is not constant. When using the maximum throughputs in this video centric scenario the cell is also saturated, so it represents values similar to the reference scenario.

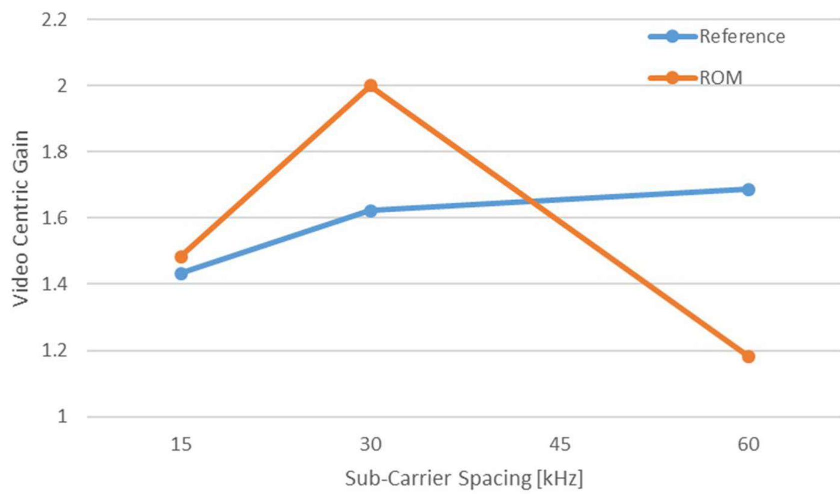

Figure 4.12. Video centric gain in function of the numerology.

4.2.5 Massive MIMO Analysis

The reference scenario can be considered only an improvement of LTE, since the big difference that benefits 5G is the fact that the bandwidths are larger. This technology also works in a new frequency band, higher to the LTE one which harms the conditions of coverage. However, another technology that characterises 5G is the massive MIMO that greatly improves the coverage conditions and capacity. In theory by doubling the MIMO order, the gain should also double, but this does not happen in reality. Since the true gain of these new systems does not exist in the literature, it is considered the best case under this thesis.

Using services with average throughputs the cell usage behavior is halved each time a higher MIMO order is used converging only from the MIMO 16 Order at 10% utilization, Figure 4.13. Since the cell is never saturated the total cell traffic is always constant, Table 4.9.

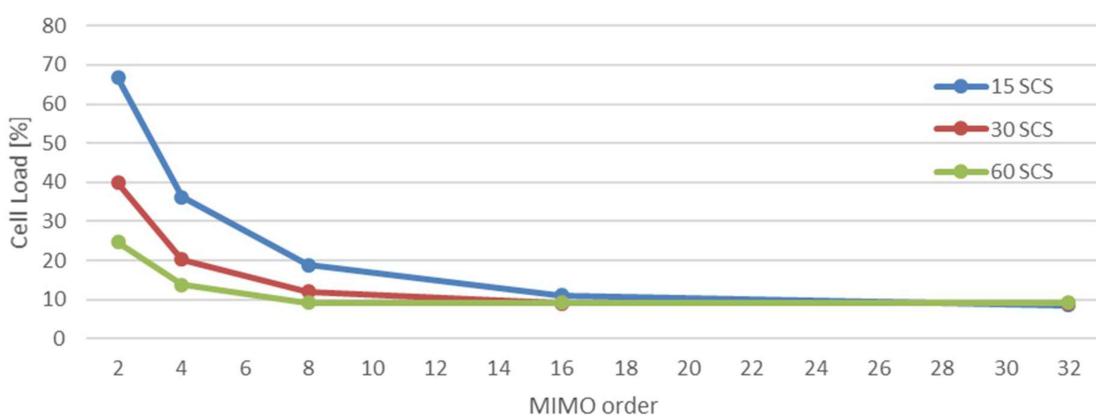

Figure 4.13. Cell Load in function of the MIMO order for multiple numerologies in Downlink.

When using maximum throughputs, which is a more realistic scenario of 5G, Figure 4.14, it is notable that the use of MIMO orders greater than 2 has a great effect, and with numerology of 15 SCS the cell is no longer saturated with the MIMO order of 16.

Table 4.9. Total Traffic for each numerology in Downlink.

Numerology [kHz]	Total Traffic [Mbps]
15	11.03
30	20.67
60	36.83

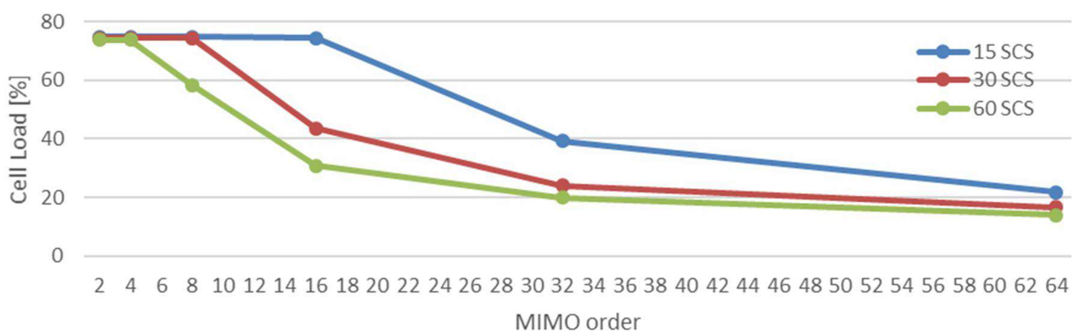

Figure 4.14. Cell Load in function of the MIMO order for multiple numerologies in Downlink using maximum throughputs.

The great benefit of using MIMO is observable with the analysis of total cell traffic in which approximately 350 Mbps are reached, Figure 4.15. This traffic is an average of what can be achieved within the cell. At 5G, peak data rates are expected in the order of Gbps, which has a relation to the expected throughput of the cell of approximately one-third. With [ViQR10], it was studied that in an LTE network the expected traffic in a cell corresponds to approximately one-third of the peak data rate. Thus, with the use of MIMO it is possible to reach peak data rate values in the order of Gbps.

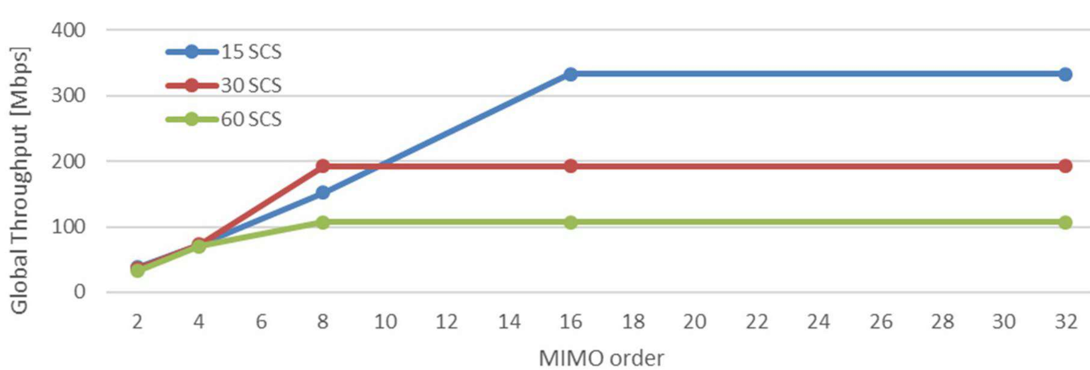

Figure 4.15. Global Throughput in function of the MIMO order for multiple numerologies.

4.3 Uplink Analysis

4.3.1 Analysis of Number of Users

Similar to the process performed in Downlink, also in Uplink the number of users to which the cell saturates is analysed. So, to test the percentage of use of the cell, the density of users is varied between 100 and 1000 users/m^2. In Uplink the great limitation of the dimensioning is the link budget, since the mobile devices have neither power nor transmission gains as big as those of the BS. In this way the number of users covered by BS is lower than in Downlink and thus a higher density of users is supported. For the numerology of 15 SCS the cell reaches 100% of use when the density of users is about 700 users/km^2. The higher the density of users the higher the gain that a higher numerology has a lower one, Figure 4.16.

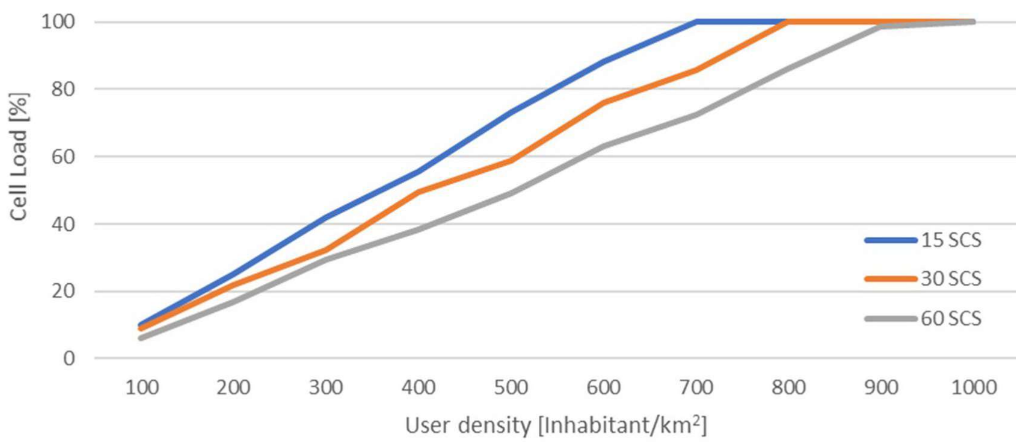

Figure 4.16. Cell Load percentage in function of the user density in Uplink.

4.3.2 Bandwidth and Frequency Band Analysis

In this section the analysis of the variation of the bandwidth and frequency in Uplink is made. Although the Uplink frequency band for 5G is 3500 MHz, the 800 and 1800 MHz bands used by the LTE network are also studied. The use of these bands is intended to aid the Uplink capability of a 5G network in order to increase its capacity. Thus, the bandwidths studied are 20, 50 and 100 MHz.

After analysing the variation of active cell users in Section 4.3.1, it is found that the best value to study the various configurations is 200 users/km^2, since the cell is not saturated and is below the reference parameter, 75 %. Also, with this value it is possible to study other frequency bands without the cell being saturated.

With reference to the 3500 MHz frequency band and 50 MHz bandwidth, Figure 4.17 shows the gains that the different bandwidths have over the reference. Therefore, the use of the 100 MHz bandwidth reduces the cell load to half while the 20 MHz bandwidth has the opposite effect by increasing the cell load by approximately 2.5 times.

With the increase in numerology its effect is not as pronounced as it was observed in Downlink, which happens because the throughputs of the services used in Uplink do not require so many resources. Thus, for most services only 1 RB of the numerology of 15 SCS is sufficient to satisfy a user.

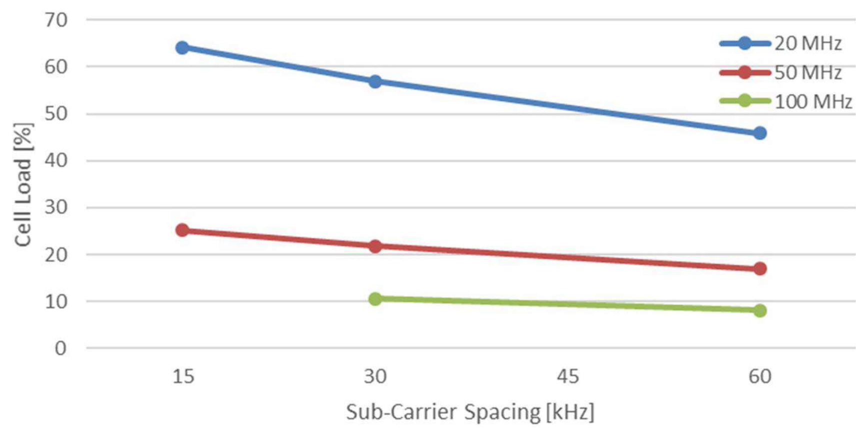

Figure 4.17. Cell load in function of the numerology for multiple bandwidths in Uplink.

On the other hand, the frequency band influences the radius of the cell. The lower the frequency band the greater the cell radius, which consequently increases the number of users covered. Thus, the frequency of 1800 MHz reaches more users than the 3500 MHz band, so the cell is in saturation in the numerology of 15 SCS, however, in the following numerology, 30 SCS, it is no longer in saturation, Figure 4.18. The impact of the 1800 MHz band generates in the use of the cell an increase of 3 times greater than the reference. As for the 800 MHz band, this allows a far greater range than the other bands and therefore covers more users. Thus, the cell in this band is always in saturation for all numerologies and bandwidths.

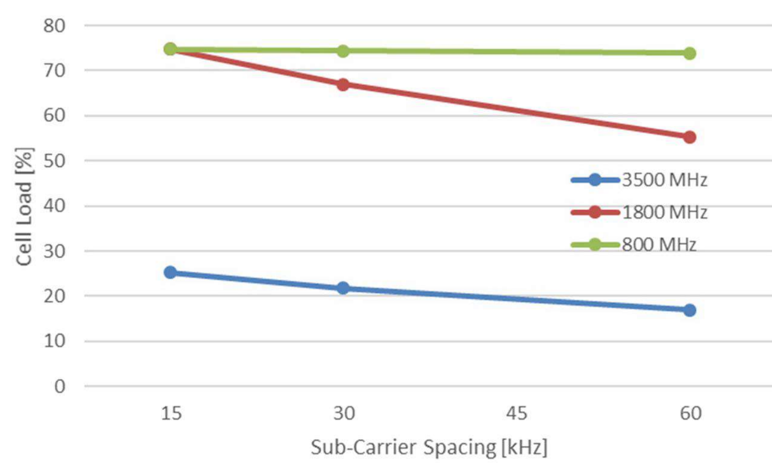

Figure 4.18. Cell Load percentage in function of the numerology for multiple band frequencies in Uplink.

When the cell is not in saturation its radius is the maximum it can obtain, however in situations where it is saturated, as is the case with the 800 MHz band in all bandwidths and the bandwidth. 1800 MHz in the 20 MHz bandwidth, the radius change is only 10%. The cell radii obtained for the reference bandwidth for the different bands are described in Figure 4.19, where the 1800 MHz band has a radius about 1.65 times greater than the reference. The cell radius of the 800 MHz band has a gain of 3.22 times over the reference.

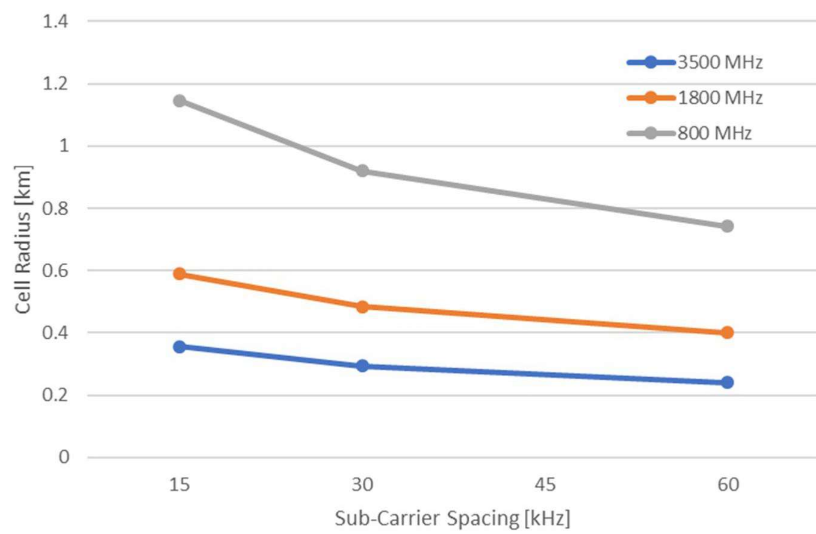

Figure 4.19. Cell Radius in function of the numerology for multiple band frequencies in Uplink.

4.3.3 Traffic Profiles Analysis

For the analysis of traffic profiles in the Uplink, the same scenario is used as in Downlink, these being the Reference, where all users are in a residential environment and the ROM. However, in Uplink one is not using all the services that are used in Downlink. Thus, the use of services in the ROM scenario are redefined in Table 4.10. There is no right value for each of the percentages, so the goal is to evaluate the use of services in several environments, emphasizing two: VoLTE and video calling.

Table 4.10. Services percentage distribution for multiple environments in Uplink.

Service	**Scenario [%]**		
	ROM		
	Residential	**Office**	**Mixed**
VoLTE	50	60	50
Video Calling	40	30	40
File Sharing	5	5	5
E-mail	5	5	5

Using the average service throughputs, the percentage of cell usage is seen in Figure 4.20, where as in Downlink also in Uplink the ROM scenario has a smaller impact on the cell being this almost half of the reference scenario. Also, the total traffic generated in Uplink, Figure 4.21, according to numerology behaves similarly to what happened in Downlink. When the maximum throughput is used, the cell utilization increases about 3 times and the total traffic increases about 5 times, not reaching saturation in any case.

In a hypothetical scenario where there is a greater concentration of the use of video services, the percentages are distributed according to Table 4.11. These percentages were adapted in order to study the impact of services in various environments. This analysis is relative so there is no exact percentage for the use of each of the services.

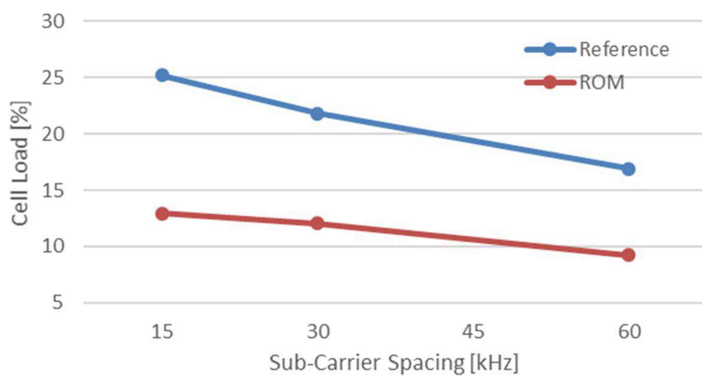

Figure 4.20. Cell Load in function of the numerology for multiple environments in Uplink.

With this scenario the cell usage and total traffic with the average service throughputs are larger than the reference number about 1.8 times.

When using maximum to medium throughputs, the cell usage gain also continues to be 3 times and the total traffic gain remains 5 times. However now the cell goes into saturation.

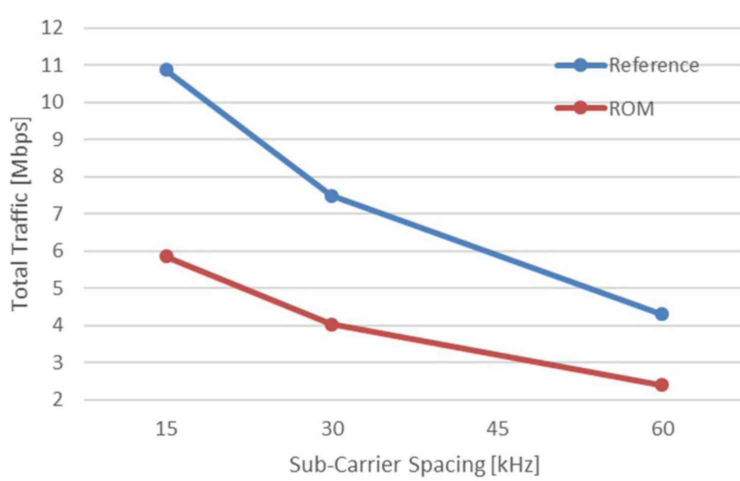

Figure 4.21. Total Traffic in function of the numerology for multiple environments in Uplink.

Table 4.11. Services percentage distribution for multiple environments in Uplink Downlink for a video centric approach.

Service	**Scenario [%]**		
	ROM		
	Residential	**Office**	**Mixed**
VoLTE	20	30	35
Video Calling	80	60	55
File Sharing	5	5	5
E-mail	5	5	5

Chapter 5

Conclusions

This chapter concludes the present dissertation, compiling a discussion and a critical analysis of the results, presenting future evolution possibilities of mobile communications, as well as mid-term future academic work proposals.

The main objective of this study was to study the implementation of a 5G network over an existing LTE network, in order to understand the advantages and disadvantages in terms of coverage and capacity that the new network brings. To complete this objective, a model was developed able to analyse several scenarios according to the input parameters and to verify several indicators of the network that allows to obtain results on one capacity and coverage. Several simulations were made by varying the input parameters to understand the impact of user density, frequency bands and bandwidths, traffic profiles and MIMO order. These simulations were done for both downlink and uplink. To simulate this network, the metropolitan region of Lisbon was chosen as the reference scenario, which contains several municipalities similar to other urban regions of the country. Thus, input parameters for each of these municipalities were used to simulate the behaviour of a 5G network.

In the first chapter of this thesis, one briefly describes the evolution of mobile communications emphasising the transition from the 4G network to the 5G generation. A brief explanation is given of the growth of mobile data in today's services. Finally, the motivation that leads to the development of this thesis is presented.

Chapter 3 begins by presenting the models developed in this thesis, as well as the simulator that implements them. As for the models, the mathematical expressions that calculate the simulation parameters and the algorithms were based on previous theses. However, their implementation was done from scratch. These models allow to simulate as realistically as possible a mobile communications network taking into account aspects such as the geographical area of implementation, population density and different traffic profiles. However, user's distribution is done uniformly throughout the cell. In reality, this distribution is not uniform, and their position depends greatly on the scenario, users are more likely to use the mobile phone when they are at a bus stop or when they are sitting in the office or in a restaurant. Though, the lack of geographic tools that simulate the dispersion of users both in indoor or outdoor environment depending on the scenario in which it is more likely a user to use mobile communications. The best option would be to use a random generator of users that distribute them not uniformly throughout the cell. Nevertheless, a random user generator would not simulate what happens in reality and by being random, the results could tend to an unrealistic value. For this reason, a uniform distribution of users throughout the cell was chosen, thus, for a certain user density according to the municipality to be analysed, the number of users covered by each of the four modulations considered in the simulation is calculated. Since the distribution of users is uniform, it means that there are as many users near the centre of the cell as they are on cell edge, and therefore, each user's SNR condition is considered to be the mean of the minimum and maximum SNR values that each modulation can serve. That is, in the processing of user's generation by the simulator, these are located in the centre of the area covered by the respective modulation. This methodology is valid only when a uniform distribution of users is considered. In order to calculate the area of each modulation, calculates first the reception power with the link budget that in turn only takes into account the slow fading margin. Then the receive power is used to calculate the path loss using a propagation model. In this thesis, one considers the propagation model described in Annex B, Winner Plus, developed specifically for recent technologies such as LTE and 5G. The expressions of throughput according to the SNR of each user are presented in Annex A. Moreover, the traffic model applied to the users covered in the cell, in order to satisfy different services and scenarios, was developed based on previous theses so that there can be a reference. Chapter 3 also describes the implementation of the models in the simulator that was done from scratch. Finally, the model was checked to ensure that all models are well implemented. In this measurement, the WINNER Plus model was compared with the COST Okumura Hata propagation model, already used by other works, verifying therefore the correct implementation, since the results of both models are coherent. It has also been confirmed that the percentage of cell usage increases with increasing user density, the number of served users decreases when the cell is in saturation and the density of users increases and the users served by the service with the most important priority are the last ones to be switched off.

Chapter 4 begins by describing the reference scenario considered in this thesis. In this scenario all the parameters used in the simulator are described, as well as their variation so that their impact on the coverage and capacity of the network can be evaluated. The study is done for the two links of the connection between BS and UE, downlink and uplink. For these connections, the impact of the user density is studied, which together with the operator penetration and usage ratios can determine the area of cell for each municipality configuration of Lisbon in an urban setting. For these municipalities margins are considered to take into consideration in the dimensioning of coverage and cell capacity, such as the percentage of indoor and outdoor users. For these users a different traffic model is applied in downlink and uplink, since the services consumed and their demand are also different. The study done for these scenarios also involves different frequency bands and bandwidths. In downlink there is only one frequency band available, however, for uplink different frequency bands can be used to support the large capacity demand on the part of the network. Also, when using lower frequency bands, the coverage area increases thus covering more users. However, the bandwidths are lower than those used in downlink. For this reason, since the reference scenario must be common to the two paths of the link, the frequency band and bandwidth is 3500 MHz and 50 MHz respectively. However, other configurations of frequency bands and bandwidths were also studied, since they have different characteristics that are worth analysing, such as the fact that they have a larger range covering a larger area. The results of this study, made for three numerologies, 15, 30 and 60 SCS, include the analysis of user density, different bandwidth and frequency bands, the impact of having a throughput reference at the cell edge, variation of service utilisation and respective throughputs taking into account various user distribution profiles and finally the impact of the use of MIMO.

In the analysis of the impact of the number of users, one density was increased until the usage percentage of the cell was 100 % for all numerologies. The density of users in downlink, which corresponds to the reference scenario, has a very low density when compared to the densities of the municipalities. Therefore, it should not be forgotten that the density of users of each municipality is multiplied by the ratio of penetration and usage to obtain the number of active users. However, the density corresponding to the downlink reference scenario is three times smaller for the average density of the municipalities of Lisbon. This is because in most cases the link that limits the cell radius is the uplink direction. Since the cell cannot be saturated in order to study the effect of the different variables in the reference scenario, the cell radius is larger, and the number of users supported is also lower. By forcing the cell to have a use limit of 75 %, with increasing user density, its radius begins to decrease, however it is higher than in uplink for the average user density that should support of a municipality of Lisbon. In uplink the study of the variation of users allows to conclude that this scenario does not impose restrictions of capacity, since a density of users greater than the intended one is supported.

By varying the frequency and bandwidth, in downlink only the study of bandwidth variation is done, since there is only one frequency band for downlink. By increasing the bandwidth to the double, in the same numerology as it would be expected the capacity of the cell is also twice, as the usage percentage decreases by half. However, it is interesting to note that with the increase in numerology, that is, with twice the bandwidth per RB, cell capacity is not doubled. This effect is due to the fact that there are users who are fully served with only one RB, and only those who need two RBs is benefiting from the increase in numerology. In uplink the use of bandwidths higher than the reference bandwidth has the same effect as in downlink, however, for this connection the 20 MHz bandwidth is also studied which causes a 2.5 times increase in usage percentage in the cell. With the use of lower frequency bands, the 1800 MHz band results in a gain in the usage percentage that is three times greater than the reference band, and with the 800 MHz band the impact cannot be determined because the cell goes into saturation. However, the cell radius impact gain is 1.65 for the 1800 MHz frequency band and 3.2 for the 800 MHz band.

As for the analysis of the impact of a reference throughput on the cell edge, this analysis can be made purely theoretical. Since the QPSK modulation serving the users in the cell edge reaches lower SNR conditions, the coverage area of this modulation concerns about 30 % of the total area covered by the cell. Thus, when applying the traffic model to users in this area, 30 % of the cell resources will also be allocated respectively, since the distribution of users is uniform, and the traffic model is the same throughout the cell. Therefore, by imposing a certain percentage of resource allocation on the cell edge, the maximum throughput reached in this area is directly influenced, or vice versa. In the natural dimensioning of the system, the cell edge will always consume about 30 % of the resources, except if it is applied a resource reduction algorithm, until it reaches manually imposed conditions.

For the reference scenario one considers that all users are in a residential environment, however, for a more realistic approach the ROM scenario is considered, which also takes into account the business environment and a mixture of the two. In both downlink and uplink connections it is seen that the ROM scenario has impact on both the percentage of cell usage and the total traffic generated of about half of the reference scenario. This study is done using the average throughput of each service, but when using the maximum throughputs, in downlink the cell gets saturated, however, in uplink the percentage of cell usage increases three times and the traffic generated increases 5 times.

By using a more realistic traffic model of what will happen in a 5G network, one considers a video centric model approach based on [Alco17], which focuses on the percentage of use of services in video. When applying this model, in downlink the percentage of cell usage and the traffic generated have a gain of 1.5 times the reference scenario, though in uplink the gain is about 1.8 times. This difference of gains between downlink and uplink is due to the traffic model applied in the cell, the services used in uplink are different, which causes different results.

Regarding the use of MIMO, this technology has real gains different from the theoretical ones, however, due to its recent implementation, data on its gains for higher MIMO orders does not yet exist in the literature. In this way this study is purely theoretical. So, when the cell usage percentage is not in saturation, the MIMO gain is exactly as predicted theoretically, reducing one percentage usage by half each time a higher MIMO order is used. However, when the cell is saturated, as in the case of using the maximum throughputs of downlink services, the necessary gain is verified so that the cell is no longer saturated. This gain is about 8 times the reference scenario and allows to achieve total traffics in the cell with values of 350 Mbps. The total traffic of a cell, according to [ViQR10], is about three times smaller than the peak data rate, which allows to conclude that the obtainable throughput in this scenario reaches the order of Gbps, as reported in the 5G literature.

The simulator implemented for the study of this network allows to conclude how the variations of some parameters of the network behave. However, a mobile communications network is more complex than the one implemented in this simulator. Like all works, there is always room to correct or improve certain aspects of the simulator. In reality, a city has buildings with different structures and heights, whereas in the simulator it is taken into account that all are equal with the same height. Another aspect of the geographical point is the distribution of users that can apply geographic models to distribute the appropriate percentage of indoor and outdoor users on the area most likely to be present, and then apply a throughput model according to each user's SNR condition. Another aspect to improve is the SNR throughput model, since there are currently no technical data on the 256 QAM modulation, to obtain the SNR throughput curves, an extrapolation was made based on the expressions of the lower modulations and with the gains theoretically calculated in the literature.

At the network level the aspects that can be improved in future works are the interference of other cells, since in this simulator the interference is equal both for users in the centre of the cell and at the edge. In the analysis of other frequency bands in uplink, load balancing methods should be used to manage the allocation of resources to users. In addition to analysing other parameters that may also influence the network such as antenna height and transmit power, another important aspect in 5G that is different from LTE is the form of communication between the BS and the UE. While in LTE this communication is done on FDD, in 5G it was TDD. Thus, for results that are closer to reality, the study of dimensioning of coverage and capacity must be done in downlink and uplink simultaneously. However, since the analysis of these links occurs in situations where the cell is not saturated and the purpose for uplink binding is to study several frequency bands. An individual analysis of each link is also consistent with the final results. Also, the MIMO analysis has a lot of room to improve by implementing real gains for the respective MIMO orders.

Annex A

Propagation Models

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

A.1 Winner Plus

This model allows one to estimate the path loss between the BS and the UE for different scenarios. This model was developed to be used in frequencies between 0.5 and 6 GHz in different configurations like rural, sub urban and urban. It also considers the possibility of the Line of Sight (LoS) and Non-Line of Sight (NLoS). In this thesis is considered only the urban case and the parameters used are based on [KMHJ10].

A.1.1 Urban Macro-Cell

In this scenario, buildings height and density are mostly homogenous, and their organisation form a regular Manhattan type of grid. Typical building heights are four floors.

The path loss for the LoS is given by:

$$L_{U[\mathrm{dB}]} = 40\log_{10}\left(d_{[\mathrm{m}]}\right) + 9.27 - 14\log_{10}\left(h'_{BS[\mathrm{m}]}\right) - 14\log_{10}\left(h'_{MS[\mathrm{m}]}\right) + 6\log_{10}\left(f_{c[\mathrm{GHz}]}\right) \tag{A.1}$$

where:

- d: Distance in meters between the BS and the UE;
- h'_{BS}: Effective height in meters of the BS;
- h'_{MS}: Effective height in meters of the UE;
- f_c: Frequency used in GHz, in this thesis it is considered the 3,5 GHz band.

The effective height of the antennas can be computed as follows:

$$h'_{x[\mathrm{m}]} = h_{x[\mathrm{m}]} - 1 \tag{A.2}$$

where h_x is the actual antenna height.

The shadow fading (σ) is 6 dB.

The expression (A.1) is applicable in the case of the break point distance (d_{BP}) being less than the distance (d), and d must be less than 5 km. The d_{BP} is given by:

$$d_{BP[\mathrm{m}]} = 4 \cdot h'_{BS[\mathrm{m}]} \cdot h'_{MS[\mathrm{m}]} \cdot \frac{f_{c[\mathrm{GHz}]}}{c_{[\mathrm{m/s}]}} \tag{A.3}$$

where c is the propagation velocity in free space ($3 \times 10^8\ m/s$).

For the NLoS, the path loss given by:

$$L_{U[\mathrm{dB}]} = \begin{cases} \left(44.9 - 6.55\log_{10}\left(h_{BS[\mathrm{m}]}\right)\right)\log_{10}\left(d_{[\mathrm{m}]}\right) + 5.83\log_{10}\left(h_{BS[\mathrm{m}]}\right) \\ \quad +16.33 + 26.16\log_{10}\left(f_{c[\mathrm{GHz}]}\right), \quad 0.45\ GHz < f < 1.5\ GHz \\ \left(44.9 - 6.55\log_{10}\left(h_{BS[\mathrm{m}]}\right)\right)\log_{10}\left(d_{[\mathrm{m}]}\right) + 5.83\log_{10}\left(h_{BS[\mathrm{m}]}\right) \\ \quad +14.78 + 34.97\log_{10}\left(f_{c[\mathrm{GHz}]}\right), \quad 1.5\ GHz < f < 2\ GHz \\ \left(44.9 - 6.55\log_{10}\left(h_{BS[\mathrm{m}]}\right)\right)\log_{10}\left(d_{[\mathrm{m}]}\right) + 5.83\log_{10}\left(h_{BS[\mathrm{m}]}\right) \\ \quad +18.38 + 23\log_{10}\left(f_{c[\mathrm{GHz}]}\right), \quad 2\ GHz < f < 6\ GHz \end{cases} \tag{A.4}$$

A.1.2 Bad Urban Macro-Cell

This scenario describes cities with buildings with distinctly inhomogeneous heights or densities. The BS is typically above the average height of the city, and this scenario also considers the possibility of higher buildings and large water areas separating the built-up areas.

The path loss for this scenario is only developed for the NLoS case and this one is equal to L_U for the NLoS scenario.

A.1.3 Urban Macro Outdoor to Indoor

Similar to the scenario A.1.1, the height of the BS is above the average height of the buildings in the city, meaning that at the higher floors there will be quite long LoS paths to the walls penetrated by the signals. On the other hand, at the lower floors there will be quite often a severe shadowing.

The path loss for this scenario is given by the followed expression:

$$L_{UOI[\mathrm{dB}]} = L_{U[dB]}\left(d_{out[\mathrm{m}]} + d_{in[\mathrm{m}]}\right) + 17.4 + 0.5d_{in[\mathrm{m}]} - 0.8h_{MS[\mathrm{m}]} \tag{A.5}$$

where:

- L_U: Path loss between the BS and the wall. This parameter can be computed as LoS or NLoS.
- d_{out}: Distance in meters between the BS and wall.
- d_{in}: Distance in meters between the wall and the indoor UE.
- h_{MS}: Is computed by the expression:

$$h_{MS[\mathrm{m}]} = 3n_{Fl} + 1.5 \tag{A.6}$$

where:

- n_{Fl}: Floor index. The ground floor has index 1.

The shadow fading (σ) is 10 dB.

The expression (5.6) is applicable if the distance (d) is between 50 meters and 5 km.

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