TÉCNICO LISBOA

LTE Fixed to Mobile Subscribers QoE evaluation

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To my family

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Abstract

The main problem addressed in this thesis is the analysis of the LTE cells performance in order to assess the quality of the data services provided by them. Taking that into account, two simulators were developed in order to characterise and analyse a sample of experimental measurements. Knowing the measurements performance one can find the cells in which the users who are connected to them cannot have an acceptable quality of service (so called pessimistic cells). That cells are defined by having more than 30% of pessimistic measurements in a sample with, at least, a total of 20 measurements. It is important to highlight that, during the off-peak hours, the LTE 1 800 MHz frequency band has not any cell with a pessimistic performance. Considering only the measurements reported during the off-peak hours, one can realise that the performance is essentially limited by the network coverage. On the other hand, during the on-peak/busy hours, the cell capacity has a direct influence on the quality of the data services which are provided to the users. In order to provide better services, some improvements in the cells capacity and in the receiver conditions can be implemented by the mobile operators. For example, an external antenna can be placed outdoors and connected to the user equipment's in order to remove the extra attenuation that comes from the indoor penetration. Considering the LTE 800 MHz band, theoretical data rate can increase from 4.64 to 49.17 Mbit/s when an outdoors antenna is added.

Keywords

LTE, Indoor Scenarios, Quality of Experience, Data Services, Data Rates, Penetration Attenuation.

Resumo

O principal objetivo desta tese passa por analisar o desempenho de células LTE de forma a avaliar a qualidade dos serviços de dados que elas disponibilizam. Tendo isso em conta, dois simuladores foram desenvolvidos de forma a caracterizar e analisar uma amostra de medições experimentais. Conhecendo o desempenho de cada uma das medições é possível identificar as células onde os utilizadores não têm uma qualidade de serviço aceitável (designadas por células pessimistas). Essas células são definidas por terem mais de 30% de medições pessimistas, numa amostra com pelo menos 20 medições. É importante realçar que, durante as horas fora de pico, a banda LTE de 1 800 MHz não têm nenhuma célula com desempenho pessimista. Considerando apenas as medições reportados pelos terminais dos utilizadores durante as horas fora de pico, é possível concluir que, neste período, o desempenho das células é essencialmente limitado pela cobertura, não dependendo da capacidade. Por outro lado, durante as horas de pico, a capacidade das células influencia de forma bastante direta a qualidade dos serviços disponibilizados aos utilizadores. Assim, de forma a disponibilizar melhores serviços, algumas melhorias relacionadas com a capacidade das células e com as condições do recetor (terminal) podem ser implementadas na rede pelos operadores de telecomunicações. Por exemplo, uma antena adicional pode ser colocada no exterior de forma a evitar a atenuação por penetração. Considerando a banda LTE de 800 MHz, os valores teóricos da taxa de dados podem aumentar dos 4.64 aos 49.17 Mbit/s quando esta antena exterior é adicionada.

Palavras-chave

LTE, Cenários Interiores, Qualidade de Experiência, Serviços de Dados, Taxa de Dados, Atenuação por Penetração.

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List of Acronyms

16-QAM	4 bits per symbol Quadrature Amplitude Modulation
3G	3rd Generation of Mobile Communications Systems
3GPP	Third Generation Partnership Project
4G	4th Generation of Mobile Communications Systems
64-QAM	6 bits per symbol Quadrature Amplitude Modulation
ACS	Auto Configuration Server
AMC	Adaptive Modulation and Coding
ANACOM	Autoridade Nacional de Comunicações
BLER	Block Error Rate
BS	Base Station
CA	Carrier Aggregation
CDF	Cumulative Distribution Function
CP	Cyclic Prefix
CQI	Channel Quality Indicator
CS	Circuit-Switched
DAS	Distributed Antenna System
DL	Downlink
DVB-T	Digital Video Broadcasting-Terrestrial
eNodeB	Evolved Node B
EPA	Extended Pedestrian A
EPC	Evolved Packet Core
EPS	Evolved Packet System
ETU	Extended Typical Urban
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
EVA	Extended Vehicular A
FDD	Frequency Division Duplex
FM	Frequency Modulation
FTP	File Transfer Protocol
FTTH	Fibre-to-the-Home
GBR	Guaranteed Bit Rate
GSM	Global System for Mobile Communications
HD	High Definition
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access

HSPA+	HSPA Evolution
HSS	Home Subscription Server
HSUPA	High Speed Uplink Packet Access
IMS	IP Multimedia Subsystems
IP	Internet Protocol
ITS	Intelligent Transportation Systems
KPI	Key Performance Indicators
LoS	Line-of-Sight
LTE	Long Term Evolution
LTE1800	LTE 1 800 MHz frequency band
LTE2600	LTE 2 600 MHz frequency band
LTE800	LTE 800 MHz frequency band
LTE-A	LTE-Advanced
M2M	Machine-to-Machine
MIMO	Multiple-Input Multiple-Output
MM	Mobility Management
MME	Mobility Management Entity
MT	Mobile Terminal
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
P2P	Peer-to-Peer
PBCH	Physical Broadcast Channel
PCRF	Policy and Charging Resource Function
PDCCH	Physical Downlink Control Channel
PDF	Probability Density Function
PDSCH	Physical Downlink Shared Channel
P-GW	Packet Data Network Gateway
PRACH	Physical Random Access Channel
PS	Packet-Switched
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QCI	QoS Class Identifier
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RB	Resource Block
RBG	Resource Block Group
RE	Resource Element
RF	Radio Frequency
RLB	Radio Link Budget

RMSE	Root Mean Squared Error
RRM	Radio Resource Management
RS	Reference Symbol
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
SAE-GW	System Architecture Evolution Gateway
SC-FDMA	Single Carrier Frequency Division Multiple Access
S-GW	Serving Gateway
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
TB	Transport Block
TDD	Time Division Duplex
TE	Terminal Equipment
TM	Transmission Mode
TR	Technical Report
UE	User Equipment
UHF	Ultra High Frequency
UL	Uplink
UMTS	Universal Mobile Telecommunications System
USIM	Universal Subscriber Identity Module
VoIP	Voice-over-IP
VRB	Virtual Resource Block
WCDMA	Wideband Code Division Multiple Access

List of Symbols

α	Confidence interval variable
$\sqrt{\overline{\varepsilon^2}}$	Root mean squared error
η_{data}	Percentage of symbols carrying user data
μ	Average value
μ_y	Average of the observations of variable y
ρ_{CCH}	Fraction of PDSCH resources interfered by control channels
ρ_{IN}	SINR
ρ_N	SNR
σ	Standard deviation
Δt	Time interval
a_i	i^{th} fitted coefficient
$a_{i,max}$	Maximum value of coefficient i, which are obtained without control channels
a_{pd}	Average power decay
B_{ch}	Channel bandwidth
B_N	Noise bandwidth
B_{RB}	Bandwidth of one RB
C_m	Extended Okumura-Hata model variable
d	Distance between the BS and the UE
f	Frequency band
F^{-1}	Inverse of the CDF F

F_i	F value in ring i
F_N	Noise figure
G_r	Gain of the receiving antenna
G_t	Gain of the transmitting antenna
h_{BSe}	Effective height of BS antenna
H_{mu}	Okumura-Hata model variable
h_{UE}	User equipment height
$h_{UE,in}$	Indoor user equipment height
$h_{UE,out}$	Outdoor user equipment height
I_{CQI}	CQI index
$\overline{I_{CQI}}$	Average CQI index
I_{RSSI}	RSSI
K_f	Okumura-Hata model correction factor
L_c	Loss in the cable between the transmitter and the antenna
$L_{p,indoor}$	Path loss coming from indoor penetration
$L_{p,outdoor}$	Path loss coming from the COST-231 Okumura-Hata model
$L_{p,total}$	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_c	Correction margin
M_{FF}	Fast fading margin

M_{SF}	Slow fading margin
n	Number of observations
$N_{\Delta t}$	Total number of measurements made during a Δt time interval
$N_{ant,DL}$	Number of configured antenna ports in DL
$N_{b/sym}$	Number of bits per symbol
N_{CRS}	Number of cell-specific reference signals multiplexed with PDSCH per RB
N_I	Number of interfering signals reaching the receiver
N_{MIMO}	MIMO order
$N_{m,n}$	Normalised number of measurements
N_{PDCCH}	Number of allocated symbols for PDCCH
N_{RB}	Number of RBs
$\overline{N_{RB}}$	Average number of RBs used
N_{RE}	Number of REs
$N_{sub/RB}$	Number of sub-carriers per RB
$N_{sym/sub}$	Number of symbols per subcarrier
N_u	Total number of users connected to a single cell
$\overline{N_u}$	Average number of users connected to a single cell
$\overline{p^{\Delta t}}$	Average of the p parameter during a Δt time interval
$\overline{p^{\Delta t,u}}$	Average of the p parameter during a Δt time interval and for all the users connected to a single cell
$p(t_n)$	p parameter in the n^{th} time instant
$p(t_n, u_m)$	p parameter of the m^{th} user in the n^{th} time instant
$p\%$	Confidence level
P_{Bch}	Percentage of the used channel bandwidth

p_i	i^{th} polynomial fitted coefficient
P_I	Interfering power
$P_{I,i}$	Interfering power coming from transmitter i
P_N	Noise power at the receiver antenna
$P_{N,RE,DL}$	Thermal noise power per RE in DL
P_r	Power available at the receiving antenna
$P_{r,RE,k}$	Estimated received power of the k^{th} RE
P_{RSRP}	RSRP
$P_{r,min}$	Power sensitivity at the receiver antenna
P_{Rx}	Power at the receiver
P_t	Power fed to the transmitting antenna
P_{Tx}	Transmitter output power
$P_{Tx,RE}$	Transmitter output power per RE
Q_{PDSCH}	Fraction of the PDSCH resources carrying user data
Q_{RSRQ}	RSRQ
R^2	R-square value
R_b	Data rate
$R_b^{p\%}$	Data rate for a $p\%$ confidence level
$R_{b,max}$	Maximum data rate over the radio channel
$R_{b,peak}$	DL peak data rates
$R_{b,RE}$	Data rate per RE
$\overline{R_{b,u}}$	Average DL data rate per user
t_n	n^{th} time instant

t_{RB}	Time duration of an RB
u_m	m^{th} user
y_i	Observation i
$\hat{y}_i$	Estimated or predicted value of y_i
z_p	Quantile value

List of Software

Inkscape	Vector graphics and images editor
MATLAB R2014b	Numerical computing environment
Microsoft Office Excel 2013	Spreadsheet application
Microsoft Office Word 2013	Word processor
Microsoft Visio 2013	Flow chart and diagram software
TI-Nspire™ CAS Student Software	Calculator and computational software
Web Intelligence Rich Client	User interface for building and analyse reports

Chapter 1

Introduction

This chapter provides a brief overview of the mobile communications systems evolution, with a particular focus on LTE. It also discusses the thesis motivation and presents the structure of this document.

1.1 Overview

In the past few years, not only the number of mobile subscribers has increased massively, but also mobile communications have known great technological developments that had a great impact at social and economic levels. According to [60SM14], nowadays there are more people around the globe owning mobile phones than a toothbrush. When ranked by importance to daily life, mobile phones are more important than cars, personal computers, television, microwave and coffee, and they are just as essential as deodorant and toothbrush.

In the past, mobile phones were used mainly for voice communication, however, currently they are used to access a wide range of services, and to do tasks that were previously only performed by computers. This implies that data services have, nowadays, the main role in mobile communications. According to [Eric14], data traffic grew around 10% quarter-on-quarter and 60% year-on-year, reaching 3.249 ExaBytes of total monthly traffic in 2014. The evolution of the mobile traffic for voice and data services (accessed by different devices) is presented in Figure 1.1.

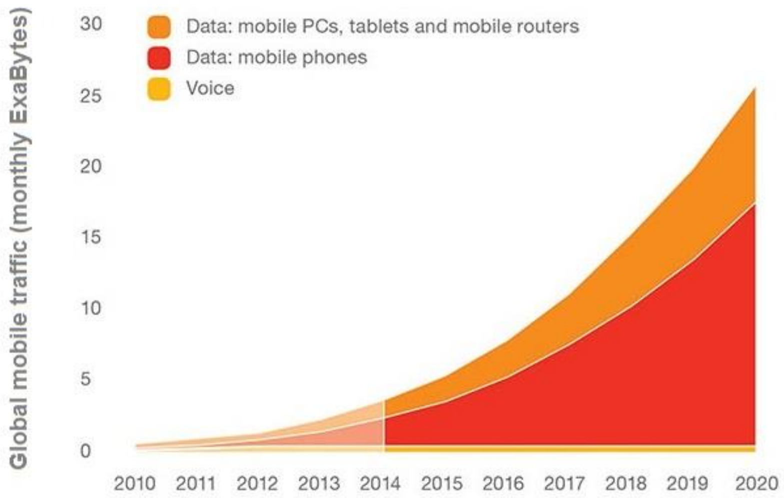

Figure 1.1 Global mobile traffic for voice and data, 2010-2020 (extracted from [Eric14]).

Due to the growing need for better users experience and higher data speeds for mobile users, new and more efficient mobile communications systems were developed over the past years. Third Generation Partnership Project (3GPP) has played an important role, being involved in the development of the latest releases concerning mobile communication technologies: Universal Mobile Telecommunications System (UMTS), also known as 3rd Generation (3G), and Long Term Evolution (LTE), so called 4th Generation (4G). Figure 1.2 presents the time schedules of 3GPP specifications and its commercial deployments. For UMTS, Wideband Code Division Multiple Access (WCDMA) Release 99 specification work was completed at the end of 1999, being followed by the first commercial deployments during 2002. The High Speed Packet Access (HSPA) standards were completed in March 2002 (High Speed Uplink Packet Access) and December 2004 (High Speed Downlink Packet Access) and the commercial deployments followed in 2005 and 2007, respectively. The first phase of HSPA Evolution (HSPA+) was completed in June 2007, and the deployments started during 2009. The LTE standard was approved at the end of 2007, backwards compatibility started in March 2009 and the first commercial networks started during 2010. LTE-Advanced (LTE-A) is the most recent release, was approved in December 2010 and it is currently in the deployment phase.

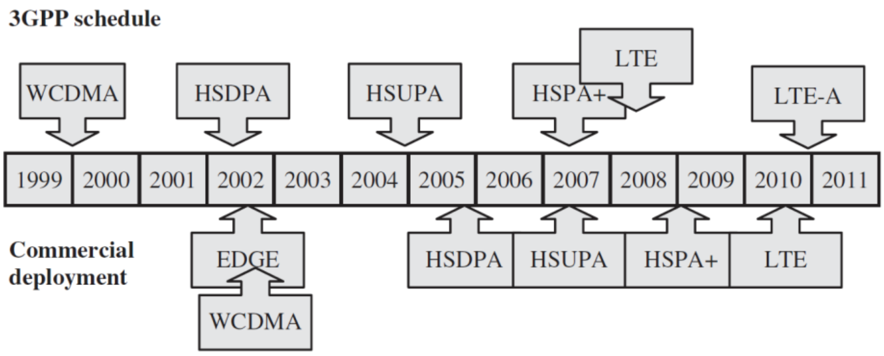

Figure 1.2 Schedule of 3GPP standard and their commercial deployments (extracted from [HoTo11]).

Since its commercial release, the number of LTE subscriptions is growing rapidly, and has reached around 350 million. In order to illustrate this growth, Figure 1.3 presents the evolution of the number of global mobile subscriptions since 2010 for different technologies. Despite the growth observed for LTE, according to [Eric14], in 2020 UMTS/HSPA will make up the majority of all subscriptions, with around 4.4 billion subscriptions, compared to around 3.5 billion for LTE.

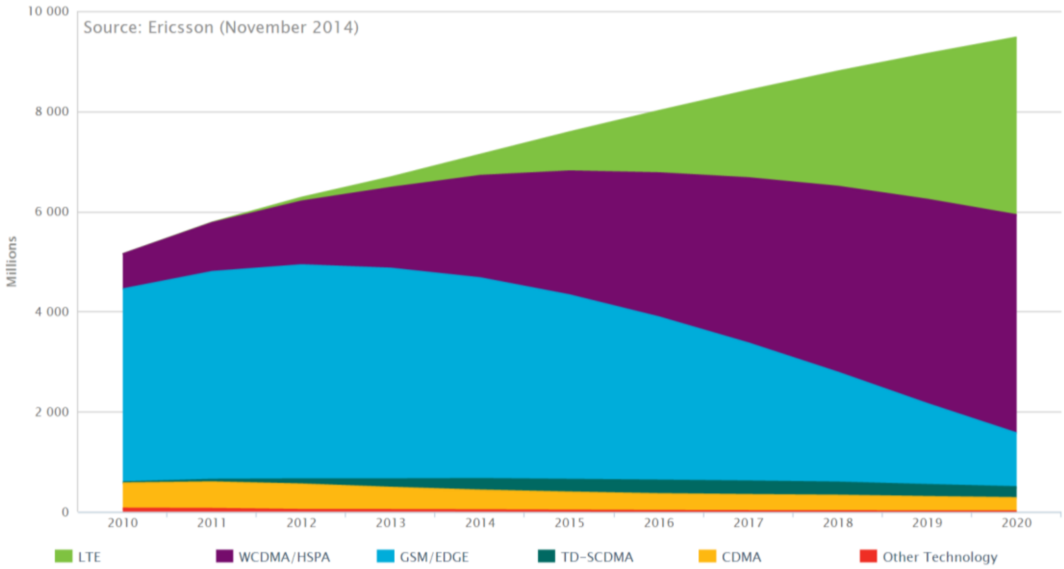

Figure 1.3 Area chart with the number of global mobile subscriptions for different technologies, 2010-2020 (extracted from [Eric14] traffic exploration tool).

Mobile users spend more than 85 % of their time indoors, and in today's connected world consumers expect to have instant access to the internet, regardless of whether they are indoors or outdoors. According to a study conducted by Ericsson [Eric14], there is a willingness to spend more on an improved experience regardless of location for mobile broadband users. Around 61 % of users are willing to pay to improve their indoors connectivity experience, and only 38 % to improve it outdoors. Thus, there are many reasons to study indoors environments and for mobile operators to provide better in-building coverage.

1.2 Motivation and Contents

Nowadays LTE networks are being deployed essentially in urban environments. LTE is optimised for data services and although being a mobile system it can be used to provide “fixed” services (e.g., wireless data connections) to users when they are at home. However, in urban areas fixed data connections provided by Fibre-to-the-Home (FTTH) are already a reality for almost all users. In terms of Quality of Service (QoS), cellular networks cannot compete with the optical fibre, but the usage of LTE to provide “fixed” services can be a good solution in rural areas, where it is more unsustainable to provide FTTH solutions. When an LTE network is designed or optimised to provide “fixed” data services, there are many matters that must be taken into account, e.g., the choice of frequency bands, the location of the base stations, and the characterisation of coverage in indoor environments. On the other hand, some performance parameters, like the QoS and the Quality of Experience (QoE), need to be evaluated in order to assess this possibility. This report addresses this problem, aiming at providing an assessment for several scenarios, and eventual guidelines for implementation.

The main objective of this thesis is the evaluation of LTE cells performance in order to assess the quality of data services. This analysis is based on the results obtained from two different models (developed from scratch) and taking a sample of more than 80 000 experimental measurements into account. The developed models, which automatically characterise the measurements and cells performance, are the main contribution of this work.

This thesis was done in collaboration with NOS, which is one of the biggest network operators in Portugal. The main conclusions taken as a result of this work are intended to give some guidelines to the operator, essentially on how can these “fixed” services be improved. It is important to notice that the measurements performed under the scope of this work were done with equipment supplied by NOS, and using its own deployed network. According to [NOS15], NOS has an LTE network covering more than 90% of the Portuguese population, offering a wide portfolio of mobile and data solutions. It is also important to mention that NOS also supported the experimental measurements results analysis.

In terms of contents, this thesis is divided into five chapters, followed by a set of annexes that add extra information and results to the main work. The present chapter makes a brief overview of the mobile wireless communication’s history evolution, showing the motivation behind the thesis.

In Chapter 2, some fundamental aspects regarding this work are introduced. It provides a brief description of LTE’s network architecture, presenting its main elements. A radio interface description follows, where aspects that distinguish LTE from previously deployed 3GPP systems are highlighted.

Coverage and capacity considerations are provided, including a summary of theoretical peak data rates achieved using different configurations for LTE. This chapter also presents information about some performance parameters, mainly focusing on the services and applications and some QoE aspects. To conclude this chapter, the state of the art related with the difficulties on the provisioning of indoor mobile data services is presented.

A description of the models used in this thesis is provided in Chapter 3, in which their mathematical formulation are detailed. Particular relevance is given to the following models: radio link budget, Signal to Noise Ratio (SNR) and Signal to Interference plus Noise Ratio (SINR), parameters on reference signal, data rate theoretical values and their respective confidence interval, channel quality indicator and, last but not least, cell coverage and capacity. The two threshold approaches implemented in MATLAB to analyse some experimental measurements are also described in this chapter. In the end, a brief assessment of the presented models.

Chapter 4 presents the scenarios description along with the models output results and their respective analysis. Some network improvements matters are also presented in the end of this chapter, essentially related with the receiver conditions and capacity issues.

Chapter 5 contains the main conclusions of this thesis, an analysis of the overall obtained results, and suggestions on future work.

Some auxiliary information and results to this thesis are provided as annexes. In Annex A, the device-capability classes defined for the user equipment in LTE Releases 8, 9 and 10 are shown. A brief explanation of the MeasurementsDataUpdated.xlsx file with a list of all the parameters, which characterise the experimental measurements, are presented in Annex B. All the data processing that were made in the original file provided by NOS, in order to create its “Updated” version, are also detailed. Annex C presents some confidential information related with this thesis, namely the conversion of some normalised values to their absolute ones, the thresholds values used in the absolute threshold model, and the two distinct manufacturers analysed in this work. In the end, Annex D and Annex E present additional results for Section 4.3.

Chapter 2

LTE Fundamentals

This chapter provides an LTE overview, mainly focussing on the network, the coverage and capacity aspects, and the performance parameters. A brief state of the art is also presented.

2.1 Cellular Network

Some key aspects of LTE's architecture and radio interface are provided in this section, based on [CCox14], [HoTo11], [SeTB11] and [Tols11].

2.1.1 Network Architecture

The cellular network architecture suffered a big revolution with the release of LTE. One of the most obvious changes between this new technology and the previous generations of cellular systems, like Global System for Mobile Communications (GSM) and UMTS, is the way that the network has been designed. Instead of GSM and UMTS that support both Circuit-Switched (CS) and Packet-Switched (PS) services, LTE is optimised to support only PS services. Furthermore, LTE has a flat architecture much more simple and with less involved nodes compared with the older systems. With this type of architecture, the latencies between nodes are reduced, improving the performance, being possible to have higher throughputs (required for higher end user data rates) and better packet delivery delays. A basic LTE network architecture is presented in Figure 2.1.

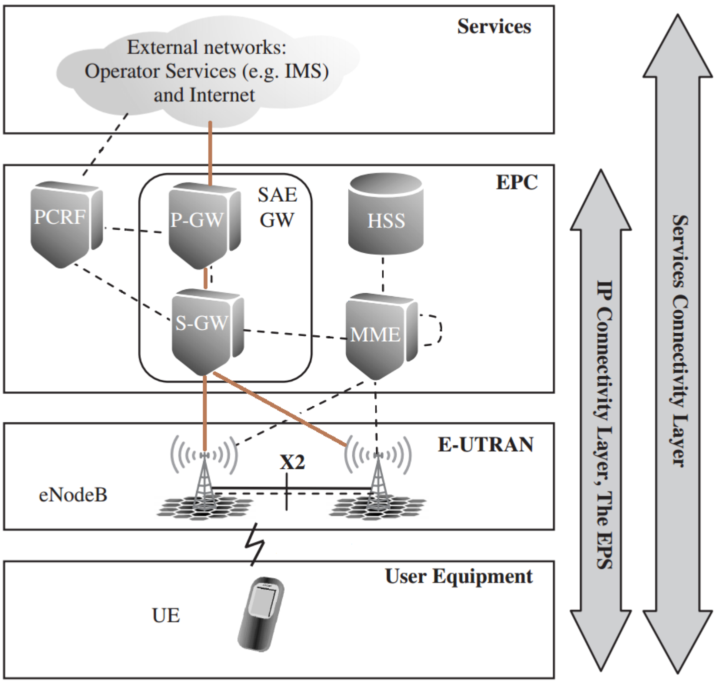

Figure 2.1 LTE architecture for E-UTRAN only network (adapted from [HoTo11]).

The elements of this architecture are divided into four main domains: the User Equipment (UE), the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN), the Evolved Packet Core (EPC), and the Services. The connections among network elements denote the traffic path (represented by brown lines in Figure 2.1) and the LTE signalling route (represented by dashed lines in Figure 2.1).

The Internet Protocol (IP) Connectivity Layer is represented by the Evolved Packet System (EPS) and is composed of the UE, the E-UTRAN and the EPC. Together, all the high level domains represent the Services Connectivity Layer.

The UE, also known as Mobile Terminal (MT) or Terminal Equipment (TE), is the device used by the user to communicate. This device has a removable Universal Subscriber Identity Module (USIM) that is used to authenticate and identify the user. The USIM is also used to protect radio interface transmissions through security keys and authentication protocols.

E-UTRAN is composed of a set of intelligent base stations called evolved Node Bs (eNodeBs), which are interconnected by the X2 interface. These eNodeBs support the radio access of the network and are responsible for establishing the connections between the UE and the EPC. Furthermore, some Control Plane functions are also performed by eNodeBs, such as Radio Resource Management (RRM) and Mobility Management (MM). The RRM allocates resources, based on requests, to control the radio interface usage. RRM is also in charge of prioritising and scheduling traffic according to the required QoS and to do the continuous monitoring of the resources usage. The MM decides when the UE performs a handover between cells, based on the measurements of the radio signal level made at the UE and at the eNodeB.

As mentioned in the beginning of this section, the EPC does not have a CS domain, so it is possible to remove some of the nodes and interfaces that were essential in the previous 3GPP systems. The main elements of this architecture are the following:

- The Mobility Management Entity (MME), which processes the signalling between the UE and the EPC. The MME is responsible for the establishment of the connection between these two domains and the management of its security;
- The System Architecture Evolution Gateway (SAE-GW), which is a combination of the Serving Gateway (S-GW) and the Packet Data Network Gateway (P-GW). The S-GW routes and forwards user data packets, serving as the mobility anchor for the data bearers during UE handovers. The P-GW is responsible for the allocation of the UE IP address and provides the connection between the UE and external packet data networks. P-GW can easily be described as the UE traffic door;
- The Policy and Charging Resource Function (PCRF), which supports the creation of rules and makes automatic policy decisions for each active subscriber on the network;
- The Home Subscriber Server (HSS), which is a database that contains user's information like: their profiles, their authentication and authorisation, and their physical location.

At last, the Services domain includes some services that are not provided directly by the mobile network operator. One example is the IP Multimedia Subsystems (IMS), which is an architectural framework for delivering IP multimedia services. It is also important to mention that Voice-over-IP (VoIP) can be natively implemented in LTE networks using these IMS services.

2.1.2 Radio Interface

Such as the network architecture, LTE's radio interface is very different compared with the interface of GSM and UMTS.

LTE multiple access uses Orthogonal Frequency Division Multiple Access (OFDMA) for downlink (DL) and Single Carrier Frequency Division Multiple Access (SC-FDMA) for uplink (UL). OFDMA allocates radio resources to multiple users over a number of sub-carriers, which are spaced orthogonally 15 kHz apart in the spectrum. The usage of orthogonal channel spacing provides a good inter-carrier isolation and an efficient use of spectrum. According to [Tols11], LTE DL spectrum utilisation can be four times better than UMTS High Speed Downlink Packet Access (HSDPA) and the UL about three times better than High Speed Uplink Packet Access (HSUPA).

OFDMA is based on Orthogonal Frequency Division Multiplexing (OFDM), but has some differences in the scheduling and resources assignment. In OFDM, all the bandwidth is assigned to a single user (for a period of time), while in OFDMA different users can share the same bandwidth at the same time. This means that in OFDMA, users can be assigned in the time and frequency domains, optimising the resource usage.

As mentioned before, UL uses SC-FDMA. The main difference between this access technique and OFDMA is that in SC-FDMA the signal looks like a single carrier modulated at a higher data rate. The average power in SC-FDMA is lower compared with OFDMA, and thus the power consumption of the UE is optimised.

LTE's resource allocation is based on Resource Blocks (RBs). An example of LTE's resource structure is presented in Figure 2.2.

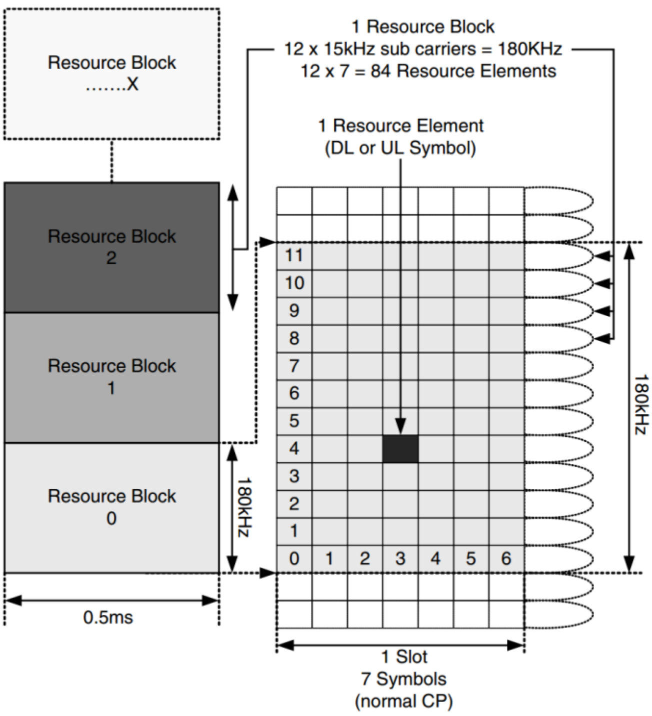

Figure 2.2 LTE's resource structure with RBs and resource elements (extracted from [Tols11]).

An RB is a group of 12 sub-carriers with 15 kHz resulting in a 180 kHz minimum bandwidth allocation. One slot can be a combination of 7 or 6 Resource Elements (REs), depending if a normal or an extended, respectively, Cyclic Prefix (CP) length is used. The RE is the smallest frequency/time unit for transmission and corresponds to one OFDM sub-carrier during an OFDM symbol interval.

The smallest resource unit that is assigned to a single user is one scheduling block, which has a duration of 1 ms. A scheduling block is a group of two consecutive RBs, each one with 0.5 ms duration. It is important to notice that the quantity of scheduling blocks assigned to a single user is proportional to the data speed required by the user.

Some Reference Symbols (RSs) are inserted, in a fixed location, into the OFDM time/frequency grid. These symbols are used to synchronise, demodulate and to evaluate the LTE channel. The reference symbols are also used for Multiple-Input Multiple-Output (MIMO) operation. LTE uses MIMO to increase the peak data rates by a factor of 2 (MIMO 2×2) or 4 (MIMO 4×4) depending on the antenna configuration.

According to [3GPP14a], there are three different types of resource allocation in DL. The resource allocation of Type 0 is based on Resource Block Groups (RBGs), which are a set of consecutive RBs. The number of RBs per RBG is variable, and depends on the system bandwidth. The resource allocation of Type 1 is based on a set of RBGs called RGB Subset. The number of RBG Subsets is equal to the number of RBs in an RBG, and each one of these subsets can be assigned to an UE. The resource allocations of Type 2 is based on a set of contiguously allocated localised Virtual Resource Blocks (VRBs) or distributed VRBs.

In order to transport data and signalling messages, LTE uses three types of channels: the Logical, the Transportation and the Physical ones. Logical channels define which type of information is transmitted in the network. These channels are composed of the control channels, which are used to transmit control plane information, and the traffic channels, which carry the data between the UE and the network. The transportation channels, used in DL and UL, define how the information is transmitted. At last, the physical channels define where the data and the signalling messages are transmitted. They are divided into: Physical Downlink Shared Channel (PDSCH), Physical Broadcast Channel (PBCH), Physical Downlink Control Channel (PDCCH), Physical Uplink Shared Channel (PUSCH), Physical Uplink Control Channel (PUCCH) and Physical Random Access Channel (PRACH). In LTE, user data in DL is transported in PDSCH, which is also used for broadcast system information not carried on the PBCH, and for paging messages. The transmission of data in the PDSCH is made in units known as Transport Blocks (TBs).

LTE can be deployed using various Radio Frequency (RF) channel configurations. According to [HoTo11], there are 22 bands specified for Frequency Division Duplex (FDD) and 9 bands for Time Division Duplex (TDD). LTE can coexist with the previous 3GPP technologies, so some bands can be used simultaneously by LTE and by other technologies. In Europe, mobile operators have over 600 MHz of spectrum available for LTE, including the 800 (LTE800), 900, 1 800 (LTE1800), 2 100 and 2 600 MHz bands (LTE2600).

In Portugal, ANACOM (the Portuguese regulator of the communications sector) issued an auction for some of the listed bands to be used to deploy LTE. According to [ANAC12a], the three major network operators in Portugal (NOS, MEO and Vodafone) bought the rights to use 29 of the 39 lots under auction. Table 2.1 describes the bands owned by Portuguese operators for LTE purposes. These values take the 6 MHz bandwidth that some operators already had in the 1 800 MHz band for GSM1800 into account. In Europe, FDD is the most used duplex mode, so the frequencies presented in Table 2.1 are related to this mode.

Lower frequency bands are currently used by mobile operators to provide LTE coverage. On the other hand, higher frequency bands have a small coverage area due to the fact that signal attenuation increases with frequency. However, these bands are also important, because they are used to increase network capacity. In the specific case of LTE in Portugal, the 2 600 MHz and 1 800 MHz bands provide up to 20 MHz or 14 MHz of additional capacity, respectively.

Table 2.1 Frequency bands allocated for the three major network operators in Portugal to LTE FDD purposes (based on [ANAC12a] and [ANAC12b]).

Band [MHz]	**Owner**	**Total spectrum [MHz]**	**Uplink band [MHz]**	**Downlink band [MHz]**
800	MEO	2×10	832 – 842	791 – 801
	Vodafone		842 – 852	801 – 811
	NOS		852 – 862	811 – 821
1 800	Vodafone	2×20	1 710 – 1 730	1 805 – 1 825
	NOS		1 730 – 1 750	1 825 – 1 845
	MEO		1 750 – 1 770	1 845 – 1 865
2 600	Vodafone		2 510 – 2 530	2 630 – 2 650
	NOS		2 530 – 2 550	2 650 – 2 670
	MEO		2 550 – 2 570	2 670 – 2 690

LTE can use three modulation schemes: the Quadrature Phase Shift Keying (QPSK), which has 2 bits per symbol; the 4 bits per symbol Quadrature Amplitude Modulation (16-QAM); and the 6 bits per symbol QAM (64-QAM). The first two modulation schemes are available in all UEs, however, 64-QAM is only supported by some devices. UEs can be divided into five categories according to their peak throughput, modulation schemes, and MIMO support, as detailed in Annex A.

The modulation scheme and coding rate may be adapted according to the channel conditions, when using Adaptive Modulation and Coding (AMC). In this situation, the transmitter tries to match the data rate for each user to the variations in received signal quality. LTE systems adjust the transmitted information data rate using both modulation scheme and channel coding rate options, to match the prevailing radio channel capacity for each user, based on a DL channel conditions prediction. That prediction is supported by the Channel Quality Indicator (CQI) feedback transmitted by the UE in UL. The CQI is the most important part of the channel information feedback and is a four bit quantity, which indicates the maximum data rate that the mobile can handle with a Block Error Rate (BLER) probability (computed on the transport blocks) not exceeding 10%. The CQI index is reported between 1 and 15, however it can also be 0 if the BLER exceeds 10%. It is important to note that the reported CQI is not a direct indication of Signal to Noise Ratio (SNR). It also depends on the implementation of the mobile receiver, because an advanced receiver (for example, with more complex signal processing algorithms) can successfully process the incoming data at a lower SNR than a more basic one. Table 2.2 shows how the CQI is interpreted in terms of the DL modulation scheme, coding rate and the number of information bits per symbol (resource element).

Table 2.2 CQI index (extracted from [HoTo11]).

CQI index	Modulation	Coding rate × 1024	Bits per symbol
0	n/a	0	0.0000
1	QPSK	78	0.1523
2		120	0.2344
3		193	0.3770
4		308	0.6016
5		449	0.8770
6		602	1.1758
7	16-QAM	378	1.4766
8		490	1.9141
9		616	2.4063
10	64-QAM	466	2.7305
11		567	3.3223
12		666	3.9023
13		772	4.5234
14		873	5.1152
15		948	5.5547

A lower coding rate can be used in poor channel conditions, and a higher one when CQI is high. In terms of modulation schemes, it is known that a low-order modulation (e.g., QPSK) is more robust, being usually selected with lower CQI indexes. On the other hand, a higher value of CQI corresponds to a better quality of the radio link, so a more efficient modulation scheme can be used (e.g., 64-QAM). Furthermore, in this case, it is possible to reduce the number of redundant bits in a frame (increasing the number of bits used for information) allowing the usage of higher coding rates.

2.2 Coverage and Capacity

This section presents a basic description of LTE's coverage and capacity, focusing on indoor environments. The content presented here is manly based on [Tols15].

2.2.1 Coverage

When one talks about coverage, it is important to distinguish three categories of environments: rural, suburban and urban. This classification is done by taking some parameters into account as: terrain undulation, vegetation density, building density and height, open areas density, and water areas density. According to [Corr13], cells are usually classified into different categories depending on the cell's radius, the relative position of the BS antennas (comparing with neighbouring buildings) and its respective transmitted power. As it can been seen in Table 2.3, there are four categories: macro- (which could be large or small), micro-, pico- and femto-cells.

Table 2.3 Cell's radius and transmitted power for the different cell categories (based on [Corr13] and [3GPP14b]).

Cell category	Radius [km]	Maximum transmitted power [dBm]
Macro	> 1	44
Micro	0.1 – 1	38
Pico	< 0.1	24
Femto	< 0.05	20

Depending on the quality of the radio link, the LTE system will adapt the modulation scheme used on the radio channel automatically according to the actual radio channel quality. The 64-QAM modulation scheme requires a good radio quality, since it has a lower robustness to interference and noise in the radio channel, so the coverage range is close to the antenna. In order to increase the coverage area the modulation must be downgraded automatically due to the degrading of quality in the radio channel. An example of how adaptive modulation affects the coverage is presented in Figure 2.3.

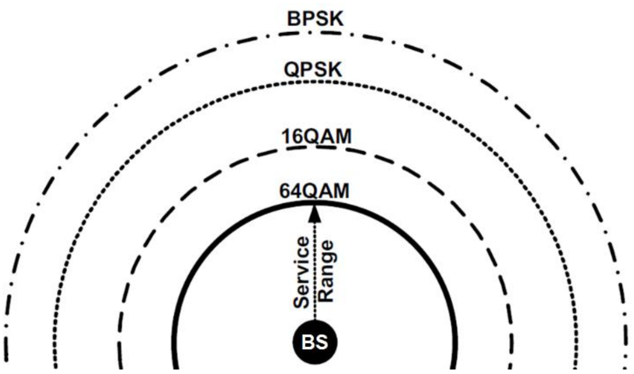

Figure 2.3 Effect of adaptive modulation on coverage range (adapted from [Tols11]).

According to [Tols11], around 80% of mobile traffic is originated inside buildings, thus, mobile operators have many reasons to provide in-building coverage. However, nowadays, there are no indoor coverage solutions inside each and every building, so the biggest part of indoor user's coverage must be provided using the outdoor network.

As shown in Figure 2.4, most of signal paths in a macro-cell network have problems with reflections and diffractions, especially if the network is deployed in urban scenarios.

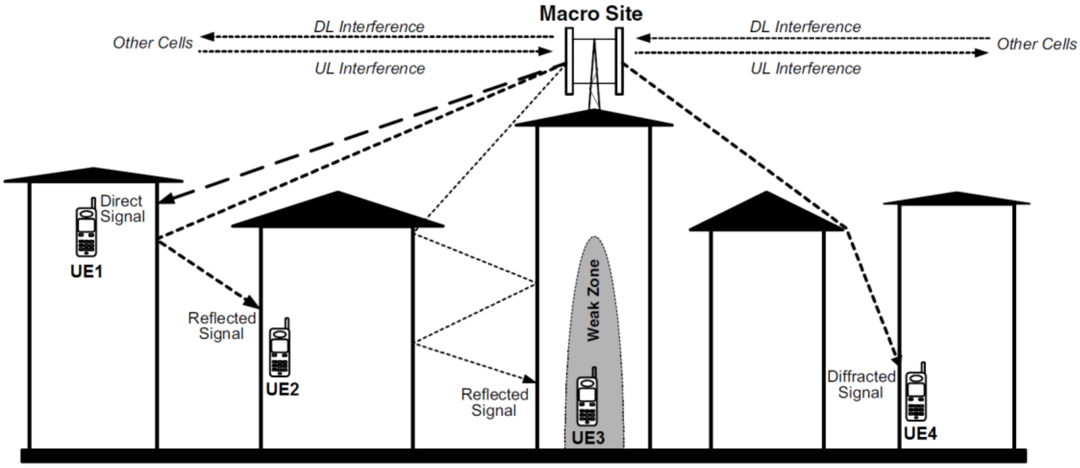

Figure 2.4 Macro-cell base station covering distinct indoor users in urban scenario (adapted from [Tols11]).

Ideally, the radio channel path should be in Line-of-Sight (LoS), with no reflections or obstructions between the Base Station (BS) and the UE. These reflections lead to the problem of multi path and high link losses between the serving macro-cell site and the UE. The high losses lead to a higher BS transmitted power that increases the expenses of mobile operators, but, more important, it causes unwanted interference with the nearby sites, degrading services and the capacity of the overall network. By increasing the number of interfering signals reaching the receiver, the interfering power increases as well, which leads to a reduction of the Signal to Interference plus Noise Ratio (SINR).

The path loss problem presented above is even more relevant when the UEs are in buildings, especially because of the extra attenuation that comes from the indoor penetration. This additional attenuation is added to the ones that exist outdoors, and can range in between 1 and 20 dB in Ultra High Frequency (UHF), according to [Corr13].

In order to maximise network coverage and capacity, it is important to reduce the distance between the serving BS and the mobile user, allowing a lower path loss, a minimum fading, and smaller UL and DL transmitted powers that reduce interference. Furthermore, in macro-cell networks, there are a lot of indoor weak coverage zones, which especially depend on the characteristics of the buildings materials, the floor where the user is, and the number of walls that the signal has to cross to reach the UE. For all these reasons, another coverage option must be considered by mobile operators.

One alternative to macro-cells is the deployment of micro-cells. According to [Tols11], micro-cells are implemented typically between 2 and 3 m below the building heights, and in a minimum of 3 to 10 m above the street level. With the usage of these cells, it is possible to solve the most of the problems described above. Compared with the macro-cell site, micro-cells have a shorter distance and a more direct signal path between the serving site and the UE, which leads to a loss reduction around 20 to 40 dB. With this approach, it is possible to minimise the in-building weak zone, increasing indoor coverage and the received signal power. In Figure 2.5, it is possible to see the main differences in the network when two micro-cell sites are implemented in the same urban scenario that is presented in Figure 2.4.

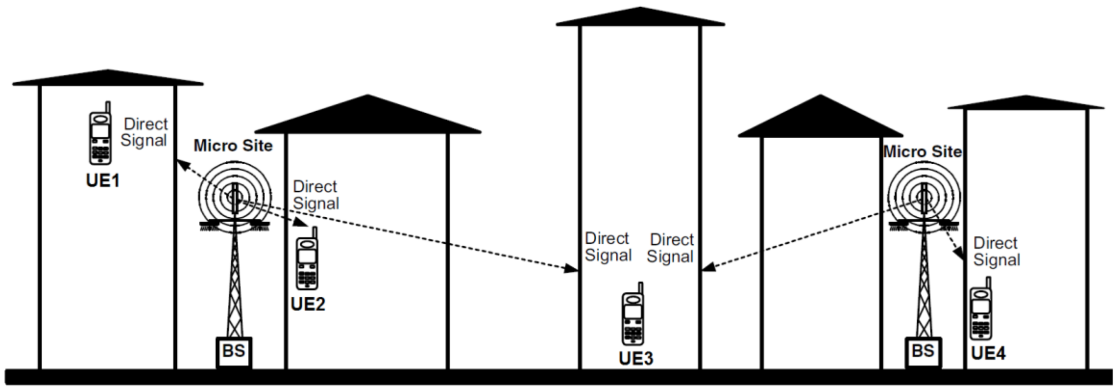

Figure 2.5 Micro-cell base stations covering distinct indoor users in urban scenario (adapted from [Tols11]).

Taking the previous information into account, it is obvious that micro-cells appear to be the ideal solution to provide indoor coverage using the outdoor network. However, there are some situations where bigger cells can be a better option. As referred in the introduction of this report, the usage of LTE to provide “fixed” services can be a good solution in rural areas. Typical rural environments are characterised by their open areas (with almost no obstacles between the BS and the UE), small buildings and low population density, which allows the usage of macro-cells. In these scenarios, lower frequencies bands (like 800 MHz band in LTE) are the most used ones by mobile operators, since they want to provide higher coverage areas.

2.2.2 Capacity

In LTE, the capacity can be associated with the number of RBs that are available in the network. It is also described as the number of users that can be served simultaneously by a BS for a given service (for example data or voice). The maximum number of users that can access the network at a given instant depends on the amount of RBs that are required by each user. The correspondence between some LTE bandwidths and the respective number of RBs is presented in Table 2.4. An approximate value of that number can be calculated by using:

$$N_{RB} = \frac{B_{ch\,[\mathrm{kHz}]}}{B_{RB\,[\mathrm{kHz}]}} \cdot \frac{P_{Bch\,[\%]}}{100} \tag{2.1}$$

where:

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

Table 2.4 Number of RBs and sub-carriers associated with each LTE channel bandwidth (extracted from [Tols15]).

Channel bandwidth [MHz]	1.4	3.0	5.0	10	15	20
Number of RBs	6	15	25	50	75	100
Number of sub-carriers	72	180	300	600	900	1 200

In terms of capacity, it is important to compare the number of RBs allocated to each user with the data rate required by each one of them. In Table 2.5, it is possible to see the variation between the DL peak data rates and the channel bandwidth, for different UEs specifications that are detailed in Annex A. The values for UL are presented in Table 2.6. By combining these tables with Table 2.4, it is possible to see that the data rate increases with the bandwidth, which corresponds to an increasing number of RBs, with the order of the coding scheme and rate, and with the number of antennas used by the transmitter and the receiver. It is also important to denote that LTE achievable peak data rates are calculated using a normal CP length (7 symbols per subcarrier).

Table 2.5 Downlink peak data rates (extracted from [Alme13]).

UEs specifications			**Peak data rates [Mbit/s]**					
			Bandwidth [MHz]					
Modulation and coding	**MIMO usage**	**Bits/symbol**	**1.4**	**3.0**	**5.0**	**10**	**15**	**20**
QPSK 1/2	–	1.0	1.0	2.5	4.2	8.4	12.6	16.8
16-QAM 1/2	–	2.0	2.0	5.0	8.4	16.8	52.0	33.6
16-QAM 3/4	–	3.0	3.0	7.6	12.6	25.2	37.8	50.4
64-QAM 3/4	–	4.5	4.5	11.3	18.9	37.8	56.7	75.6
64-QAM 1/1	–	6.0	6.0	15.1	25.2	50.4	75.6	100.8
64-QAM 3/4	2×2 MIMO	9.0	9.1	22.7	37.8	75.6	113.4	151.2
64-QAM 1/1	2×2 MIMO	12.0	12.1	30.2	50.4	100.8	151.2	201.6
64-QAM 1/1	4×4 MIMO	24.0	24.2	60.5	100.8	201.6	302.4	403.2

Table 2.6 Uplink peak data rates, considering no MIMO (extracted from [Alme13]).

UEs specifications		**Peak data rates [Mbit/s]**					
		Bandwidth [MHz]					
Modulation and coding	**Bits/symbol**	**1.4**	**3.0**	**5.0**	**10**	**15**	**20**
QPSK 1/2	1.0	1.0	2.5	4.2	8.4	12.6	16.8
16-QAM 1/2	2.0	2.0	5.0	8.4	16.8	25.2	33.6
16-QAM 3/4	3.0	3.0	7.6	12.6	25.2	37.8	50.4
16-QAM 1/1	4.0	4.0	10.1	16.8	33.6	50.4	67.2
64-QAM 3/4	4.5	4.5	11.3	18.9	37.8	56.7	75.6
64-QAM 1/1	6.0	6.0	15.1	25.2	50.4	75.6	100.8

According to [SeTB11], Shannon established a theoretical expression to calculate the maximum data rate over the radio channel, which is known as channel capacity:

$$R_{b,max\ [\mathrm{Mbit/s}]} = B_{ch\ [\mathrm{MHz}]} \cdot \log_2(1 + \rho_N) \tag{2.2}$$

where:

- B_{ch}: available channel bandwidth;
- ρ_N: SNR (in linear units).

From Shannon's model, it is possible to notice that there are two parameters limiting the capacity of the radio channel: the bandwidth and the quality of the channel.

As shown in Figure 2.6, data rates (throughputs) decrease strongly with the reduction of the SNR/SINR, which leads to a reduction of the channel capacity. This problem is especially important in indoor scenarios, because of the extra attenuation that comes from the indoor penetration, which leads to a significant decline of the SNR. It is important to notice that the curves presented in Figure 2.6 were obtained using expressions and values detailed in [Alme13].

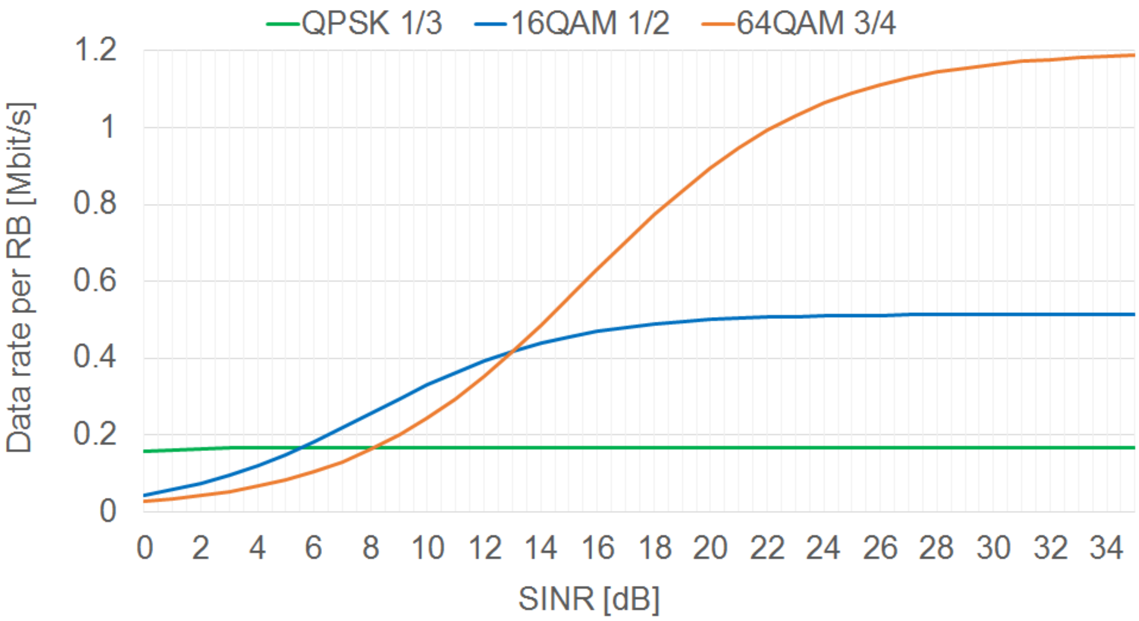

Figure 2.6 Relationship between SINR and throughput per RB in DL, for different modulation schemes and coding rates.

2.3 Performance Parameters

This section presents some information about performance parameters, mainly focusing on the services and applications and some QoE aspects.

2.3.1 Services and Applications

In the past, mobile phones were used mainly for voice communication, however, presently they are used to access a wide range of services and to do tasks that were previously only performed by computers. This fact, together with the increasing usage of mobile networks by other devices (e.g. tablets and laptops), implies that data services have, nowadays, the main role in mobile communications. The number of mobile data subscriptions is increasing rapidly, as well as the average data volume per each one of those subscribers. According to [Eric14], data traffic grew around 10% quarter-on-quarter and 60% year-on-year, reaching 3.249 ExaBytes of total (UL and DL) monthly traffic in 2014. Around 35% of that value corresponds to the traffic that comes from mobile PCs, routers and tablets and the remaining percentage corresponds to the one that comes from smartphones. It is important to notice that there are some variances in the volume of data traffic that different devices generate when they are using the same application. In Figure 2.7, it is possible to see the differences if the user is using a Mobile PC a Tablet or a Smartphone.

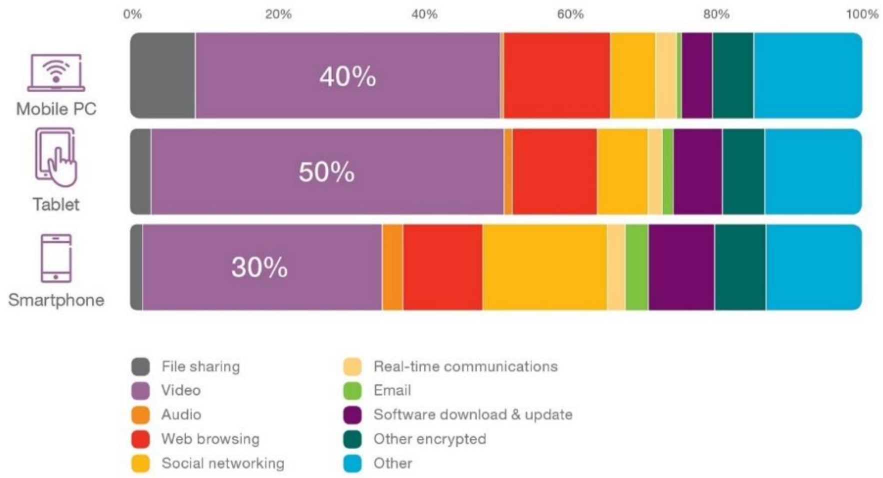

Figure 2.7 Application mobile data traffic volumes by device type (extracted from [Eric13a]).

With the increasing availability of multiple connected devices, it becomes apparent that the usage profile of activities performed via apps or telecom services is significantly affected by the device type. The smartphone is the preferred device for activities where mobility is the key requirement, such as messaging and voice calls. On the other hand, laptops and tablets are more used in indoor environments. Thus, users want reliable access for their apps whatever the equipment they use and wherever they are in the network. In order to deliver the best possible experience to mobile broadband subscribers, operators need to manage their networks in the most efficient way. However, it is not possible to deliver a good network performance for each application everywhere and all the time; furthermore, it is very difficult to measure what their specific requirements are. A cell that can serve many megabits per second in DL near the BS might only have a few hundred kilobits per second at the edges of its coverage area. Hence, a successful approach involves considering the requirements of the most used app types (see Figure 2.7) and setting performance targets that will cater for them. Managing these targets will ensure a high probability that the most widely used apps will perform well throughout the network coverage area.

Traffic information is very important when designing and optimising a network. In order to characterise traffic in UMTS, 3GPP specified four different QoS classes: conversational, streaming, interactive and background. These classes are detailed in Table 2.7.

Table 2.7 UMTS QoS classes (adapted from [Alme13]).

Service class	Conversational	Streaming	Interactive	Background
Real time	Yes	Yes	No	No
Symmetric	Yes	No	No	No
Guaranteed rate	Yes	Yes	No	No
Delay	Minimum fixed	Minimum variable	Moderate variable	High variable
Buffer	No	Yes	Yes	Yes
Bursty	No	No	Yes	Yes

Although these services and classes were not specifically done for LTE, they provide some insights into the different natures of traffic. Concerning these QoS classes, different services can be considered: voice, music, file sharing, web browsing, social networking, email, video calling, video streaming and Machine-to-Machine (M2M) applications like smart meters, e-Health, Intelligent Transportation Systems (ITS) and surveillance. Each one is characterised by its maximum (Max.), average and minimum (Min.) data rate, and its size or duration. These values for the listed services are presented in Table 2.8.

Table 2.8 Services characteristics (extracted from [Sina14]).

Service		Service class	Data rate [kbit/s]			Duration [s]	Size [kB]
			Min.	Average	Max.		
Voice		Conversational	5.3	12.2	64.0	60.0	–
Music		Streaming	16.0	64.0	160.0	90.0	–
File sharing		Interactive	384.0	1024.0	–	–	2042.00
Web browsing		Interactive	30.5	500.0	–	–	180.00
Social networking		Interactive	24.0	384.0	–	–	45.00
Email		Background	10.0	100.0	–	–	300.00
M2M	**Smart meters**	Background	–	200.0	–	–	2.50
	e-Health	Interactive	–	200.0	–	–	5611.52
	ITS	Conversational	–	200.0	–	–	0.06
	Surveillance	Streaming	64.0	200.0	384.0	–	5.50
Video	**Calling**	Conversational	64.0	384.0	2048.0	60.0	–
	Streaming	Streaming	500.0	5120.0	13000.0	3600.0	–

These services have different QoS priorities according to their requirements, so they are treated differently when the network cannot provide the resources that users need. This means that while deploying a new service in the network, the service configurator will select what kind of treatment the corresponding traffic will experience while carried through the mobile network. If data rates reduction strategies are applied in the network, the first services to be reduced are the ones with the lower QoS priority (that corresponds to a higher priority value). In many situations, a UE may be running multiple applications, with different QoS requirements, at the same time. For example, a UE could be doing a VoIP call at the same time that a File Transfer Protocol (FTP) file is being downloaded. Thus, in order to support multiple QoS requirements different bearers are set up in EPS. According to [SeTB11], those bearers can be classified into two categories, based on the nature of the QoS they provide: Minimum Guaranteed Bit Rate (GBR) bearers, which can be used for applications as VoIP; and Non-GBR bearers, which can be used for applications such as web browsing or FTP transfer, since they do not guarantee any specific data rate.

Each bearer has an associated QoS Class Identifier (QCI), which is characterised by priority, packet delay budget, and acceptable packet loss rate. The QCI label for a bearer determines the way it is handled in the eNodeB. Some QCIs have been standardised so that vendors can all have the same understanding of the underlying service characteristics and thus provide the corresponding treatment (management, conditioning and policing strategy). This standardisation ensures that an LTE operator can expect identical traffic handling behaviour throughout the network, regardless of the manufacturers of the eNodeB equipment. The standardised QCIs and their characteristics are detailed in Table 2.9.

Table 2.9 Standardised QoS Class Identifiers (QCIs) for LTE (extracted from [SeTB11]).

QCI	Resource Type	Priority	Packet Delay Budget [ms]	Packet Error Loss Rate	Example Services
1	GBR	2	100	10^{-2}	Conversional voice
2	GBR	4	150	10^{-3}	Conversional video (live streaming)
3	GBR	5	300	10^{-6}	Non-conversional video (buffered streaming)
4	GBR	3	50	10^{-3}	Real time gaming
5	Non-GBR	1	100	10^{-6}	IMS signalling
6	Non-GBR	7	100	10^{-3}	Voice, video, (live streaming), interactive gaming
7	Non-GBR	6	300	10^{-6}	Video (buffered streaming)
8	Non-GBR	8	300	10^{-6}	TCP-based (e.g. e-mail), chat, FTP, Peer-to-Peer (P2P), file sharing, progressive video, etc.
9	Non-GBR	9	300	10^{-6}	–

2.3.2 Quality of Experience

With the growth of mobile services, it has become very important for an operator to measure the QoS and the QoE of its network, being imperative to provide the best experience to users in a cost-effective, competitive and efficient way. This will help maintain both customer loyalty and competitive edge. Although QoS is from the network view point and QoE from the user's perspective, they are interdependent parameters and it makes sense to study them simultaneously. However, this section is mainly focused on QoE issues. Unlike QoS, QoE is not just limited to the technical performance of the network, and there are also non-technical aspects, which have a lot of influence on the user's perspective, as it is exemplified in Figure 2.8.

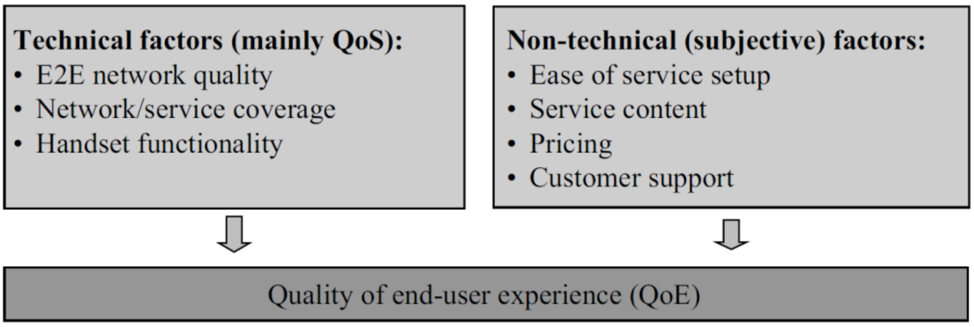

Figure 2.8 Technical and non-technical aspects of service that influence QoE (extracted from [SoLC06]).

According to [SoLC06], there are two practical approaches to measure QoE in mobile networks: a service level approach using statistical samples, and a network management system approach using QoS parameters. The first method is very good for benchmarking various services, because it is an inexpensive tool, highly scalable, to measure the quality of the network. Furthermore, operators can also measure QoE provided by its competitors. As it detailed in [SoLC06], service level approach using statistical samples involves some essentials phases:

- Determination of the weighting of key service applications;
- Identification of the QoE Key Performance Indicators (KPI);
- Conception of a proper statistical sample (geographic areas, traffic mix, time of day, etc.) and collecting the QoE KPI;
- Utilisation of mobile agents (that can provide extra information on this process) in some handsets to make the results more accurate;
- Ascription of an overall QoE score (index) from KPI values for each separate service and a service mix.

Although these measurements rely on statistical samples, if the number of observations is correctly selected the results will get close to achieving a 100% precision. Concerning the second method, network management system approach using QoS parameters is made by using a network management system, which collects KPIs from network elements and compares them with the reference levels. As explained in [SoLC06], this method involves some phases:

- Identification of the relationship between QoS KPI and their effect on QoE;
- Measurement of QoS KPI in the network;
- Rating QoE through measured QoS KPI using some mapping metrics (on a spreadsheet, for example).

Classifying the correct relationship between network QoS KPIs and user experience (QoE) is an extremely challenging task, so the best option is to use both of these methods in a complementary way. Together, these two methods provide a most accurate representation of user experience and give very important information to the network operator.

When identifying QoE metrics, it is important to understand the expectations of the end user. There will be as many different expectations as there are users, but most of these expectations can be grouped into two main categories: reliability and quality. Reliability is the availability, accessibility and maintainability of the content, the service network, and the end-user device and application software. Some KPIs related to reliability expectations are presented in Table 2.10.

Table 2.10 QoE KPI according to reliability expectations (adapted from [SoLC06]).

QoE KPI	Most important measures
Service availability (anywhere) [%]	Ratio of territory coverage
Service accessibility (anytime) [%]	Ratio of refused connections
Service access time (service setup time) [s]	Average call or session setup time
Continuity of service connection (service retainability) [%]	Service interruption ratio

On the other hand, quality refers to the quality of the content, the bearer service, and the user device and application software features. Some key parameter indicators related to quality expectations are presented in Table 2.11.

Table 2.11 QoE KPI according to quality expectations (adapted from [SoLC06]).

QoE KPI	Most important measures
Quality of session [%]	Service application layer packet loss ratio
Data rate [%]	Average bearer data rate achieved as ratio of data rate demanded by application
Data rate variation [%]	Bearer stability: data rate variation around negotiated data rate
Active session throughput [kbit/s]	Average throughput towards mobile
System responsiveness [s]	Average responsive time
Ent-to-end delay [ms]	Average end-to-end delay
Delay variation [%]	Jitter

2.4 State of the art

With the quickly development of mobile Internet and the popularity of mobile devices, wireless data usage are growing exponentially. Meanwhile, multimedia data services require a higher rate and transmission quality of the wireless network. Operators have been forced to invest and develop new solutions to increase the capacity they can offer to their subscribers.

New generations of cellular technologies, like LTE, are mainly focused on the provision of broadband mobile services with the highest spectral efficiency. However, in indoors the through-the-walls propagation losses put additional difficulties on the provisioning of mobile services with enough quality. In [GIAO11], a new approach is proposed to improve LTE FDD indoor coverage in LTE 2 600 MHz band from a macro-cell. According to the authors, the method takes advantage of the legacy coaxial TV cable transport infrastructure, deployed in buildings, to carry LTE signals, fulfilling 3GPP and Common Telecommunication. This infrastructure is defined on frequency bands up to 2 150 MHz, and can distribute and broadcast Frequency Modulation (FM) radio, Digital Video Broadcasting-Terrestrial (DVB-T), analogue terrestrial TV and other possible existing technologies for digitally modulated data transmission. It has been assessed that TV coaxial infrastructure can carry 2 600 MHz LTE band with only a moderate increment on power losses in respect of lower frequencies signals, which allows carrying LTE over buildings without using frequency shifting and costly stable frequency oscillators, supposing a low complexity solution. This new method allows an improvement on LTE coverage in indoors, increasing indoors LTE range and user data rate, due to the improvement of users' received SNR. This concept can be used for improving coverage on LTE macro-cell border, high density urban areas or large buildings. The approach only needs to add a few new elements without introducing any modifications in buildings coaxial TV networks. So, it simplifies traditional mobile networks deployments using an inexpensive solution.

LTE indoor small cell solutions are an important part of the heterogeneous network ecosystem. The benefits of this coverage solution are mainly due to spectral re-use over small distances, giving significant capacity and coverage improvements. In [SBDK13], the coverage and capacity gain achievable from two types of LTE indoor small cell product (2×21 dBm and 2×24 dBm) are investigated. In this paper, simulation results show that significant coverage gains up to 25% can be achieved on the high power product compared to the lower one. Furthermore, the results also indicate that capacity gains up to 26% can be achieved on the 2×24 dBm, due to higher order modulation and coding. The gain results are sensitive to propagation assumptions, such as models and path loss exponents.

MIMO is one of the most important technologies that enhance the performance of LTE networks. For indoor coverage, it is difficult to implement MIMO, essentially because of the costs in doubling the number of needed antennas. In [WaLi13], two indoor MIMO Distributed Antenna System (DAS) solutions are proposed by using frequency converting and signal combining and separating by upgrading the existing indoor DAS. Some tests show that DL throughputs are almost the same for frequency conversion solutions, dual single-polarised antenna solution and traditional MIMO DAS solution in near and middle areas. However, in far and edge areas, the frequency conversion and the dual single-polarised antenna solutions have more than two times higher throughputs values, comparing with a traditional MIMO DAS solution.

Fixed wireless systems are candidate solutions to connect billions of users not yet connected to the Internet. In [FJBS11], the capabilities of High Speed Packet Access (HSPA) and LTE fixed wireless systems in terms of coverage, data rates, and capacity are discussed and evaluated. Some results indicate that in an Indian rural scenario with an inter-site distance of 40 km, monthly data volumes of

430 MB (in both DL and UL) per user, together with a cell-edge data rate of 5 Mbit/s in DL and 2 Mbit/s in UL are reached in LTE. A key enabler is the use of directional rooftop terminal antennas. LTE is designed to support full mobility, so scenarios with fixed terminals are obviously supported. Many of the techniques used to reach high performance in mobile scenarios also improve performance in a fixed scenario, which has slower channel variations. In order to assess the fixed wireless capabilities of HSPA and LTE, in this paper, the systems are evaluated in the Rural Indian Open Area scenario, which is based on radio propagation measurements and geographical and demographical characteristics of rural India. With the more advanced LTE configuration, supporting MIMO, it is possible to achieve higher data rates and cell throughputs, when comparing with HSPA. With the usage of directional antennas, average data rates of 50 Mbit/s are achieved at low load. Furthermore, some results shows that even at the highest loads (15 Mbit/s sector throughput), several Mbit/s are achieved at the cell-edge. Results indicate that significant gains in data rates, coverage, and capacity can be obtained by the use of outdoor directional terminal antennas.

A new approach to network performance and app coverage was proposed by Ericsson in [Eric13a]. From a user's perspective, app coverage is defined as the probability that the network will deliver sufficient performance to run a particular app at an acceptable quality level and from the operator's perspective, it deals with cell-edge performance. In order to illustrate app coverage in a realistic environment, a traffic profile of 500 MB per subscriber per month was applied, which includes the usage of particular applications types (streaming music, streaming video, and video telephony) as well as circuit-switched voice. The coverage area and indoor penetration was predicted for each of the application types, using the radio characteristics of a UMTS/HSPA network (with 5 MHz bandwidth in the 2.1 GHz band). Three scenarios were explored focusing on a 4 km^2 area: base case (11 three-sector macro sites), tuning and optimisation (site count unchanged) and macro densification (add 10 macro sites for a total of 21 three-sector sites). Table 2.12 presents the effect of these different radio network designs on coverage.

Table 2.12 The effect of different radio network designs on coverage in a 4 km^2 area for some particular types of services (adapted from [Eric13a]).

Service	**Threshold [kbit/s]**	**Base case**		**Tuning and optimisation**		**Macro densification**	
		Total Coverage [%]	**Indoor penetration [%]**	**Total Coverage [%]**	**Indoor penetration [%]**	**Total Coverage [%]**	**Indoor penetration [%]**
Voice	12.5 (UL/DL)	94	85	95	88	97	93
Music streaming	160 (DL)	88	70	89	71	93	82
Video telephony	320 (UL/DL)	70	24	76	38	83	55
Video streaming	720 (DL)	48	17	68	40	73	47

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. This chapter ends with a brief assessment of the presented models.

3.1 Model Development

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

3.1.1 Radio Link Budget

The Radio Link Budget (RLB) is an important tool for network planning, taking all gains and losses from the transmitter to the receiver into account. According to [Corr13], the power available at the receiving antenna can be expressed by:

$$P_{r\,[\mathrm{dBm}]} = P_{t\,[\mathrm{dBm}]} + G_{t\,[\mathrm{dBi}]} + G_{r\,[\mathrm{dBi}]} - L_{p,total\,[\mathrm{dB}]} \tag{3.1}$$

where:

- 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 BS antenna gain depends essentially on the antenna type and on the number of sectors. For a typical 3-sector antenna, the gains can range from 15 up to 21 dBi. On the other hand, the UE antenna gain depends on the type of device and on the frequency band. Small handheld terminals at a low frequency band can have an antenna gain of -5 dBi, while a fixed wireless terminal with a directive antenna can have a gain up to 10 dBi, according to [HoTo11].The power fed to the transmitting antenna is defined as:

$$P_{t\,[\mathrm{dBm}]} = P_{Tx\,[\mathrm{dBm}]} - L_{t\,[\mathrm{dB}]} \tag{3.2}$$

where:

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

As it can be seen in [HoTo11], in DL the transmitter output power can range from 43 up to 48 dBm. For UL the transmitted power, it is assumed to be around 24 dBm.

The power at the receiver is given by:

$$P_{Rx\,[\mathrm{dBm}]} = P_{r\,[\mathrm{dBm}]} - L_{r\,[\mathrm{dB}]} \tag{3.3}$$

where:

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

According to [HoTo11], the cable loss can range from 1 up to 6 dB. It depends on the cable length and type, and frequency band. The loss in the UE is typically included for voice, where the terminal is held close to the user's head and can range from 3 up to 5 dB, [HoTo11]. However, in the specific case of this thesis, only data services are considered so this value can be ignored.

The path loss experienced by a signal travelling between the BS and the UE can be calculated by using the COST-231 Okumura-Hata model, detailed in [DaCo99], when the UE is outdoors. In this thesis, the usage of LTE is mainly used to provide “fixed” data services in rural or suburban scenarios, where it is more unsustainable to provide FTTH solutions. Thus, this propagation model can be used to compute the loss in the outdoor path, since it deals with scenarios with large distances (above 5 km) and with urban, suburban, or rural environments. The path loss for the COST-231 Okumura-Hata model is described by:

$$\begin{aligned} L_{p,outdoor\,[\mathrm{dB}]} = {} & 69.55 + 26.16 \cdot \log_{10}\left(f_{[\mathrm{MHz}]}\right) - 13.82 \cdot \log_{10}\left(h_{BSe\,[\mathrm{m}]}\right) \\ & + \left[44.90 - 6.55 \cdot \log_{10}\left(h_{BSe\,[\mathrm{m}]}\right)\right] \cdot \log_{10}\left(d_{\,[\mathrm{km}]}\right) - H_{mu\,[\mathrm{dB}]} - K_{f\,[\mathrm{dB}]} \end{aligned} \tag{3.4}$$

where:

- f: frequency band;
- h_{BSe}: effective height of BS antenna;
- d: distance between the BS and the UE;
- K_f: correction factor;

$$H_{mu\,[\mathrm{dB}]} = \begin{cases} \left[1.10 \cdot \log_{10}\left(f_{[\mathrm{MHz}]}\right) - 0.7\right] \cdot h_{UE\,[\mathrm{m}]} - \left[1.56 \cdot \log_{10}\left(f_{[\mathrm{MHz}]}\right) - 0.8\right], & \text{small city} \\ 8.29 \cdot {\log_{10}}^2\left(1.54 \cdot h_{UE\,[\mathrm{m}]}\right) - 1.10\,, & f \leq 200\ \mathrm{MHz}\,, \text{large city} \\ 3.20 \cdot {\log_{10}}^2\left(11.75 \cdot h_{UE\,[\mathrm{m}]}\right) - 4.97\,, & f \geq 400\ \mathrm{MHz}\,, \text{large city} \end{cases} \tag{3.5}$$

in which:

- h_{UE}: user equipment height.

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

$$\sigma_{[\mathrm{dB}]} = \begin{cases} 0.70 \cdot {\log_{10}}^2\left(f_{[\mathrm{MHz}]}\right) - 2.5 \cdot \log_{10}\left(f_{[\mathrm{MHz}]}\right) + 11.10\,, & \text{urban scenarios} \\ 0.98 \cdot {\log_{10}}^2\left(f_{[\mathrm{MHz}]}\right) - 3.4 \cdot \log_{10}\left(f_{[\mathrm{MHz}]}\right) + 11.88\,, & \text{suburban and rural scenarios} \end{cases} \tag{3.6}$$

and is valid for the following values:

- $f \in [150, 1\,500]$ MHz;
- $d \in [1, 20]$ km;
- $h_{BSe} \in [30, 200]$ m;
- $h_{UE} \in [1, 10]$ m.

Since the allowed frequency range only contains the 800 MHz frequency band (excluding the 1 800 MHz one) one must consider the Okumura-Hata model extension for frequencies between 1.5 and 2.0 GHz:

$$\begin{aligned} L_{p,outdoor\,[\mathrm{dB}]} = {} & 46.30 + 33.90 \cdot \log_{10}\left(f_{[\mathrm{MHz}]}\right) - 13.82 \cdot \log_{10}\left(h_{BSe\,[\mathrm{m}]}\right) \\ & + \left[44.90 - 6.55 \cdot \log_{10}\left(h_{BSe\,[\mathrm{m}]}\right)\right] \cdot \log_{10}\left(d_{\,[\mathrm{km}]}\right) - H_{mu\,[\mathrm{dB}]} + C_{m\,[\mathrm{dB}]} - K_{f\,[\mathrm{dB}]} \end{aligned} \tag{3.7}$$

in which:

$$C_{m\,[\mathrm{dB}]} = \begin{cases} 0\,, & \text{small cities} \\ 3\,, & \text{urban centres} \end{cases} \tag{3.8}$$

To calculate the estimation of the total path loss when the UEs are indoors, some margins and an extra attenuation coming from penetration into the buildings must be added to the path loss computed with the COST-231 Okumura-Hata model:

$$L_{p,total\,[\mathrm{dB}]} = L_{p,outdoor\,[\mathrm{dB}]} + L_{p,indoor\,[\mathrm{dB}]} + M_{SF\,[\mathrm{dB}]} + M_{FF\,[\mathrm{dB}]} \tag{3.9}$$

where:

- $L_{p,indoor}$: path loss coming from indoor penetration, which can range from 1 up to 20 dB;
- M_{SF}: slow fading margin;
- M_{FF}: fast fading margin.

Concerning propagation characteristics, the slow fading margin is 8.8 dB with 8 dB of standard deviation for LTE, according to [HoTo11]. On the other hand, the fast fading margin can be neglected as it is not necessary in LTE, because it does not use fast power control in DL, [HoTo11]. Power control is only specified for UL, having an important role at the UE level, since it balances the need for sufficient transmitted energy to satisfy the required QoS, against the need to minimise interference on the other users of the system. It also maximises the UE's battery life.

3.1.2 SNR and SINR

The performance of any radio channel is not only related to the absolute signal level, but also to the quality of the signal. This is described by the SNR, and the bigger the ratio between the desired signal and the noise, the better performance the link will have (which can lead to higher data rates). When there are no active communications between the BSs and the UEs, the interfering power is not considered and only the SNR is used to determine the radio channel conditions for a given UE. As it can be seen in [Corr13], SNR can be computed using:

$$\rho_{N\,[\mathrm{dB}]} = P_{Rx\,[\mathrm{dBm}]} - P_{N\,[\mathrm{dBm}]} \tag{3.10}$$

where:

- P_{Rx}: power at the receiver;
- P_N: average noise power at the receiver antenna.

The average noise power can be estimated, according to [SeTB11], by:

$$P_{N\,[\mathrm{dBm}]} = -174 + 10\log_{10}\left(B_{N\,[\mathrm{Hz}]}\right) + F_{N\,[\mathrm{dB}]} \tag{3.11}$$

where:

- B_N: noise bandwidth;
- F_N: noise figure, which can range from 6 up to 11 dB.

The noise bandwidth is given by:

$$B_{N\,[\mathrm{Hz}]} = N_{RB} \cdot B_{RB\,[\mathrm{Hz}]} \tag{3.12}$$

where:

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

Interference must be considered, in order to study the radio channel conditions for a given UE when there are active communications. It is important to note that interference can be classified as inter-cell one, when the UE receives signals from more than one BS, or intra-cell, when different UEs under the coverage of the same BS interfere with each other, Figure 3.1. The usage of SC-FDMA in UL provides an orthogonal transmission by the different UEs, which minimises intra-cell interference, compared with previous 3GPP systems. As such, only inter-cell interference is considered. However, when calculating inter-cell interference, one should know that not all of the sub-carriers emitted by different BSs and received at the same UE interfere with each other – only the sub-carriers with the same frequency have a negative impact on system performance.

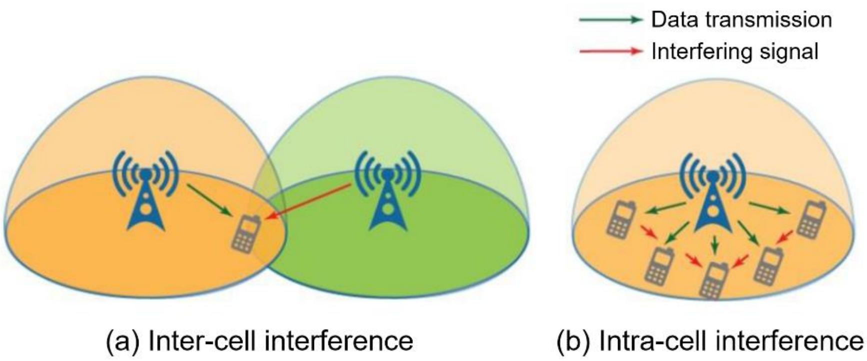

Figure 3.1 Inter-cell and intra-cell interference (extracted from [Alme13]).

According to [SeTB11], LTE was designed to operate with a frequency reuse factor of 1, also called Universal Frequency Reuse, in order to maximise spectral efficiency. This reuse scheme provides the best throughput for users in the cell-centre, as they are the ones who experience the higher SINR, while deteriorating service quality for cell-edge users, which experience a significantly lower SINR. Thus, the SINR available at each UE's receiver must be computed in order to study the impact of interference on system performance:

$$\rho_{IN\,[\mathrm{dB}]} = 10\log_{10}\left(\frac{P_{Rx\,[\mathrm{mW}]}}{P_{N\,[\mathrm{mW}]} + P_{I\,[\mathrm{mW}]}}\right) \tag{3.13}$$

where:

- P_I: interfering power.

The interfering power is calculated as the sum of the power of the signals that are supported in sub-carriers placed in the same frequency as the desired signal:

$$P_{I\,[\mathrm{dBm}]} = \sum_{i=1}^{N_I} P_{I,i\,[\mathrm{dBm}]} \tag{3.14}$$

where:

- $P_{I,i}$: interfering power coming from transmitter i;
- N_I: number of interfering signals reaching the receiver.

It is important to notice that only the interfering signals that have power equal or greater than noise are considered, since those signals are the only ones that may have a negative impact on system performance.

In a cellular system the difference between the SINR measured at the cell-centre and at the cell-edge is usually very high, reaching almost 20 dB according to [Khan09]. Furthermore, the disparity can be even higher in a coverage-limited cellular system. This phenomenon leads to very low data throughputs for cell-edge users in comparison with the ones who are at the cell-centre, creating a large QoS discrepancy. The cell-edge performance can be noise- or interference-limited. In a noise-limited situation (typically occurring in large cells in rural areas) the performance of the system can generally be improved by providing an extra power gain. On the other hand, in interference-limited situations (mainly occurring in small cells) there is an inter-cell interference in addition to noise, which also contributes to the degradation of the cell-edge SINR. In this case, providing a higher transmit power gain may not help, because as the signal power goes up, the interference one also increases. Thus, the only solution is the reduction of inter-cell interference in order to improve the SINR, changing for example the antenna tilt (the angle of the main beam of the antenna below or above the horizontal plane), in which positive and negative angles can be referred as down- and up-tilts, respectively.

3.1.3 Parameters on Reference Signal

According to [EESh14], an UE can measure and report two parameters on reference signal: Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ). RSRP is the average power of Resource Elements (REs) that carry cell specific Reference Signals (RSs) over the entire bandwidth. It is only measured in the symbols carrying RSs, and can range between -140 and -44 dBm. RSRP values can be obtained by using:

$$P_{RSRP\,[\mathrm{dBm}]} = 10\log_{10}\left(\frac{1}{N_{RE}}\sum_{k=1}^{N_{RE}} P_{r,RE,k\,[\mathrm{mW}]}\right) \tag{3.15}$$

where:

- N_{RE}: number of REs;
- $P_{r,RE,k}$: estimated received power of the k^{th} RE.

RSRQ is the ratio of the RSRP and E-UTRAN carrier Received Signal Strength Indicator (RSSI) to the reference signals. It can ranges between -3 and -19.5 dB, and it is computed via:

$$Q_{RSRQ\,[\mathrm{dB}]} = 10\log_{10}\left(\frac{N_{RB}\cdot P_{RSRP\,[\mathrm{mW}]}}{P_{RSSI\,[\mathrm{mW}]}}\right) \tag{3.16}$$

in which:

$$P_{RSSI\,[\mathrm{dBm}]} = 12\cdot N_{RB}\cdot P_{RSRP\,[\mathrm{mW}]} + P_{N\,[\mathrm{mW}]} + P_{I\,[\mathrm{mW}]} \tag{3.17}$$

E-UTRAN carrier RSSI is the total received wideband power on a given frequency. It includes the noise coming from the interfering cells and from all the others sources. The value of RSSI is not directly reported by the UE as an individual measurement, being only used to compute the RSRQ value.

3.1.4 Data Rate

To analyse the scenarios of this thesis, it is important to compare some experimental data rates with their respective theoretical values. Theoretical data rates, in DL, can be obtained as a function of the RSRP, however, it is not possible to relate them in one simple equation. First of all it is necessary to compute the total path loss associated with an RSRP value:

$$L_{p,total\,[\mathrm{dB}]} = P_{Tx,RE\,[\mathrm{dBm}]} - P_{RSRP\,[\mathrm{dBm}]} + G_{t\,[\mathrm{dBi}]} - L_{c\,[\mathrm{dB}]} - M_{c\,[\mathrm{dB}]} \tag{3.18}$$

where:

- $P_{Tx,RE}$: transmitter output power per RE;
- P_{RSRP}: reference signal received power;
- L_c: losses in the cable between the transmitter and the antenna;
- M_c: correction margin.

The transmitter output power per RE can be calculated by using:

$$P_{Tx,RE\,[\mathrm{W}]} = \frac{N_{ant,DL}\cdot P_{Tx\,[\mathrm{W}]}}{N_{RE}} \tag{3.19}$$

where:

- $N_{ant,DL}$: number of configured antenna ports.

Knowing the value of the path loss, one can compute the SINR, which, according to [Eric13b], is given by:

$$\rho_{IN\,[\mathrm{dB}]} = 10\log_{10}\left(\frac{1}{[\rho_{CCH} + (1-\rho_{CCH})\cdot Q_{PDSCH}]\cdot F_i + \frac{P_{N,RE,DL\,[\mathrm{mW}]}\cdot L_{p,total}}{P_{Tx,RE\,[\mathrm{mW}]}}}\right) \tag{3.20}$$

where:

- ρ_{CCH}: fraction of PDSCH resources interfered by control channels;
- Q_{PDSCH}: fraction of the PDSCH resources carrying user data;
- F_i: F value in ring i;
- $P_{N,RE,DL}$: thermal noise per RE in DL.

Finally, in order to establish a relationship between the SINR and the data rate per RE, the following expression is also presented [Eric13b]:

$$R_{b,RE\,[\mathrm{kbit/s}]} = \begin{cases} \max\left[0\,, a_{3\,[\mathrm{kbit/s}]} + \left(a_{0\,[\mathrm{kbit/s}]} - a_{3\,[\mathrm{kbit/s}]}\right) \cdot e^{-\ln(2)\cdot\left(\frac{\rho_{IN\,[\mathrm{dB}]} - a_{1\,[\mathrm{dB}]}}{a_{2\,[\mathrm{dB}]}}\right)^{a_4}}\right], & \rho_{IN\,[\mathrm{dB}]} < a_{1\,[\mathrm{dB}]} \\ a_{0\,[\mathrm{kbit/s}]}, & \rho_{IN\,[\mathrm{dB}]} \geq a_{1\,[\mathrm{dB}]} \end{cases} \tag{3.21}$$

where:

- a_0, a_1, a_2, a_3, a_4: fitted coefficients.

In DL, the fitted coefficients a_0 and a_3 have to be adjusted according to:

$$a_{i\,[\mathrm{kbit/s}]} = a_{i,max\,[\mathrm{kbit/s}]} \cdot \left(1 - \frac{N_{PDCCH}}{14} - \frac{N_{CRS}}{168} - \frac{48 - N_{ant,DL}}{140 \cdot N_{RE}}\right) \tag{3.22}$$

where:

- $a_{i,max}$: maximum value of coefficient i, which are obtained without control channels;
- N_{PDCCH}: number of allocated symbols for PDCCH;
- N_{CRS}: number of cell-specific reference signals multiplexed with PDSCH per RB.

To obtain the total data rate per frame, it is necessary to multiply the results obtained in (3.21) by the number of REs. In this thesis, only the 10 and 20 MHz bandwidths are considered, which correspond to the 800 and 1 800 MHz frequency bands, respectively. Since the REs correspond to one OFDM sub-carrier during an OFDM symbol interval, one can compute the total data rate by using the number of sub-carriers (for each bandwidth) presented in Table 2.4.

The value of each one of the fitted coefficients (a_i) depends on the antenna arrangement, the channel model and the Doppler frequency. The antenna arrangement for Release 10 in DL is reflected in nine Transmission Modes (TMs): single transmit antenna (TM 1), transmit diversity (TM 2), open loop spatial multiplexing with cyclic delay diversity (TM 3), closed loop spatial multiplexing (TM 4), multi-user MIMO (TM 5), closed loop spatial multiplexing using a single transmission layer (TM 6), beamforming (TM 7), dual-layer beamforming (TM 8) and 8 layer transmission (TM 9). Channel models are classified according to low, medium and large delay spreads, as previously done for GSM and UMTS. The Extended Pedestrian A (EPA) model provides a low delay spread (with a root mean square delay spread of 43 ns), being employed in an urban environment with fairly small cell sizes. On the other hand, the Extended Vehicular A (EVA) and Extended Typical Urban (ETU) models are associated with medium (with a root mean square value of 357 ns) and large (with a root mean square value of 991 ns) delay spreads, respectively. These models are also applied with low (5 Hz), medium (70 Hz) and high (300 Hz) Doppler shifts, which enable the common combinations EPA 5 Hz, EVA 5 Hz, EVA 70 Hz and ETU 70 Hz.

A graphical representation of the total data rates as a function of RSRP is presented in Figure 3.2. All the values used to compute these curves are detailed in Section 4.1.

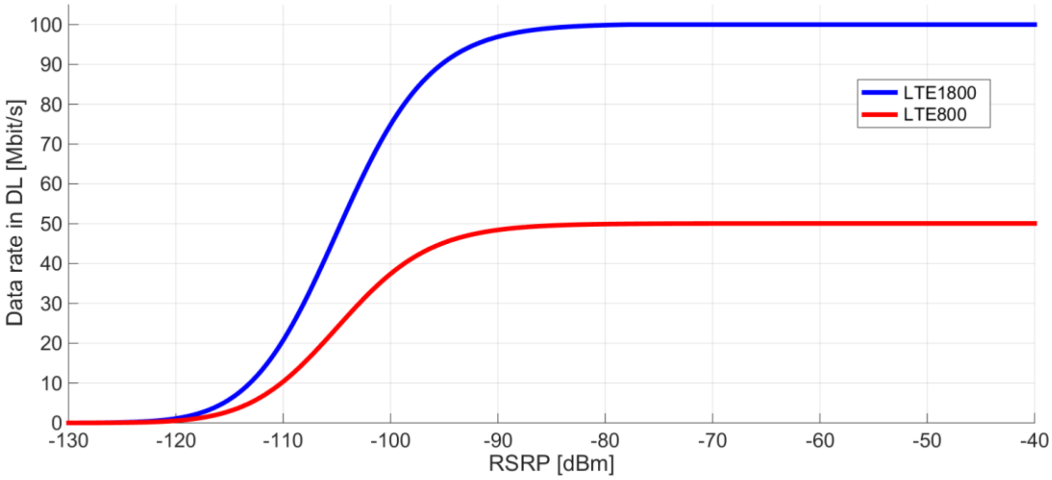

Figure 3.2 Variation of theoretical data rates with the RSRP for both LTE800 and LTE1800.

3.1.5 Confidence Interval

As previously mentioned, it is important to compare data rates obtained from experimental measurements with the respective theoretical values computed with the models presented in Section 3.1.4. In order to have a better comparison of these values, taking a confidence level into account, one should define a confidence interval associated to the theoretical data rates. According to [Pire00], the confidence interval for a given confidence level, $p\%$, can be obtained by using:

$$R_{b\,[\mathrm{Mbit/s}]}^{p\%} \in \left[\, \mu_{\,[\mathrm{Mbit/s}]} - z_p \cdot \sigma_{[\mathrm{Mbit/s}]} \;\; ; \;\; \mu_{\,[\mathrm{Mbit/s}]} + z_p \cdot \sigma_{[\mathrm{Mbit/s}]} \,\right] \tag{3.23}$$

where:

- μ: average value;
- z_p: quantile value;
- σ: standard deviation.

The average values, used to obtain the confidence interval, correspond to the theoretical data rates computed by using the models described in Section 3.1.4. On the other hand, in order to obtain the quantile value one must know the Probability Density Function (PDF) that better describes the variation of the number of measurements with RSRP. Thus, it is possible to compute the quantile using the inverse of the Cumulative Distribution Function (CDF) of the obtained distribution:

$$z_p = F^{-1}\left(1 - \frac{\alpha}{2}\right) \tag{3.24}$$

where:

- F^{-1}: inverse of the CDF F.

$$\alpha = 1 - \frac{p\%}{100} \tag{3.25}$$

The confidence interval can be implemented by using two different approaches to obtain the standard deviation: compute its value for each RSRP using all data rate measurements, or using the average value of all standard deviations. An example of a confidence interval obtained with these two approaches, using $z_p = 2$, is presented in Figure 3.3.

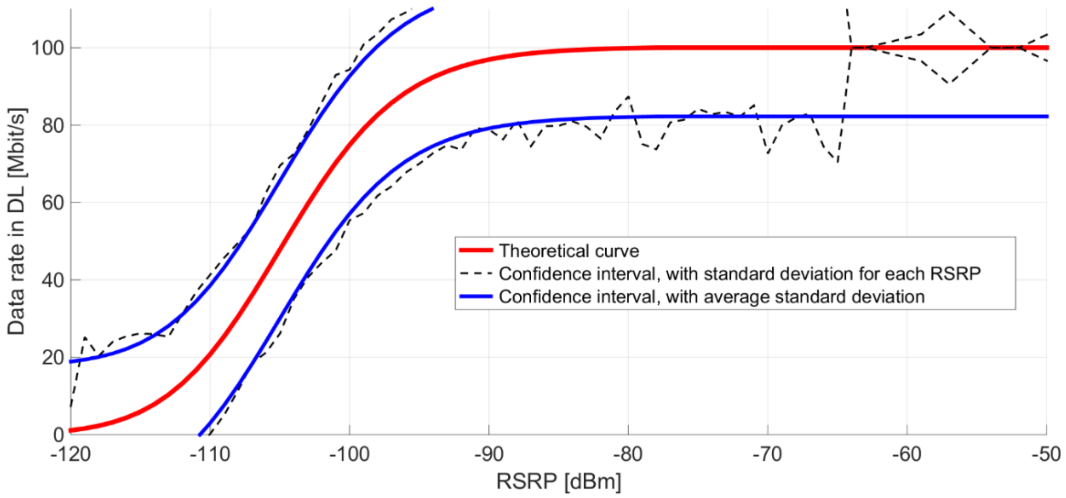

Figure 3.3 Variation of the theoretical data rates with the RSRP for DL, and respective confidence intervals using the two different approaches to compute the standard deviation.

At last, it is important to notice that if the confidence level increases, the quantile value (z_p) will increase, and consequently the confidence interval will be larger. In Figure 3.4, it is possible to see the variation of this relationship for three different examples:

- 70% of confidence level, which corresponds to an interval of one standard deviation ($z_p \approx 1$);
- 90% of confidence level;
- 95% of confidence level, which corresponds to an interval of two standard deviations ($z_p \approx 2$).

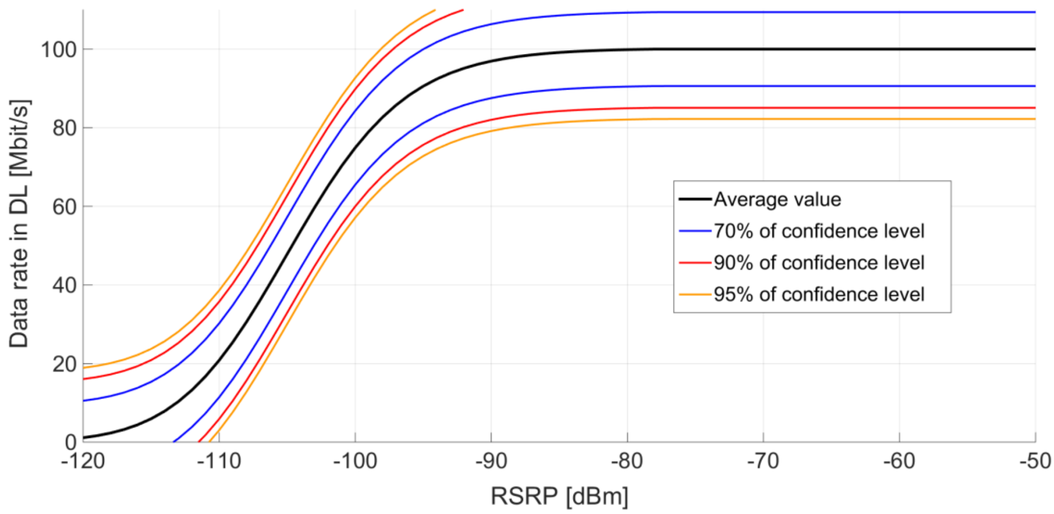

Figure 3.4 Influence of the confidence level in the confidence interval.

3.1.6 Channel Quality Indicator

As detailed in Section 2.1.2, CQI is the most important part of the channel information feedback. It indicates the maximum data rate that the UEs can handle with a BLER probability not exceeding 10%.

Table 2.2 only shows how the CQI is interpreted in terms of the DL modulation scheme, coding rate and the number of information bits per symbol. So, in order to relate the CQI index with their corresponding DL data rates, one must start by defining the relationship between the theoretical data rates and the number of bits per symbol:

$$R_{b\,[\mathrm{Mbit/s}]} = \frac{N_{sub/RB} \cdot N_{sym/sub} \cdot N_{RB} \cdot N_{b/sym\,[\mathrm{bit}]} \cdot N_{MIMO}}{t_{RB\,[\mu\mathrm{s}]}} \cdot \eta_{data} \tag{3.26}$$

where:

- $N_{sub/RB}$: number of sub-carriers per RB (12 when considering a 15 kHz sub-carrier spacing, which fulfil the 180 kHz bandwidth of an RB);
- $N_{sym/sub}$: number of symbols per subcarrier (7 when the normal CP length is used);
- $N_{b/sym}$: number of bits per symbol, which depends on the modulation scheme and coding rate;
- N_{MIMO}: MIMO order (2, for 2×2 MIMO);
- t_{RB}: time duration of an RB, which is 500 µs;
- η_{data}: percentage of symbols carrying user data.

According to [Eric13b], the percentage of symbols carrying user data are computed by:

$$\eta_{data\,[\%]} = \left(1 - \frac{N_{PDCCH}}{14} - \frac{N_{CRS}}{168} - \frac{48 - N_{MIMO}}{140 \cdot N_{RB}}\right) \cdot 100 \tag{3.27}$$

Combining (3.26) and (3.27) with the data presented in Table 2.2 it is possible to obtain the variation of the theoretical data rates with the CQI index. Table 3.2 presents the theoretical data rates obtained for both LTE800 and LTE1800, taking a normal CP length and a 2×2 MIMO into account. All the remaining values used to compute these results are detailed in Table 4.1.

Taking the data rate results presented in Table 3.2 into account and using the MATLAB *Curve Fitting Tool* [Math15b] to fit the values with a polynomial of order 2, it was possible to obtain a curve given by:

$$R_{b\,[\mathrm{Mbit/s}]} = p_{1\,[\mathrm{Mbit/s}]} \cdot {I_{CQI}}^2 + p_{2\,[\mathrm{Mbit/s}]} \cdot I_{CQI} + p_{3\,[\mathrm{Mbit/s}]} \tag{3.28}$$

where:

- I_{CQI}: CQI index;
- p_1, p_2, p_3: fitted coefficients.

The corresponding values for the fitted coefficients used in (3.28) are presented in Table 3.1, for both LTE800 and LTE1800, since they depend on the frequency band.

Table 3.1 Values of the fitted coefficients used to compute theoretical data rates in function of the CQI index, for both LTE800 and LTE1800.

Fitted coefficient	**Coefficient value [Mbit/s]**	
	LTE800	**LTE1800**
p_1	0.2391	0.4805
p_2	0.9449	1.8990
p_3	-0.0836	-0.1679

Table 3.2 Theoretical data rates computed for each CQI index, taking a normal CP length and a 2×2 MIMO into account.

CQI index	Bits per symbol	Data rate [Mbit/s]	
		LTE800	LTE1800
0	0.0000	0.0000	0.0000
1	0.1523	1.8108	3.6384
2	0.2344	2.7869	5.5997
3	0.3770	4.4824	9.0064
4	0.6016	7.1528	14.3720
5	0.8770	10.4272	20.9512
6	1.1758	13.9798	28.0894
7	1.4766	17.5562	35.2754
8	1.9141	22.7579	45.7271
9	2.4063	28.6099	57.4855
10	2.7305	32.4646	65.2306
11	3.3223	39.5008	79.3684
12	3.9023	46.3968	93.2244
13	4.5234	53.7814	108.0622
14	5.1152	60.8177	122.2001
15	5.5547	66.0432	132.6996

To validate the fitted coefficients presented in Table 3.1, it is important to examine the goodness-of-fit statistics using some parametric models defined in [Math15a]:

- R-square, which measures how successful the fit is in explaining the variation of the data. It is the square of the correlation between the response and the predicted response values, and it is also defined as the ratio of the sum of squares of the regression and the total sum of squares.
- Adjusted R-square, which uses the R-square statistic defined above, and adjusts it based on the residual degrees of freedom. It can take value less than or equal to 1, with a value closer to 1 indicating a better fit.
- Root Mean Squared Error (RMSE), which is an estimate of the standard deviation of the random component in the data. An RMSE value closer to 0 indicates a fit that is more useful for prediction.

The R-square value can be computed via:

$$R^2 = \frac{\sum_{i=1}^{n} \left(\hat{y}_i - \mu_y\right)^2}{\sum_{i=1}^{n} \left(y_i - \mu_y\right)^2} \tag{3.29}$$

where:

- y_i: observation i;
- $\hat{y}_i$: estimated or predicted value of y_i;

- μ_y: average of the observations of variable y;
- n: number of observations.

To compute the RMSE one can use:

$$\sqrt{\overline{\varepsilon^2}} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \tag{3.30}$$

The obtained results for the defined parametric models are presented in Table 3.3, in which their values were obtained using the MATLAB *Curve Fitting Tool* [Math15b].

Table 3.3 Goodness-of-fit statistics to access the variation of theoretical data rates with the CQI index fitting curves.

Frequency band [MHz]	R-square	Adjusted R-square	RMSE
800	0.9988	0.9986	0.0062
1 800			0.0124

Since these fittings have an R-square and an adjusted R-square value of almost 100%, and a normalised RMSE value almost equal to 0, one can use (3.28) to describe the theoretical variation of the user's data rates with the CQI index. A graphical representation of these relationship is presented in Figure 3.5.

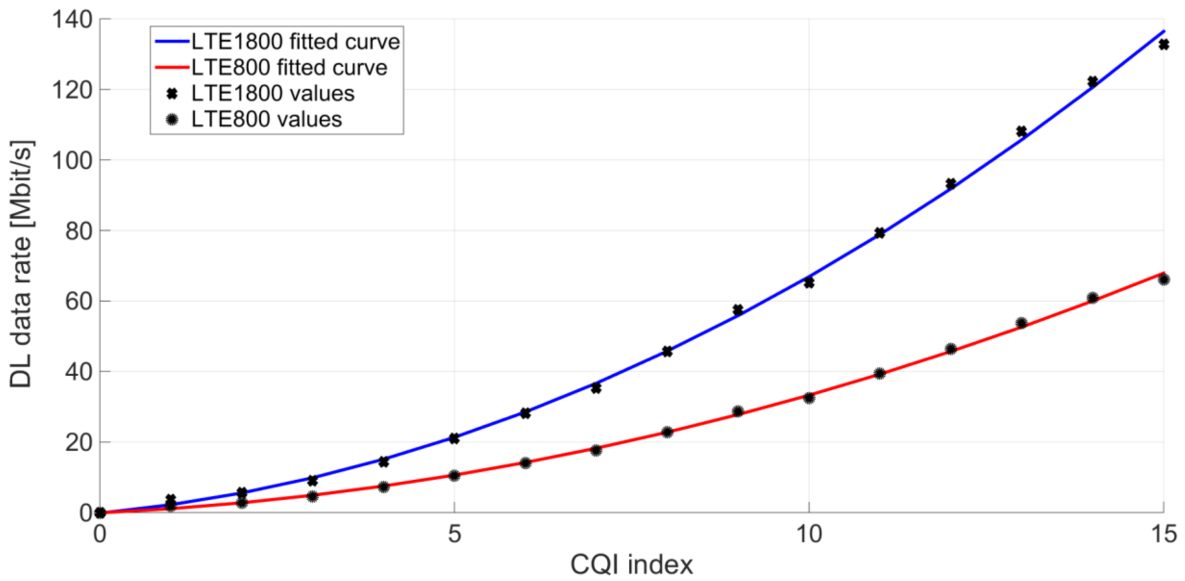

Figure 3.5 Variation of theoretical DL data rates with the CQI index, for both LTE800 and LTE1800.

3.1.7 Cell Coverage and Capacity

As mentioned in Section 2.1.2, LTE can be deployed in three different frequency bands: 800, 1 800 and 2 600 MHz. The higher band has a data capacity larger than the other two, so it can deal with many more people connecting at once. However, it does not perform so well over long distances, due to its attenuation, making it ideal for cities or other densely populated areas. On the other hand, the 800 MHz band cannot provide the same data capacity as the 2 600 MHz one, but it can easily travel over long distances covering wider areas. Being a low frequency, it is also better at penetrating walls than the higher ones, so it will provide an improved signal when users are indoors. The 1 800 MHz band strikes a good balance between coverage and capacity.

Concerning the calculations of coverage, it is possible to determine the coverage range of a cell by using an adequate environment propagation model and the link budget expression, presented in (3.1):

$$R_{\max\,[\mathrm{km}]} = 10^{\frac{P_{t\,[\mathrm{dBm}]}+G_{t\,[\mathrm{dBi}]}-P_{r,min\,[\mathrm{dBm}]}+G_{r\,[\mathrm{dBi}]}-L_{p,total\,[\mathrm{dB}]}}{10^{a_{pd}}}} \quad (3.31)$$

where:

- $P_{r,min}$: power sensitivity at the receiver antenna;
- a_{pd}: average power decay.

It is important to notice that the coverage range corresponds to the maximum distance between the users and the BS, for a given data rate, since, according to [Pire12], this is the best characterisation for coverage concerns.

Since the total path loss increases with the frequency band, as shown in (3.4), by using (3.31) one can easily conclude that the coverage of a cell reduces when the frequency increases (if all the other parameters remains unchanged). A more visual representation of the coverage range variation for the three different frequency bands is presented in Figure 3.6.

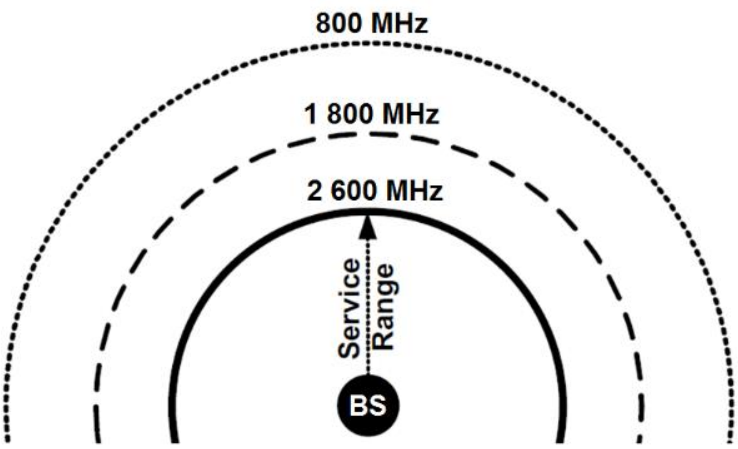

Figure 3.6 Cell's radius for the different LTE frequency bands (adapted from [Tols11]).

When a network is designed or optimised to provide "fixed" data services, the choice of the frequency bands to be used is one of the most important matters that must be taken into account. As previously detailed, the 800 MHz band is better at travelling over long distances, which means users can get the signal even when they are a long way from the site, thus this band is one of the most used for the deployment of the system. However, it has a comparatively low capacity, which means that it cannot always deal with a high number of users trying to connect at once, particularly if they are carrying out demanding services, such as streaming High Definition (HD) video. So, even in places with good radio channel conditions, the 800 MHz band may not always deliver reliable data rates, especially in areas where there is likely to be a lot of data traffic. Taking that fact into account, mobile operators can add a cell with a higher frequency band in the sites that have capacity problems. As detailed in Section 4.1, in this work only the 800 and the 1 800 MHz frequency bands are considered, since these are the frequencies for which measurements were collected. So, in this specific case, only 1 800 MHz carriers are considered to improve the capacity of the 800 MHz cells with capacity issues.

According to the specifications implemented in the network, when the UEs are in idle mode (i.e. they are not engaged in traffic) and have completed the cell selection/reselection process, they stay camped on the cell with the higher frequency band. Thus, when a new 1 800 MHz carrier is added to a site, it is assumed that all UEs start to be camped on this new cell. However, the cells with the lower frequency band have a higher coverage, thus, some UEs that are in the 800 MHz cell-edge will stay camped in that lower band cell, since they are not covered by the 1 800 MHz cell, as it can be seen in Figure 3.7.

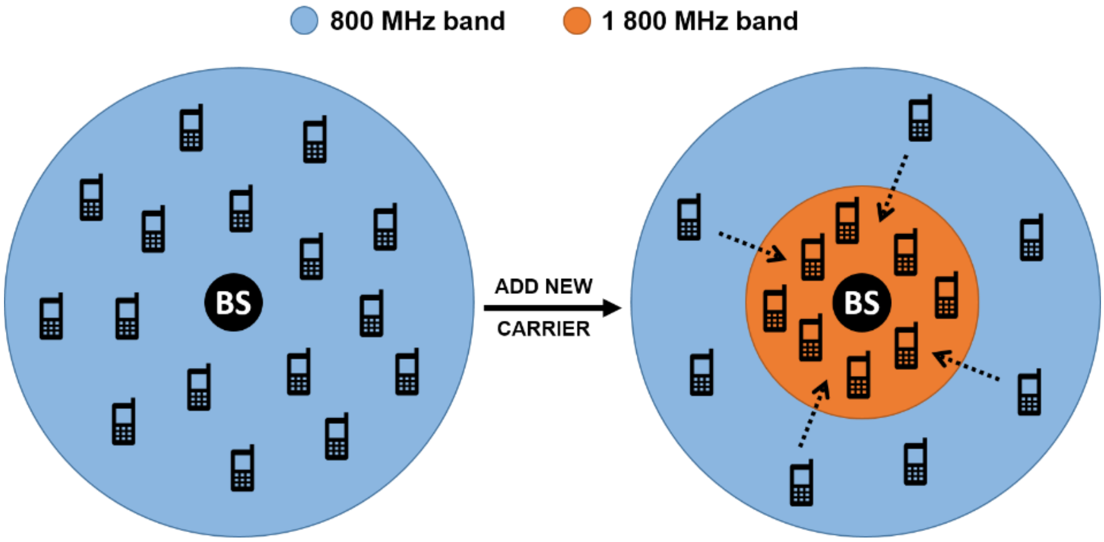

Figure 3.7 UEs cell selection when a 1 800 MHz carrier is added to a site which already has an 800 MHz cell.

In order to evaluate the capacity of the LTE frequency bands, it is important to analyse the average number of users who are connected to a single cell for each band. Assuming that SNR is a non-limiting factor and that each user requires the same throughput, one can define the average number of users connected to a single cell by:

$$\overline{N_u} = \left\lfloor \frac{R_{b,peak\,[\mathrm{Mbit/s}]}}{\overline{R_b^u}_{\,[\mathrm{Mbit/s}]}} \right\rfloor \tag{3.32}$$

where:

- $R_{b,peak}$: DL peak data rates;
- $\overline{R_b^u}$: average DL data rate per user.

Assuming that all users require, on average, a data rate of 5 Mbit/s, and taking the DL peak data rates presented in Table 2.5 into account, it is possible to compute the average number of users who are connected to a single cell, for different frequency bands and UEs specifications, using (3.32). The obtained values, for both LTE800 and LTE1800, are presented in Table 3.4.

Table 3.4 Average number of users connected to a single cell, for both LTE800 and LTE1800, taking an average data rate per user of 5 Mbit/s into account.

UEs specifications			**Average number of users**	
Modulation and coding	**MIMO usage**	**Bits/symbol**	**LTE800**	**LTE1800**
QPSK 1/2	–	1.0	1	3
16-QAM 1/2		2.0	3	6
16-QAM 3/4		3.0	5	10
64-QAM 3/4		4.5	7	15
64-QAM 1/1		6.0	10	20
64-QAM 3/4	2×2 MIMO	9.0	15	30
64-QAM 1/1		12.0	20	40
64-QAM 1/1	4×4 MIMO	24.0	40	80

3.2 Model Implementation

The models described in Section 3.1 were implemented using a simulator developed with the MATLAB programming language. In order to allow a wider analysis of the scenarios described in Section 4.1, two distinct approaches used to define some comparison thresholds were implemented: relative and absolute ones. This section describes the implementation of the simulator for each of these approaches.

3.2.1 Relative Threshold Approach

One of the main problems addressed in this thesis concerns the analysis of LTE cells performance, in order to assess the quality of the data services provided by those specific cells. Taking it into account, a simulator was developed in order to characterise some experimental measurements obtained in the network. The simulator is composed of some different algorithms, its main structure being presented in Figure 3.8.

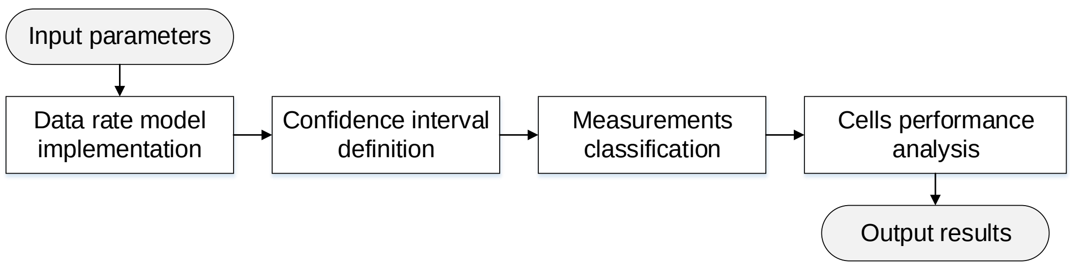

Figure 3.8 Simulator main structure for a relative threshold approach.

The only input file needed in this simulator is MeasurementsDataUpdated.xlsx, which is an Excel file that contains information about a sample of experimental measurements collected in the real network. Each measurement contains information about a data service provided to a specific customer. It is important to notice that a single customer can have more than one measurement, which can be reported by the UE in distinct moments. This file is the main source of data that was treated in this work. It has “Updated” in its name because it does not match exactly the file provided by NOS. This means that some processing was made in order to guarantee a better data analysis. All the data processing made in the original file, together with an explanation of all the measurements parameters presented in this file are detailed in Annex B.

The updated files are read by the simulator using the MATLAB *xlsread* command, which reads the first worksheet in the Excel spreadsheet workbook and returns the data in a numeric matrix, using as argument a string with the complete file directory (including the file name). This string is an input value, and is one of the most important ones, because it allows the simulator to correctly read and import the Excel file with all the experimental measurements data. After reading the input file and importing all of its data to a matrix, the simulator organises and selects the measurements, taking the following parameters into account:

- frequency band associated with the maximum available bandwidth;
- commercial tariff plan of the measurement, which defines the maximum value of data rate;
- time interval in which the measurements were collected.

These parameters are also input values and need to be defined by the user before running the simulator, as well as the confidence level, which will be used to compute the confidence interval.

A dialog box was implemented in order to request all these input parameters in an easier and more direct way. It was created using the MATLAB *inputdlg* command, which returns user input for multiple prompts in a cell array. Some default values to display for each prompt were also specified.

Some values assessment were applied to the input parameters in the simulator in order to guarantee the models’ correct implementation. If the users insert an unexpected value for each of the input parameters, a dialog box with an error message is displayed. More details about the accepted values for these parameters are presented in Section 4.1.

To achieve some goals of this thesis, it is important to compare the data rates of the experimental measurements with their respective theoretical values, which are computed using the model provided in Section 3.1.4 and the parameters detailed in Table 4.1. In order to fit the specifications of the NOS network, a correction margin of 7 dB should also be taken into account in (3.18), increasing the accuracy of the theoretical values. It is important to notice that the study of each frequency band and tariff plan type are done separately, because the theoretical curves are different for different values of these input parameters.

In order to have a better comparison of the theoretical and experimental values, one should define a confidence interval associated with the theoretical data rates using the model defined in Section 3.1.5. As previously mentioned, in order to obtain this interval, a quantile function must be defined. Therefore, one must know the PDF that better describes the variation of the number of measurements with the RSRP. Taking the sample of experimental measurements into account, and plotting the normalised number of measurements, it is possible to analyse the variation of these values in order to get the best PDF. The normalisation is done by taking the measurements maximum value, which is presented in Annex C, into account. Using the MATLAB *Curve Fitting Tool* [Math15b] to fit the samples with a Normal (or Gaussian) distribution, it is possible to obtain the curve given by (3.33) and presented in Figure 3.9.

$$N_{m,n}(P_{RSRP}) = 0.97 \cdot e^{-\frac{\left(P_{RSRP\,[\mathrm{dBm}]}-\mu\right)^2}{2\,\sigma^2}} \tag{3.33}$$

where:

- $N_{m,n}$: normalised number of measurements;
- μ: average value, which is -95.95 dBm;
- σ: standard deviation, which is 11.98 dBm.

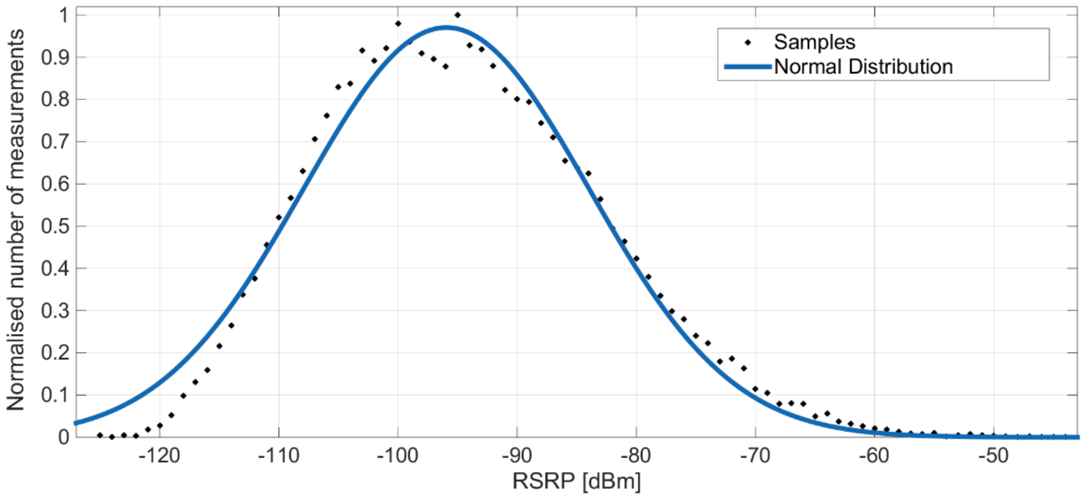

Figure 3.9 Normalised number of measurements in function of RSRP fitted with a normal distribution.

To validate this fitting, it is important to examine the goodness-of-fit statistics using some parametric models defined in [Math15a] and already specified in Section 3.1.6. The following results for that parametric models were obtained using the MATLAB *Curve Fitting Tool* [Math15b]:

- R-square: 0.9831
- Adjusted R-square: 0.9827
- RMSE: 0.0463

With an R-square and an adjusted R-square values close to 1, and with an RMSE value almost equal to 0, one can conclude that it is possible to use the inverse normal distribution, Φ^{-1}, to compute the quantile value, z_p. This value is obtained in the simulator using the *norminv* MATLAB command.

After computing the theoretical values for the data rates (as a function of RSRP) and defining the confidence interval (for a specified confidence level), one can analyse the experimental measurements and characterise them according to three different categories:

- Optimistic: measurements outside the confidence interval with higher data rates;

- Normal: measurements within the confidence interval;
- Pessimistic: measurements outside the confidence interval with lower data rates.

Some measurements examples, characterised for different categories, are presented in Figure 3.10. The presented data rates are normalised to their maximum value, which is presented in Annex C.

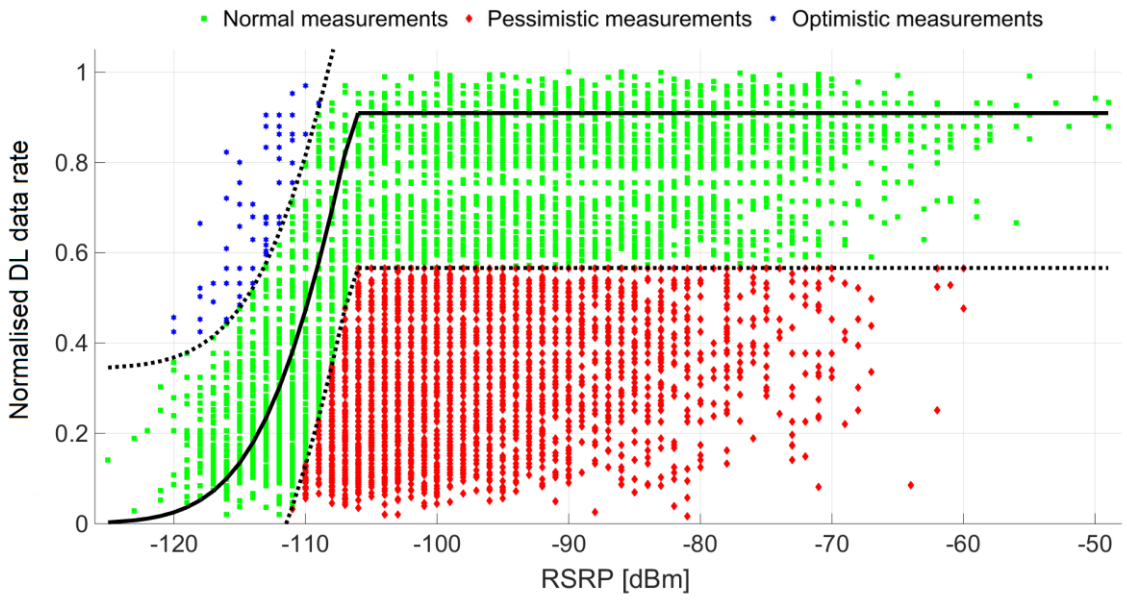

Figure 3.10 Measurements classification for a relative threshold approach (taking a confidence level of 95% and a limitative commercial tariff plan into account).

Together with the previous characterisation, the simulator computes and displays the total number of analysed measurements, the percentage of measurements of each category, the number of distinct cells, and the percentage of those cells that have pessimistic measurements.

By isolating the measurements with pessimistic results, it is possible to analyse the cells where these measurements were made. The simulator evaluates those cells, and computes the following values for each one of them:

- total number of measurements;
- number of pessimistic measurements and respective percentage;
- date of the more recent measurement.

An Excel file is automatically created with these output values, being a tool to study and compare the performance of the cells. A new file is generated for each simulation, containing the results for a specific combination of the input parameters. In order to better identify the files that correspond to each of the simulations, the output files are named Output_Frequency_Plan_Time_Confidence.xlsx, in which the “Frequency”, the “Plan”, the “Time” and the “Confidence” in their names correspond to the frequency band, the commercial tariff plan, the time interval, and the confidence level defined by the user as input parameters, respectively.

3.2.2 Absolute Threshold Approach

In parallel to the previous approach, one can analyse the performance of the cells with an absolute threshold approach. As described in Section 3.2.1 the measurements classification in the relative approach is based on the comparison between the experimental and theoretical values for data rate. However, in this new approach, the classification is made by taking a specific threshold for data rate and RSRP into account. The simulator for this approach is simpler than the one presented in Figure 3.8, its structure being presented in Figure 3.11.

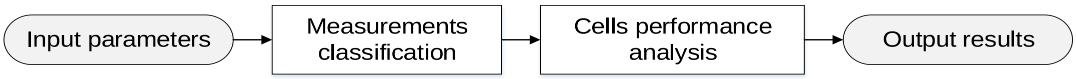

Figure 3.11 Simulator main structure for an absolute threshold approach.

In this approach, all the following input parameters must be explicitly given to the simulator:

- MeasurementsDataUpdated.xlsx file;
- Complete MeasurementsDataUpdated.xlsx file directory (including the file name);
- frequency band;
- time interval;
- data rate threshold for DL;
- RSRP threshold.

After the simulator reads MeasurementsDataUpdates.xlsx, using as argument the string with the complete file directory, it returns the data in a numeric matrix, as it also happens in the relative threshold approach. The simulator analyses the measurements data of that matrix taking the frequency band and the time interval of each measurement into account. Although the analysis of each frequency band and time interval could be done at the same time, it is made separately in order to distinguish the 800 MHz and 1 800 MHz cells, and the two different time intervals (off-peak and on-peak). The study of the commercial tariff plans is done simultaneously, because this analysis does not depend on the theoretical curves, and the threshold for data rates is the same for all plans. Similarly to the relative threshold approach in this phase, a dialog box (with some values assessment) was implemented in MATLAB in order to request all the needed parameters.

The measurements classification in this approach is made by comparing the thresholds for RSRP and the data rate (defined by the user) with the experimental measurements. With this analysis, it is possible to characterise the measurements according to two different categories:

- Normal: measurements outside the thresholds interval;
- Pessimistic: measurements within the thresholds interval.

Some measurements examples, characterised for the two categories, are presented in Figure 3.12. As previously done for the relative threshold approach, the presented data rates are normalised to their maximum value, which is presented in Annex C.

From this step until the end of the simulation, the simulator works exactly the same way as the one detailed in Section 3.2.1, making an equivalent cell performance analysis and generating the same type of output results.

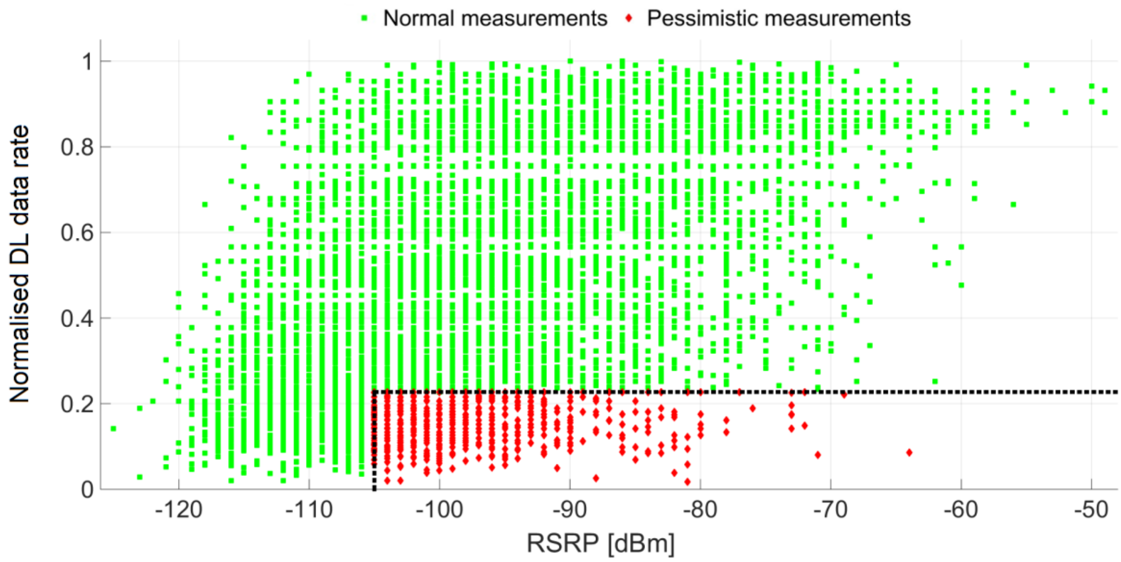

Figure 3.12 Measurements classification for an absolute threshold approach with a threshold for data rate which is 22.7% of the nominal value and a -105 dBm one for RSRP.

As in the relative threshold approach, a new file is automatically generated for each simulation, containing the results for a specific combination of the input parameters. It is important to notice that these files are named Output_Frequency_Time_DR_RSRP.xlsx, in which the “Frequency”, the “Time”, the “DR” and the “RSRP” in their names correspond to the frequency band, the time interval, the data rate threshold and the RSRP one defined in the input parameters, respectively.

An extension to the simulator to study UL performance, using the same absolute threshold approach that is used for DL, was also implemented.

3.3 Model Assessment

During model development, in order to validate its implementation, the obtained results were subjected to a set of empirical tests. As the MATLAB scripts were under construction, a careful examination of all variables and formulas was made, in order to check if they were coherent and also accurate from a theoretical viewpoint. Hence, the final outputs obtained with the model, as well as some intermediate steps, were confirmed using some Microsoft Excel tools or a scientific calculator. Different tests were carefully chosen to cover all the calculations done by the implementation of both model approaches, which are detailed in Section 3.2.1 and Section 3.2.2.

A list with the most critical tests performed for the relative threshold approach is provided in Table 3.5. Table 3.6 presents a list with the tests made for the absolute threshold approach.

Table 3.5 List of empirical tests that were made to validate the implementation of the relative threshold model approach.

Test	Description
1	Check if the MeasurementsDataUpdated.xlsx file exists and are located in the directory provided by the user to the simulator using the implemented dialog box.
2	Check if the parameters of the MeasurementsDataUpdated.xlsx file are in the correct column of the first sheet, according to the details provided in Annex B.
3	Validation of the remaining input parameters provided by the user to the simulator, using the *isequal* MATLAB command. This command returns logical 1 (true) if the input values are equal to the expected values; otherwise, it returns logical 0 (false) and a dialog box with an error message is displayed.
4	Validation of the MeasurementsDataUpdated.xlsx input file read, by verifying if the matrix created with the loaded values is equal to the table of the input Excel file.
5	Validation of the measurements selection algorithm, by comparing the number of imported measurements and the number of measurements in the input file which have the LTE frequency band, the commercial plan and the time interval defined by the user.
6	Validation of the data rate theoretical model provided in Section 3.1.4: using a scientific calculator to compute some specific values and compare them with the ones obtained in the simulator; and plotting the simulator results in order to visually inspect their correctness.
7	Validation of the confidence level model provided in Section 3.1.5 using the same approach used to validate the data rate theoretical model in test 6.
8	Scatter plot of all the imported measurements using a different colour for each measurement classification (red, green and blue for pessimistic, normal and optimistic measurements, respectively), in order to visually inspect the correctness of the measurement classification algorithm.
9	Validation of the .xlsx output file creation with the cells output results, by verifying if the table of the created Excel file is equal to the matrix with the results computed by the simulator.

Table 3.6 List of empirical tests that were made to validate the implementation of the absolute threshold model approach.

Test	Description
1	Check if the MeasurementsDataUpdated.xlsx file exists and are located in the directory provided by the user to the simulator using the implemented dialog box.
2	Check if the parameters of the MeasurementsDataUpdated.xlsx file are in the correct column of the first sheet, according to the details provided in Annex B.
3	Validation of the remaining input parameters provided by the user to the simulator, using the *isequal* MATLAB command. This command returns logical 1 (true) if the input values are equal to the expected values; otherwise, it returns logical 0 (false) and a dialog box with an error message is displayed.

Table 3.6 (contd.) List of empirical tests that were made to validate the implementation of the absolute threshold model approach.

4	Validation of the MeasurementsDataUpdated.xlsx input file read, by verifying if the matrix created with the loaded values is equal to the table of the input Excel file.
5	Validation of the measurements selection algorithm, by comparing the number of imported measurements and the number of measurements in the input file which have the LTE frequency band, the commercial plan and the time interval defined by the user.
6	Validation of the thresholds defined by the user using a plot to visually inspect their correctness.
7	Scatter plot of all the imported measurements using a different colour for each measurement classification (red and green for pessimistic and normal measurements, respectively), in order to visually inspect the correctness of the measurement classification algorithm.
8	Validation of the .xlsx output file creation with the cells output results, by verifying if the table of the created Excel file is equal to the matrix with the results computed by the simulator.

Chapter 4

Results Analysis

This chapter presents the considered scenarios description along with the obtained results and their respective analysis. Some network improvements matters are also presented in the end of this chapter.

4.1 Scenarios Description

The scenarios studied in this thesis are based on a sample of 81 501 measurements (collected between 22nd of August 2014 and 3rd of May 2015), each one containing information about an LTE data service provided to a specific customer (who is anonymous). It is important to denote that only DL is analysed, since there are not enough experimental data to make an appropriate UL analysis. Measurements were reported by the UE using the Technical Report 069 (TR-069), detailed in [DLSH15], which defines an application layer protocol for remote management of end-user devices. It provides communication between the UEs, which are indoors (in the specific case of this thesis), and an Auto Configuration Server (ACS). It is important to notice that all the UEs considered in this work support this protocol. When a new UE is connected to the network, the ACS sends an automatic command to the equipment in order for it to report the cell ID, the signal level and to start performing some quality measurements. Moreover, this command can also be triggered remotely whenever the operator wants. One of the most important quality measurements reported by the UE is the DL data rate associated with each customer, since it is an indicator about the service quality perceived by the user. The UE downloads an FTP file from the server to compute the data rate value – knowing the duration of the download and the size of the file, which is variable according to the radio channel conditions (i.e., a smaller file is downloaded when the network has poor radio channel conditions). A list with some of the measurements parameters, reported by this protocol, is presented in Annex B.

It is known that data traffic is not equally distributed over a 24 hour period. The busy-hour in data networks, like LTE, is typically during the evening, but this kind of traffic is also generated during all the other hours. Thus, it is important to divide the measurements into time intervals over a day, according to the hours in which they were reported:

- Off-peak interval: measurements reported between 3 am and 8 am;
- On-peak interval: measurements reported between 8 pm and 12 am.

The off- and on-peak measurements correspond to 67.2% and 27% of the total, respectively; the remaining 5.8% were reported in arbitrary hours outside the previous intervals.

Moreover, each measurement is associated with a commercial tariff plan, defined by the operator, which limits the data rate maximum value, for both DL and UL, according to three different tariff plans: P1, P2 and P3, which are specified in Annex B. The measurements associated with P1, P2 and P3 correspond to 28.5%, 51.3% and 20.2% of the total number of measurements, respectively. It is also important to refer that P1 is the most limitative plan and P3 the less one. Measurements in which DL or UL data rates are 10% higher than the limit of the plan are considered as measurements of the plan with the lower limitation. New clients have an initial period of a few days in which they have a trial service, which does not have limits for the allowed data rates. Thus, from an analysis viewpoint, they have a service equivalent to the ones that have the plan with the higher threshold. However, an important remark should be done: the TR-069 protocol [DLSH15] has a maximum allowed data rate, which is lower than the P3 plan limit. Thus, the real data rates associated with P3 measurements are unknown, and it is impossible to correctly analyse the measurements for this commercial plan. The analysis of the measurements has been done taking the DL scenario into account, and considering two different frequency bands, associated with their maximum available bandwidths:

- 800 MHz band (LTE800) with a bandwidth of 10 MHz, which provides coverage;
- 1 800 MHz band (LTE1800) with a bandwidth of 20 MHz, which provides extra capacity.

As detailed in Annex B, the measurements also contain information about the RSRP value associated with each one of them. It is important to notice that measurements with an RSRP value smaller than -125 dBm are not considered, because the receivers do not work in this range of values. In such specific cases (only 0.026% of the measurements) data were reported/received with errors.

To analyse the experimental measurements, one can use the relative or the absolute threshold approaches described in Section 3.2. In the relative threshold approach, the data rates of the measurements are compared with their respective theoretical values, which are computed using the model provided in Section 3.1.4 and the parameters detailed in Table 4.1. Transmitter output power is 46 dBm (which corresponds to 40 W), being divided among all the REs available in the frequency band under analysis.

Table 4.1 Configuration of parameters for the data rate model for DL.

Parameter description	**Parameter value in DL**	
Frequency band [MHz]	800	1 800
Number of configured antenna ports ($N_{ant,DL}$)	2	
Transmitter output power (P_{Tx}) [W]	40	
Number of RE for the deployed bandwidth (N_{RE})	600	1 200
Gain of the transmitting antenna [dBi] (G_t)	18.5	
Cable losses [dB] (L_c)	0.8	
PDSCH resources interfered by control channels [%] (ρ_{CCH})	11.8	
PDSCH resource blocks carrying user data [%] (Q_{PDSCH})	55	
F value in ring i (F_i)	1.64	
Thermal noise per RE [dBm] ($P_{N,RE,DL}$)	-114.4	
Maximum value of fitted coefficient a_0 [kbit/s] ($a_{0,max}$)	1 489.2	
Fitted coefficient a_1 [dB]	56.8	
Fitted coefficient a_2 [dB]	41.0	
Maximum value of fitted coefficient a_3 [kbit/s] ($a_{3,max}$)	0	
Fitted coefficient a_4	4	
Number of allocated symbols for PDCCH (N_{PDCCH})	3	
Number of cell-specific reference signals multiplexed with PDSCH per RB (N_{CRS})	12	
Antenna arrangement	TM3	
Channel model and Doppler frequency [Hz]	EPA 5	

The values presented in Table 4.1 are based on [Eric13b], with the exception for cable losses, which are defined in order to fit the specifications of the network where the measurements were collected. Category 3 of UEs (which are able to support DL throughputs up to 100 Mbit/s, according to Annex A) with a 2×2 MIMO configuration are considered. All users are in EPA 5.

According to NOS, and in order to ensure a minimum QoS associated with the relationship between the data rate and the RSRP value, the analysis of the measurements with bad performance were done taking only the absolute threshold approach into account. This approach was also chosen because the relative one can lead to some misleading results – measurements with high RSRP values and relative high data rates can be classified as pessimistic if a small confidence interval is considered.

4.2 Scenarios Analysis

Using the scenarios described in Section 4.1 and the model detailed in Section 3.2.2, it is possible to analyse the measurements that were reported by the UEs during several months. In this section, that analysis is made for DL. As previously detailed, the study of each frequency band is done separately in order to distinguish in between the 800 MHz and the 1 800 MHz cells, as well as the analysis of the two time intervals (on-peak and off-peak). The tariff plans P1 and P2 are studied simultaneously.

The characterisation of the measurements as normal or pessimistic (using the simulator implemented in Section 3.2.2) is the first step of the analysis. For DL, one can consider that the pessimistic measurements are the ones with high values of RSRP and low data rates. Thus, one has analysed the scenarios in which users have an acceptable RSRP value but do not have suitable data rates to guarantee an adequate QoS; for the RSRP, one has used a -105 dBm power threshold to define an acceptable received signal. Moreover, a reference value for the data rate has also to be considered in order to define an adequate threshold for it; as seen in Table 2.8, video streaming is the most demanding service, requiring a minimum data rate of 500 kbit/s and an average one near 5 Mbit/s, in order for it to work properly, which led to the thresholds for data rates presented in Annex C. It is important to denote that the data rate threshold for LTE1800 is twice the one for LTE800, since it has two times more available RBs (as seen in Table 2.4).

4.2.1 Off-Peak Results

In the off-peak interval, performance is essentially limited by network coverage and basically does not depend on capacity, since it is expected that a low number of users (less than 80) is connected to the network during these hours. The obtained results during the off-peak interval, for LTE800 and LTE1800, can be seen in Figure 4.1 and Figure 4.2, respectively.

The figures present the data rates normalised for their maximum value, which are specified in Annex C. One highlight that it is possible to extract from these two figures, is the higher concentration of measurements for two distinct data rates, which correspond to the maximum data rates allowed in P1 and P2. Thus, one can conclude that some customers have their data rates limited by the hired commercial tariff plan instead of limited by network conditions.

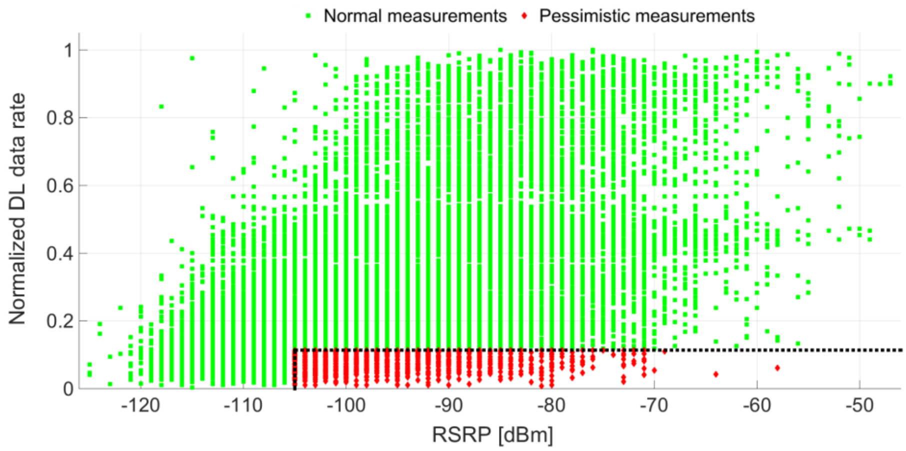

Figure 4.1 DL measurements classification for the 800 MHz band during the off-peak time interval.

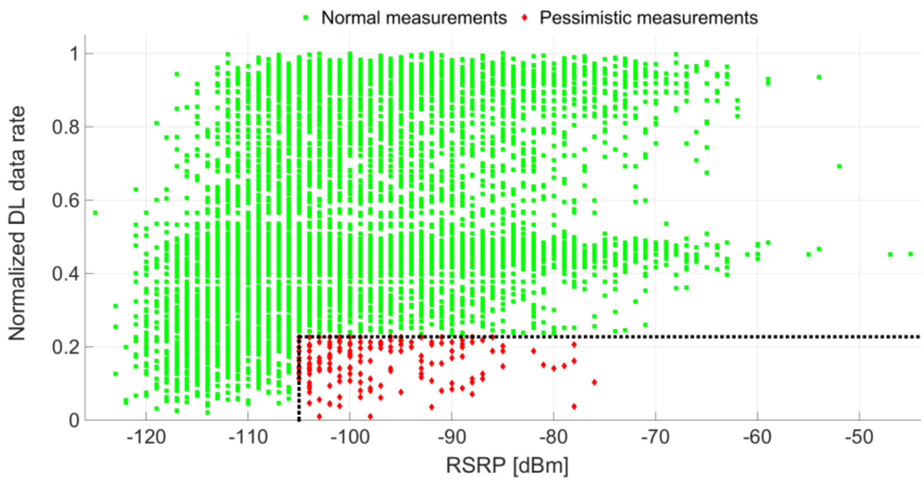

Figure 4.2 DL measurements classification for the 1 800 MHz band during the off-peak time interval.

Together with the measurements characterisation, the simulator computes the total number of measurements, the percentage of measurements of each category, the number of distinct cells, and the percentage of the cells that have pessimistic measurements. These output values, for both LTE800 and LTE1800, are presented in Table 4.2. It is important to note that LTE800 has almost 3 times more measurements than LTE1800, so this means that the results obtained in that band have more statistical relevance compared with the ones obtained for the higher band.

The first insight that one can extract from the following results is the high performance of LTE1800, since it has more than 98% of normal measurements. LTE800 has 6.97% of measurements that have low data rates despite their high values of RSRP, so in general one can say that it also has a good performance.

Table 4.2 Simulator DL output results, for both 800 MHz and 1 800 MHz bands during the off-peak time interval.

Parameter	LTE800	LTE1800
Total number of measurements	31 881	11 189
Number of normal measurements [%]	93.03	98.24
Number of pessimistic measurements [%]	6.97	1.76
Total number of cells	1 382	1 277
Number of cells with pessimistic measurements [%]	46.53	9.63

As seen in Table 4.2, there are more 5.21 percentage points of pessimistic measurements for LTE800 comparing with LTE1800. One can expect this better performance for the higher band, even having a more demanding threshold for data rate, because LTE1800 can achieve higher data rates, comparing to LTE800, since it has twice the bandwidth and correspondingly twice the number of RBs.

In terms of cells, LTE1800 has only 9.63% of cells with at least one pessimistic measurement against 46.53% for LTE800. Taking only those cells (with at least one pessimistic measurement) into account, the simulator creates an Excel file with information about: the total number of measurements, the number of pessimistic measurements, and the date of the more recent measurement. It is important to highlight that these values are individually computed for each cell, in order to allow the comparison and the analysis of their performance. One of the main topics of this thesis is precisely the analysis of the cells with a pessimistic performance, in which the users who are connected to them cannot have an acceptable quality of service. One can define a cell with a pessimistic performance if it has more than 30% of pessimistic measurements in a sample with, at least, a total of 20 measurements. Using the Excel data filter tool to isolate the cells that fit that definition, it is possible to list only the cells with bad performance, for both LTE800 and LTE1800, obtaining the results presented in Table 4.3.

Table 4.3 Number of pessimistic cells, for both 800 MHz and 1 800 MHz bands, in DL and taking the off-peak time interval into account.

Parameter	LTE800	LTE1800
Number of cells with pessimistic performance	14	0
Number of cells with pessimistic performance [%]	1.01	0.00

As seen in Table 4.3, LTE1800 does not have any cell with a pessimistic performance. This can be explained by the fact that the main constrain of higher frequency bands is signal attenuation, which increases with frequency. It is important to recall that, in the first place, this analysis is made taking the measurements with high values of RSRP into account, so the attenuation is not the main topic under study. Thus, one can expect this high performance for LTE1800. On the other hand, there are 14 cells with a pessimistic performance for LTE800, which correspond to approximately 1% of all 1 382 cells. In terms of cells, one can conclude that LTE1800 has also a much higher performance compared with the 800 MHz band. It is important to refer that the LTE800 cell with the worst performance has 41.18% of pessimistic measurements, so all the cells have more than half of the measurements with normal results.

4.2.2 On-Peak Results

During the on-peak hours, performance depends essentially on the network capacity. According to [Noki14], the network has the maximum number of connected users those busy-hours, during which the quality of service associated with each costumer does not depend only on network characteristics. The number of users who are connected to the network at the same time has a direct influence on the quality of service that is provided to all of them, e.g., some customers with a high RSRP value and a high CQI index may be without service if there are no available RBs in the network.

The obtained results during the on-peak interval, for LTE800 and LTE1800, can be seen in Figure 4.3 and Figure 4.4, respectively. The figures present the data rates normalised for their maximum value, which are specified in Annex C.

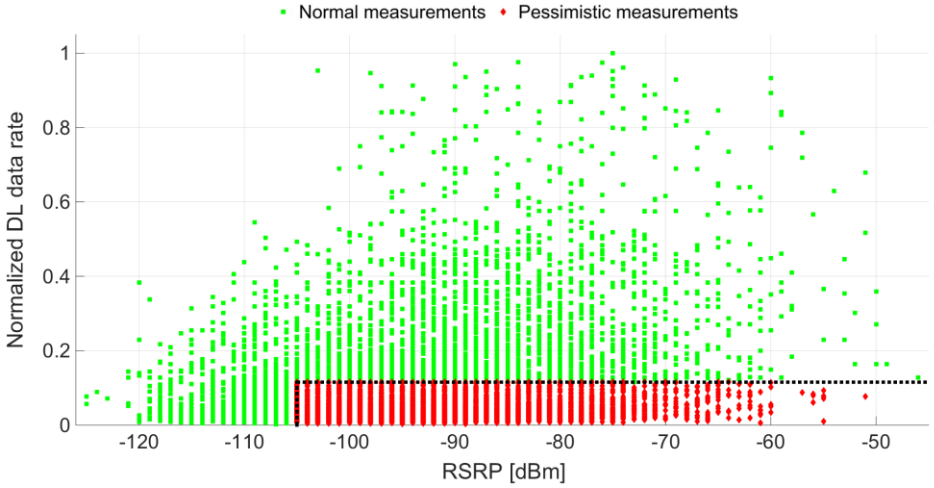

Figure 4.3 DL measurements classification for the 800 MHz band during the on-peak time interval.

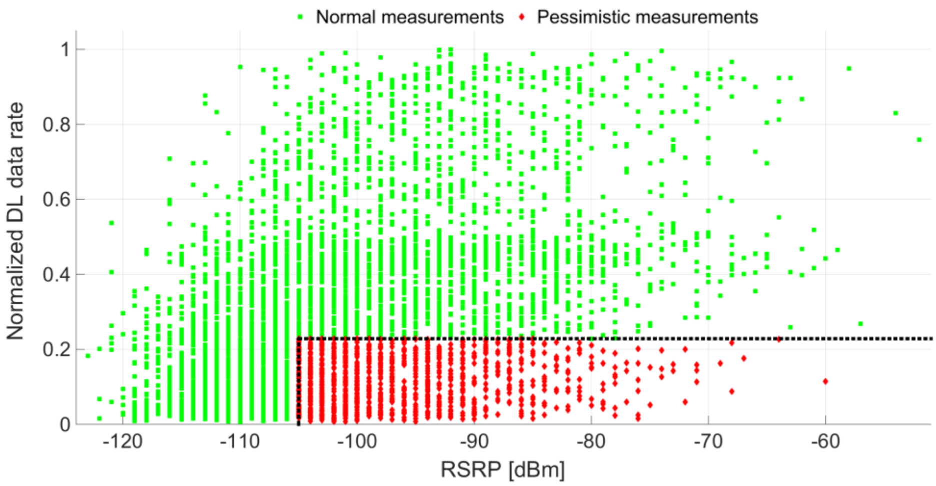

Figure 4.4 DL measurements classification for the 1 800 MHz band during the on-peak time interval.

As in the off-peak scenario, together with the measurements characterisation, the simulator computes some output values, which are presented, for both LTE800 and LTE1800, in Table 4.4.

Table 4.4 Simulator DL output results, for both 800 MHz and 1 800 MHz bands during the on-peak time interval.

Parameter	LTE800	LTE1800
Total number of measurements	12 636	5 454
Number of normal measurements [%]	35.28	75.61
Number of pessimistic measurements [%]	64.72	24.39
Total number of cells	1 321	1 092
Number of cells with pessimistic measurements [%]	73.35	31.04

By analysing these results, one can see the higher performance of LTE1800 compared with LTE800, as in the previous scenario. As expected, during the busy-hours both frequency bands have worst measurements comparatively with the ones reported during the off-peak period. LTE800 has 64.72% of measurements that have low data rates despite their high values of RSRP, which correspond to almost 10 times more pessimistic measurements compared with the off-peak scenario. Despite the decrease of the number of LTE1800 normal measurements from 98.24% (in off-peak) to 75.61% (in on-peak), this band continues with a good performance, since it only has 24.39% of pessimistic measurements. Comparing the two bands, Table 4.4, there are more 40.33% of pessimistic measurements for LTE800, which is a much higher difference than the one observed in the first scenario (5.21%). With this insight, one can conclude that the performance of LTE800 is considerably more influenced by capacity issues than the performance of LTE1800.

In terms of cells, LTE1800 has 31.04% of cells with at least one pessimistic measurement against 73.35% for LTE800. Based on those cells (with at least one pessimistic measurement), as in the off-peak scenario, the simulator creates an Excel file with information about: the total number of measurements, the number of pessimistic measurements and the date of the more recent measurement. Using the cell with pessimistic performance definition already specified, it is possible to list only the cells with bad performance for both LTE800 and LTE1800, obtaining the results presented in Table 4.5.

Table 4.5 Number of pessimistic cells, for both 800 MHz and 1 800 MHz bands, in DL and taking the on-peak time interval into account.

Parameter	LTE800	LTE1800
Number of cells with pessimistic performance	165	31
Number of cells with pessimistic performance [%]	12.49	2.84

As it can be seen in Table 4.5, in the busy-hours, LTE1800 has cells with a pessimistic performance, which does not happen in the off-peak scenario. For LTE800, there are 165 cells with a pessimistic performance in a total of 1 321 cells. Comparing these values with the ones obtained for the first scenario, they increase from 1.01% to 12.49% and from 0% to 2.84%, for LTE800 and LTE1800, respectively. At last, it is important to refer that 6.06% of LTE800 cells with pessimistic performance have 100% of pessimistic measurement. Once again, these results demonstrate the worst performance of the network during the on-peak time intervals and for LTE 800.

4.3 Cell Performance Analysis

Since 1 800 MHz band cells have much better performance than 800 MHz ones (LTE1800 does not have any cell with a pessimistic performance during off-peak intervals), from now on the analysis takes only the cells with the lower frequency band into account.

In order to study LTE800 cells with a pessimistic performance, one should also take cells with a normal (i.e., non-pessimistic) performance into account. With the comparison between these two distinct categories of cells, it is possible to understand the influence of some parameters in cells performance. However, it is important to notice that the network has BSs provided by two distinct manufacturers: A and B, as detailed in Annex C. Due to the fact that each manufacturer has distinct characteristics and takes parameters measurements in distinct ways, the comparison between the normal and the pessimistic cells must be made using cells provided by the same manufacturer. Thus, four different LTE800 cells were arbitrarily selected (based on the results obtained in Section 4.2) to be analysed in this section: a normal cell and pessimistic one from manufacturer A, and two similar others from manufacturer B. Using the Web Intelligence Rich Client platform, detailed in [BuOb08], and some cell statistics collected in the network, it is possible to study the following parameters for the selected cells: average DL data rate per user ($\overline{R_{b,u}}$), average number of users connected to a single cell ($\overline{N_u}$), average CQI index ($\overline{I_{CQI}}$), and average number of RBs used ($\overline{N_{RB}}$).

The $\overline{N_u}$ and the $\overline{N_{RB}}$ parameters are obtained by using (4.1), in which their values correspond to the average of all measurements made during a Δt time interval, while $\overline{R_{b,u}}$ and $\overline{I_{CQI}}$ are obtained by using (4.2), in which their values correspond to the average of all measurements made during a Δt time interval and the average of all measurements made by each of the users connected to the cell under analysis:

$$\overline{p^{\Delta t}} = \frac{1}{N_{\Delta t}} \sum_{n=1}^{N_{\Delta t}} p(t_n) \tag{4.1}$$

where:

- $N_{\Delta t}$: total number of measurements made during a Δt time interval;
- $p(t_n)$: p parameter in the n^{th} time instant (t_n).

$$\overline{p^{\Delta t,u}} = \frac{1}{N_u N_{\Delta t}} \sum_{m=1}^{N_u} \sum_{n=1}^{N_{\Delta t}} p(t_n, u_m) \tag{4.2}$$

where:

- N_u: total number of users connected to a single cell;
- $p(t_n, u_m)$: p parameter of the m^{th} user (u_m) in the n^{th} time instant (t_n).

The Δt time interval used to compute the parameters average values was defined by NOS, corresponding to 1 hour, so $N_{\Delta t} = 3.6 \times 10^6$, since a new measurement is performed every millisecond. Figure 4.5 to Figure 4.8 present the hourly average values for all the considered parameters, during 15 days, taking a pessimistic and a normal cell into account (represented by the orange and the green lines, respectively). Figure 4.5 to Figure 4.8 only present the results for manufacturer A, the results for manufacturer B being shown in Annex D. The black dashed lines, also presented in these figures, correspond to the average value of the considered parameters during all days (15 days for manufacturer A and 14 days for B). These average values are specified for both manufacturers in Table 4.6.

As seen in Figure 4.5, the average DL data rates per user, obtained by using (4.2), suffer a large variation along the hours, for both normal and pessimistic cells. As expected, the data rates decrease as the time goes by, since off-peak hours occur during the early hours of the morning and the on-peak ones happens late at night. However, some occasional exceptions to this trend can be observed – for example, in the first day under analysis, one can see an increase of around 6 Mbit/s (which correspond to an increase of 45.7%) in the normal cell data rate between 7 am and 10 am (early office hours).

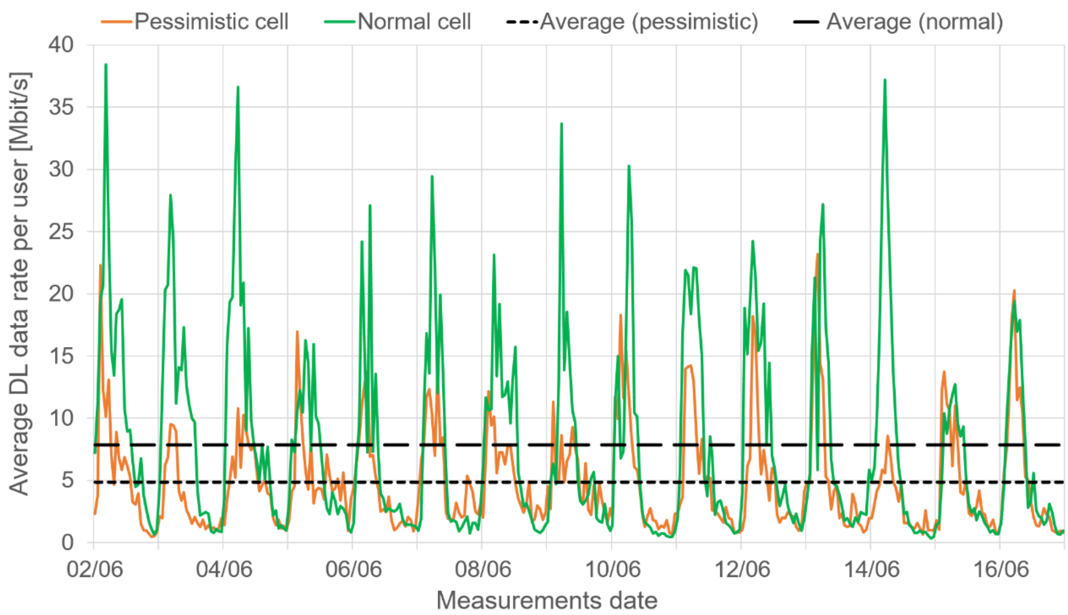

Figure 4.5 Average DL data rates per user measured in each hour during 15 days, taking a normal cell and a pessimistic one from manufacturer A, from the 2nd to the 17th of June 2015.

As shown in Table 4.6, normal cell users have on average 61% higher DL data rates (for manufacturer A) than the ones obtained in the pessimistic cell, which is a relatively small difference, when one see the difference in absolute value: 2.98 Mbit/s. This result can be justified by the data rates achieved during on-peak hours, which are almost zero for both cells. Thus, as expected, the differences between normal and pessimistic cells are more evident during off-peak hours, when usually the data rates per user reach their maximum values. Analysing only the daily peak values of the data rates per user, the normal cell can achieve an average value of 27.04 Mbit/s (considering only the higher value of each day), and the pessimistic cell can achieve an average value of 15.12 Mbit/s. Comparing these average peak values with the global average values presented in Table 4.6, one can see that there is a difference of 19.19 Mbit/s and 10.25 Mbit/s, for the normal and pessimistic cells, respectively. In other words, the normal and the pessimistic cells have average peak values 3.45 and 3.11 times higher than their global average values, respectively. Comparing these results with the ones obtained for manufacturer B (presented in Annex D), one can conclude that a cell classified as pessimistic has users with lower DL data rates in comparison with the data rates achieved by the users who are connected to a normal cell. Thus, as expected, the values of this parameter depend on the cell classification.

The average number of users connected to a single cell, obtained by using (4.1), are presented in Figure 4.6. As expected, in general the number of users increase along the day, contrary to the trend that is observed for the data rate per user presented in Figure 4.5. However, a few exceptions to this trend can also be observed – for example, on the 15th of June the normal cell under analysis had the maximum number of users connected to them at 2 pm.

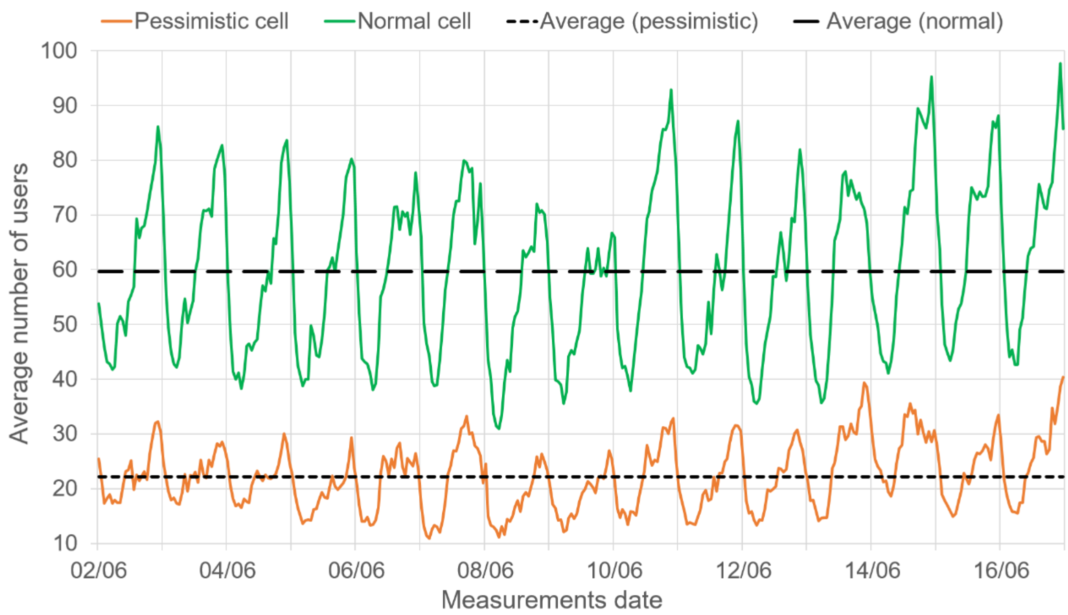

Figure 4.6 Average number of users connected to a single cell measured in each hour during 15 days, taking a normal cell and a pessimistic one from manufacturer A, from the 2nd to the 17th of June 2015.

Analysing the values presented in Table 4.6, it is possible to see that the normal cell has on average 37.43 more users connected to it (for manufacturer A) than the pessimistic one, which is a 2.68 times higher value.

Assuming that 80 (see Table 3.4) is the maximum number of users who can be connected to the same cell in order to avoid capacity issues, by analysing Figure 4.6 one can see that, for manufacturer A, the normal cell can have some capacity problems during on-peak hours – for example, on the 16th of June at 10 pm, the normal cell has on average almost 98 users connected to it simultaneously. On the other hand, the pessimistic cell does not have any problem related with capacity constrains, since it always has on average less than 40 users connected at the same time. In order to solve the capacity problems, the mobile operators can add a cell with a higher frequency band in the sites that have this kind of problems, as already detailed in Section 3.1.7.

Comparing manufacturer A results with the ones obtained for manufacturer B (presented in Annex D), one can conclude that the average number of users who are connected to a specific cell does not depend on the cell classification. For manufacturer A, the pessimistic cell has on average less connected users than the normal one, however for manufacturer B the normal cell is the one with an average lower number. Thus, this is not the best parameter to compare these two different types of cells.

Similarly to the data rates per user, the average CQI index, obtained by using (4.2), suffers a large variation along the day, for both normal and pessimistic cells, as seen in Figure 4.7. A simple analysis reveals that the CQI values decrease along the day, as expected.

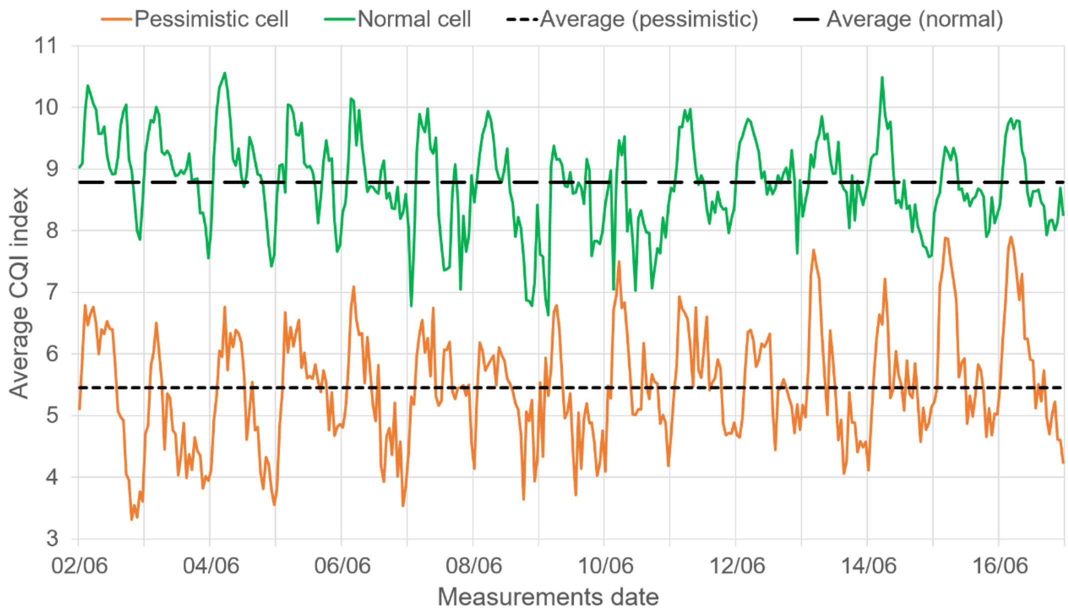

Figure 4.7 Average CQI index measured in each hour during 15 days, taking a normal cell and a pessimistic one from manufacturer A, from the 2nd to the 17th of June 2015.

Analysing the values presented in Table 4.6, it is possible to notice that the normal cell has on average 61% higher CQI index in comparison with the values of the pessimistic cell (for manufacturer A).

Assuming that 10 is the minimum acceptable CQI index, since it is the first index that allows 64-QAM, Figure 4.7 shows, for manufacturer A, that both cells have interference problems – only during some few hours the CQI index is higher than 10 in the normal cell, reaching its maximum value (10.56) on the 14th of June at 5 am. This means that can exist some overlapping in the coverage of neighbours cells, leading to some inter-cell interference problems. In order to solve these problems, a network coverage optimisation must be made, e.g., the tilt of the transmitting antenna can be adjusted, in order to change the signal power distribution along the cell, reducing inter-cell interference.

Comparing the results obtained for manufacturer A with the ones presented in Annex D for manufacturer B, one can conclude that a cell classified as pessimistic has lower CQI index compared with the values that can be achieved by the users who are connected to a normal cell. So, as expected, this index depends on the cell classification and influences the data rates that can be achieved by each user. A more detailed analysis of the relationship between the CQI index and the data rates per user is done in Section 4.4.

Figure 4.8 presents the average number of RBs used by all the users, obtained by using (4.1). The percentage of used RBs increases a lot during the day – for example, going from 4.71% (5 am) to 97.06% (8 pm) in the first day under analysis (for manufacturer A).

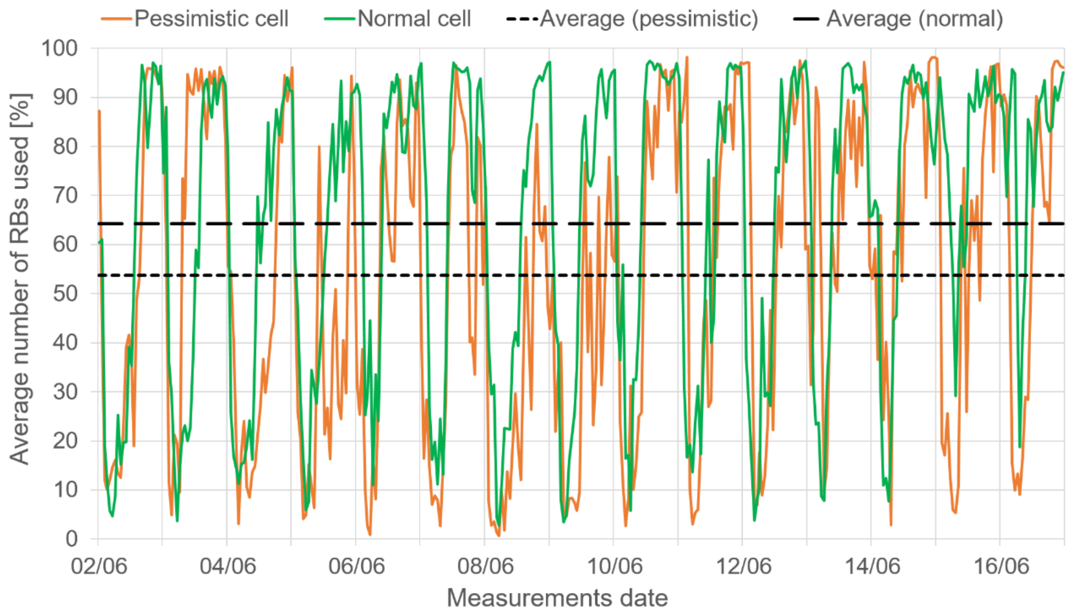

Figure 4.8 Average number of RBs used in each hour during 15 days, taking a normal cell and a pessimistic one from manufacturer A, from the 2nd to the 17th of June 2015.

Analysing the values presented in Table 4.6, it is possible to see that the normal cell has on average 64.20% of RBs used and the pessimistic cell only has 57.3%. This means, that on average the normal cell has 10.49% more RBs used in comparison with the pessimistic one (for manufacturer A).

Comparing manufacturer A results with the ones obtained for manufacturer B (presented in Annex D), it is possible to conclude that this parameter does not depend on the cell classification. For manufacturer A the pessimistic cell has on average less RBs used than the normal cell, however, for manufacturer B the normal cell is the one with an average lower number of RBs used. Thus, in addition to the number of users, this is not the best parameter to compare these two different types of cells.

Together with the global average presented in Table 4.6, the standard deviation of the considered parameters can also be used to analyse the differences between the normal and the pessimistic cells. Table 4.7 presents the standard deviation values computed for the considered parameters for both manufacturers, during all the days (15 days for manufacturer A or 14 days for manufacturer B).

Table 4.6 Comparison between a normal and a pessimistic cell, for two distinct manufacturers, taking the global average for the considered parameters during all the days into account.

Cell parameter	Manufacturer A		Manufacturer B	
	Normal	Pessimistic	Normal	Pessimistic
$\overline{\overline{R_{b,u}^{hour}}}^{days}$ [Mbit/s]	7.85	4.87	7.78	3.17
$\overline{\overline{N_{u}^{hour}}}^{days}$	59.66	22.23	22.58	29.17
$\overline{\overline{I_{CQI}^{hour}}}^{days}$	8.79	5.46	8.74	6.03
$\overline{\overline{N_{RB}^{hour}}}^{days}$ [%]	64.20	53.71	52.02	65.34

Table 4.7 Comparison between a normal cell and a pessimistic one, for two manufacturers, taking the standard deviation for the considered parameters during all days into account.

Cell parameter	Manufacturer A		Manufacturer B	
	Normal	Pessimistic	Normal	Pessimistic
$\sigma_{\overline{R_{b,u}^{hour}}}^{days}$ [Mbit/s]	7.80	4.10	3.64	2.13
$\sigma_{\overline{N_{u}^{hour}}}^{days}$	14.84	6.05	5.87	7.17
$\sigma_{\overline{I_{CQI}^{hour}}}^{days}$	0.74	0.91	0.80	1.17
$\sigma_{\overline{N_{RB}^{hour}}}^{days}$ [%]	30.89	32.32	26.44	31.89

Analysing the values presented in Table 4.7, it is possible to see that the normal cell data rates per user suffer a 90% and a 71% higher deviation in comparison with the pessimistic cell, for manufacturer A and manufacturer B, respectively. On the other hand, the CQI index and the number of RBs used have a higher deviation in the pessimistic cell compared with the deviation of the normal one: the CQI index deviation of the pessimistic cell is 23% and 46% higher, for manufacturer A and manufacturer B respectively, compared with the deviation of the normal cell; and the deviation of the number of RBs used in the pessimistic cell is 5% and 21% higher, for manufacturer A and manufacturer B respectively, also when it is compared with the deviation of the normal cell. The number of users connected to the manufacturer A normal cell suffer a 2.45 times higher deviation in comparison with the pessimistic one. In contrast, the number of users connected to the manufacturer B normal cell suffers an 18% lower deviation in comparison with the one cell.

4.4 Quality Parameter Analysis

Using the experimental data for LTE800, which were analysed in Section 4.3, it is possible to study the influence of the CQI index in the DL data rates per user. Figure 4.9 to Figure 4.11 present the variation of the average DL data rates per user with the average CQI index, both obtained by using (4.2), for measurements acquired with the normal and the pessimistic cells. Figure 4.9 presents the results without distinguishing the time intervals, however Figure 4.10 and Figure 4.11 only show the measurements obtained during the off-peak and the on-peak time interval, respectively. It is also important to notice that the both manufacturers' measurements are analysed simultaneously. Three black dashed lines are also presented in Figure 4.9, representing the theoretical values fitted curve, the pessimistic and the normal cell measurements fitted curve. These fitted curves are obtained using the MATLAB Curve Fitting Tool and are given by:

$$R_{b\,[\mathrm{Mbit/s}]} = p_{1\,[\mathrm{Mbit/s}]} \cdot {I_{CQI}}^2 + p_{2\,[\mathrm{Mbit/s}]} \cdot I_{CQI} + p_{3\,[\mathrm{Mbit/s}]} \tag{4.3}$$

where:

- I_{CQI}: CQI index;
- p_1, p_2, p_3: fitted coefficients.

in which, the corresponding values for the fitted coefficients, for the LTE800 theoretical curve and for the pessimistic and normal cell measurements fitted curves, are presented in Table 4.8.

Table 4.8 Values of the fitted coefficients used for the LTE800 theoretical curve and for the pessimistic and normal cell measurements fitted curves.

Fitted coefficient	**Coefficient value [Mbit/s]**		
	Pessimistic cell measurements	**Normal cell measurements**	**LTE800 theoretical curve**
p_1	0.1305	0.4587	0.2391
p_2	-0.0710	-3.1840	0.9449
p_3	0.0000	0.2100	-0.0836

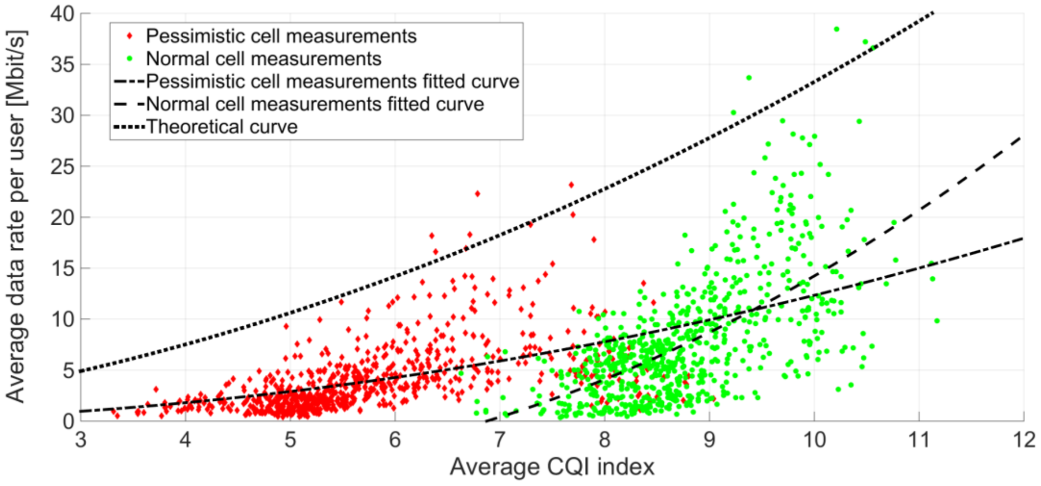

Figure 4.9 Variation of the average DL data rates per user with the CQI index, for measurements obtained with normal and pessimistic cells.

By analysing Figure 4.9, one can easily see that, as expected, the normal cells (in green) have higher average CQI values than the pessimistic ones (in red). Thus, the users who are connected to the normal cells can achieve higher data rates than the ones connected to the pessimistic cells. It is also important to highlight that almost all the measurements are below the theoretical curve, and that the majority of them have much smaller data rates. Comparing the pessimistic and the normal cell measurements fitted curves, one can see that the normal curve has a much higher slope than the pessimistic one, i.e., with a lower increment of the CQI index the users connected to a normal cell can achieve higher data rates.

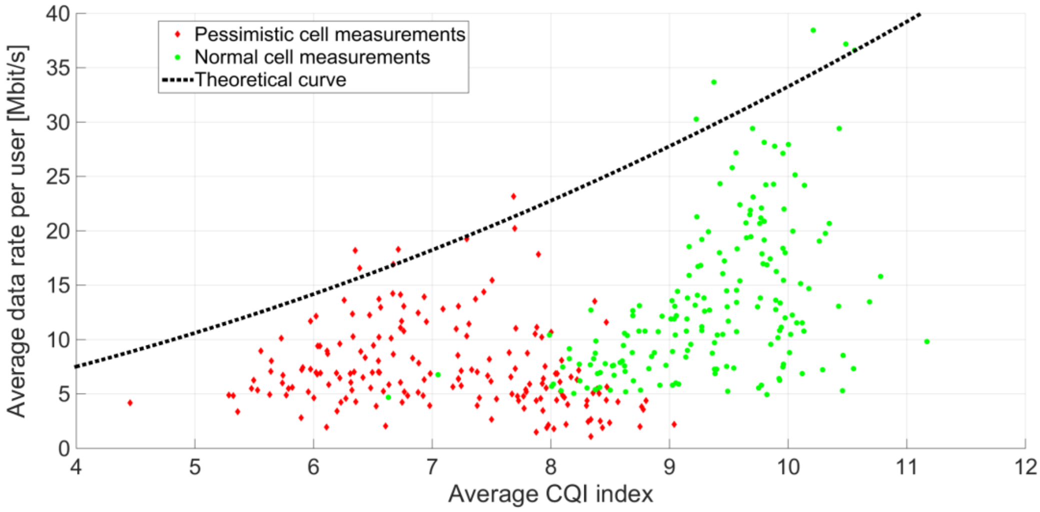

Figure 4.10 Variation of the average DL data rates per user with the CQI index, for measurements obtained with normal and pessimistic cells during the off-peak time interval.

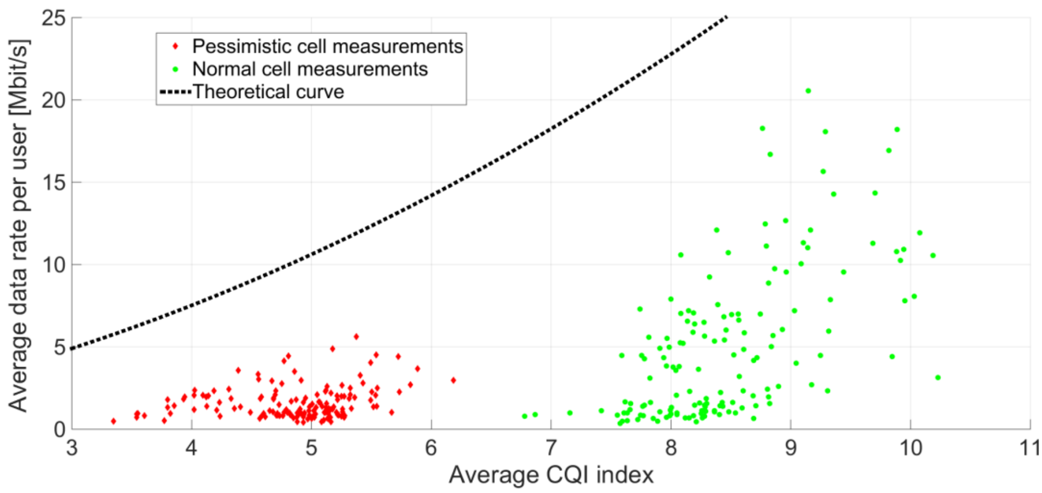

Figure 4.11 Variation of the average DL data rates per user with the CQI index, for measurements obtained with normal and pessimistic cells during the on-peak time interval.

Analysing only the measurements obtained during the off-peak hours, the pessimistic cells have CQI index and data rate values closer to the ones achieved by the normal cells, however the difference in performance remains obvious. One can also see that the users can achieve their higher data rates during this time interval, having values closer to the theoretical ones. On the other hand, the difference in the performance of each type of cell is much more notorious if one considers only the measurements made during the on-peak time interval –users have data rates far below the theoretical curve. Moreover, during the busy-hours, the higher CQI index achieved by the pessimistic cell is 6.19, while the normal cell has a minimum CQI index of 6.78, in other words, the normal cell minimum index is 10% higher than the pessimistic cell maximum index.

4.5 Cell Capacity Improvement

As mentioned previously, LTE800 has lower capacity and may not always deliver reliable data rates compared with higher frequency bands. Thus, in order to solve some capacity problems, the mobile operators can add a cell with a higher frequency band (LTE1800 in the specific case of this work) in sites that have this kind of problems, as already stated in Section 3.1.7.

Using the Web Intelligence Rich Client platform [BuOb08], and some cell statistics collected in the network, it is possible to study the impact of the addition of a new LTE1800 carrier in the sites that already have an LTE800 carrier with capacity problems. In this thesis, this study is based on a sample of experimental measurements collected in two distinct sites (one provided by manufacturer A and other by manufacturer B), which were upgraded to provide data services using the 1 800 MHz frequency band. The parameters under analysis in this section are exactly the same that were used in the analysis made in Section 4.3: average DL data rate per user ($\overline{R_{b,u}}$), average number of users connected to a single cell ($\overline{N_u}$), average CQI index ($\overline{I_{CQI}}$) and average number of RBs used ($\overline{N_{RB}}$). Figure 4.12 to Figure 4.15 present the hourly average values obtained for the manufacturer A site (results for manufacturer B are shown in Annex E) taking two distinct intervals into account: when the site only has the LTE800 carrier, and when the site has both LTE800 and LTE1800 carriers. It is important to notice that when a new LTE1800 carrier is added to a site, it is assumed that all UEs start to be camped on this new cell, however, some UEs that are in the 800 MHz cell-edge will stay camped in that lower band cell. The black dashed lines, also presented in these figures, correspond to the average value of the considered parameters during all days (30 days for manufacturer A or 29 days for manufacturer B). These average values are specified for both manufacturers in Table 4.9.

As seen in Figure 4.12, the average DL data rates per user, obtained by using (4.2), increase when the LTE1800 carrier is added in the site. The users that stay in the LTE800 cell increase on average 1.31 times their data rates, and the ones who change to the LTE1800 cell increase on average 4.78 times.

Analysing only the daily peak values of the data rates per user, the LTE800 cell can achieve an average value of 16.34 Mbit/s before the addition of the new LTE1800 carrier. Comparing this average peak value with the one obtained for the same cell after the addition of the new carrier, one can see that there is a 2% reduction of the average peak values, since the users who stay camped in the LTE800 cell must be in the cell-edge, having lower radio channel conditions, which influences the data rate values. However, when one compares the average data rate peak values obtained by the users before the new carrier addition with the ones obtained by them when they start to be camped in the new higher frequency band cell, one can see that the average peak values increase 2.81 times. Thus, as expected, in general the addition of the new carrier provides much higher capacity to the site.

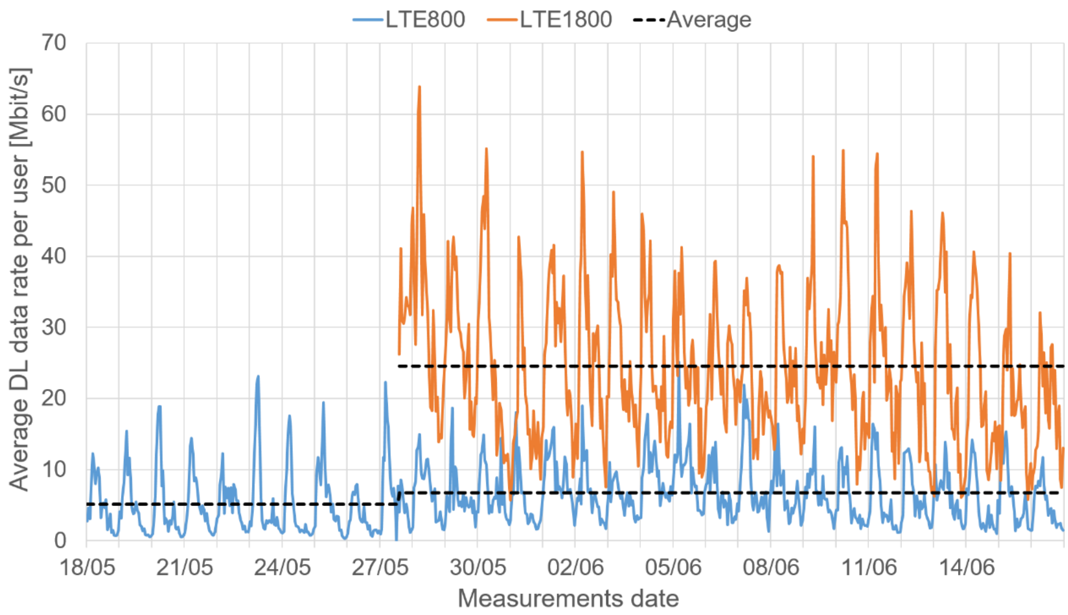

Figure 4.12 Variation on the average DL data rates per user with the addition of a new LTE1800 carrier, taking manufacturer A cells into account. Measurements collected between the 15th of May and the 17th of June 2015.

The variation of the average number of users connected to a single cell, obtained by using (4.1), is presented in Figure 4.13.

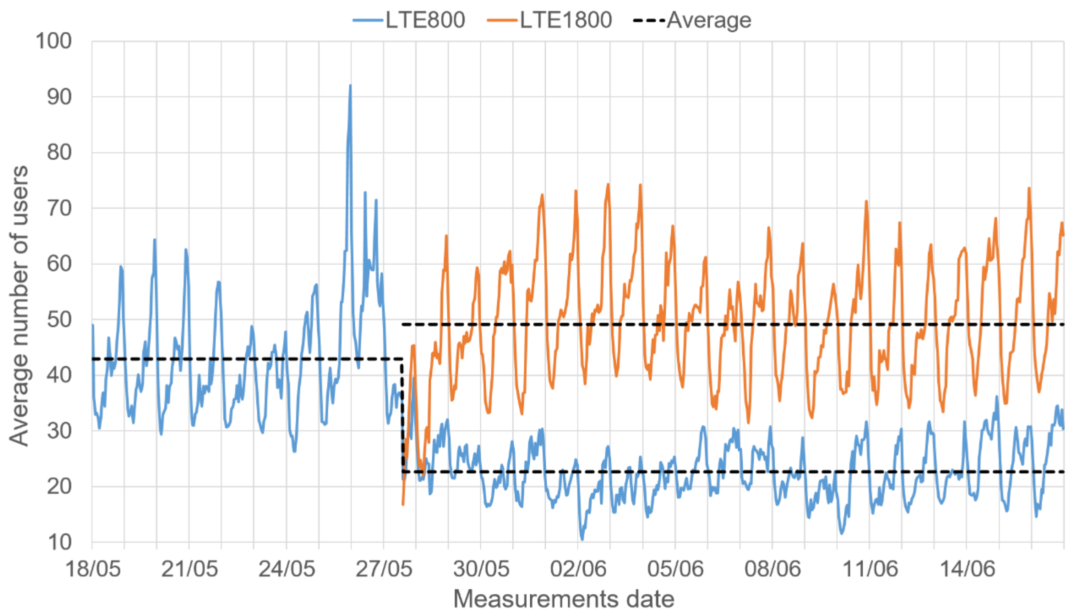

Figure 4.13 Variation on the average number of users connected to a single cell with the addition of a new LTE1800 carrier, taking manufacturer A cells into account. Measurements collected between the 15th of May and the 17th of June 2015.

Comparing the LTE800 cell average value before the addition of the new LTE1800 carrier with the one obtained for the same cell after the its addition, one can see that there is a 47% reduction of users who are connected to the lower frequency cell. Analysing the LTE1800 cell, on average it has 2.17 times more users connected to them compared with the average value of the LTE800 cell (after the new added carrier).

As mentioned in Section 3.1.7, when the UEs are in idle mode and have completed the cell selection/reselection process they stay camped on the cell with the higher frequency band. However, this parameterisation can lead to some additional capacity problems if the load between frequency bands is not balanced. An example of a non-balanced site is presented in manufacturer B results shown in Figure E.2 – after the addition of the new carrier, the LTE1800 cell has on average 84.95 users connected to it, while the LTE800 cell only has on average 19.67 users. Thus, in order to solve that problems, some load balancing algorithms should be implemented in the network.

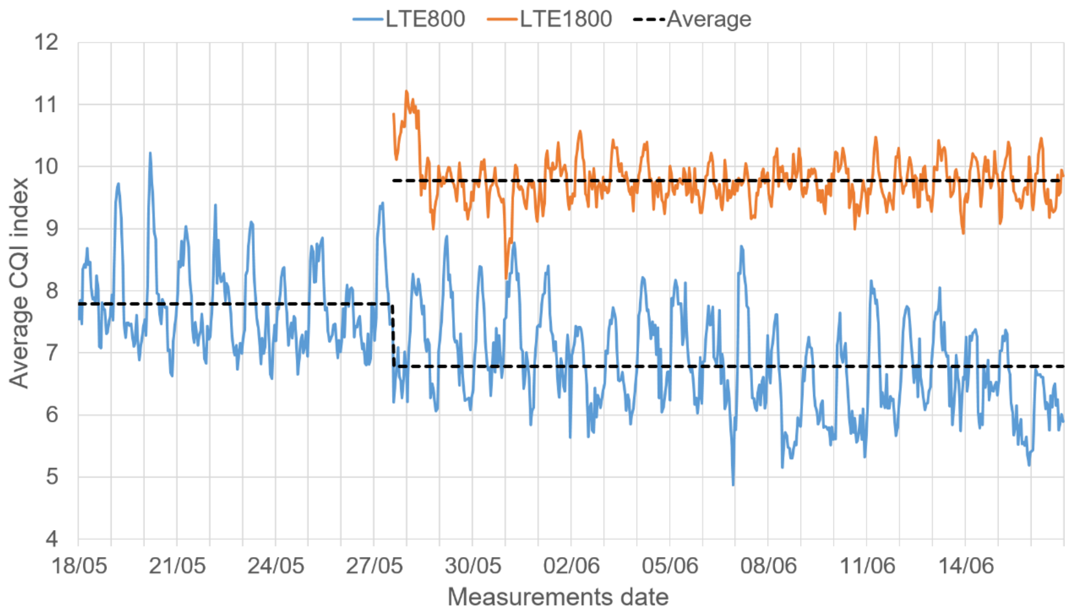

Figure 4.14 Variation on the average CQI index with the addition of a new LTE1800 carrier, taking manufacturer A cells into account. Measurements collected between the 15th of May and the 17th of June 2015.

Comparing the average CQI index, obtained by using (4.2), for the LTE800 cell during the first interval with the index obtained for the same cell in the second interval, it is possible to see, in Figure 4.14, that there is on average a 13% reduction of the CQI index after the addition of the new carrier. As for the average number of users, this result is due to the fact that the users who stay camped in the LTE800 cell must be in the cell-edge, having lower radio channel conditions, which decreases the average CQI index. On the other hand, the users who change from LTE800 to LTE1800 cell increase their index 25% on average. Thus, a user who is in the LTE1800 cell has on average a CQI index 44% higher than a user who is in LTE800 after the addition of the new carrier.

Continuing to assume that 10 is the minimum acceptable CQI index, since it is the first index that allows 64-QAM, by analysing Figure 4.14 one can notice that this site has some interference problems, for both

LTE800 and LTE1800 cells. Only during some hours the CQI index is higher than 10 in the LTE1800 cell. The addition of the new carrier does not solve the interference problems, so in order to solve that problems a network coverage optimisation must be made by the operator, as previously mentioned.

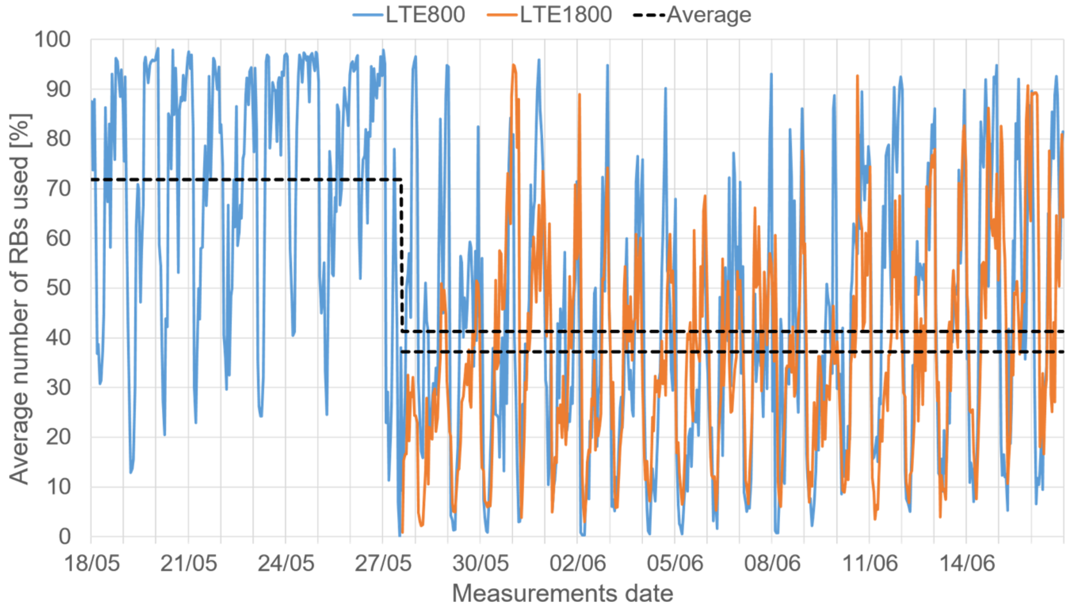

Figure 4.15 Variation on the average number of RBs used with the addition of a new LTE1800 carrier, taking manufacturer A cells into account. Measurements collected between the 15th of May and the 17th of June 2015.

The variation of the average number of RBs used, obtained by using (4.1), is presented in Figure 4.15. Comparing the LTE800 cell average value before the addition of the new LTE1800 carrier with the one obtained for the same cell after the addition of the new carrier, one can see that there are a 43% reduction of the number of RBs used in the lower frequency cell. Analysing the LTE1800 cell, on average it has 10% less RBs used then the average value of the LTE800 cell after the new carrier been added.

Table 4.9 Variation on a cell performance with the addition of a new LTE1800 carrier, taking the global average for the considered parameters into account, for Manufacturer A.

Cell parameter	**LTE800 before**	**LTE800 after**	**LTE1800**
$\overline{\overline{R_{b,u}^{hour}}}^{days}$ **[Mbit/s]**	5.13	6.72	24.52
$\overline{\overline{N_{u}^{hour}}}^{days}$	42.96	22.62	49.16
$\overline{\overline{I_{CQI}^{hour}}}^{days}$	7.79	6.78	9.77
$\overline{\overline{N_{RB}^{hour}}}^{days}$ **[%]**	71.86	41.29	37.16

In addition to the global average presented in Table 4.9, Table 4.10 presents the standard deviation computed for the considered parameters taking manufacturer A into account.

Table 4.10 Variation on a cell performance with the addition of a new LTE1800 carrier, taking the standard deviation for the considered parameters into account, for Manufacturer A.

Cell parameter	LTE800 before	LTE800 after	LTE1800
$\sigma_{R_{b,u}^{hour}}^{days}$ [Mbit/s]	4.76	4.08	10.69
$\sigma_{N_{u}^{hour}}^{days}$	10.50	4.85	10.22
$\sigma_{I_{CQI}^{hour}}^{days}$	0.72	0.78	0.38
$\sigma_{N_{RB}^{hour}}^{days}$ [%]	24.69	26.43	21.31

By analysing the values presented in Table 4.10, it is possible to see that the average data rates per user, for the LTE800 cell after the addition of the new carrier, suffer a 14% lower deviation in comparison with the LTE800 one before the addition of the new carrier. On the other hand, the average data rates per user deviation for the LTE1800 is 2.25 times higher compared with the LTE800 cell (before the addition of the new carrier), being 2.62 times higher than the ones obtained for LTE800 cell after the addition of the LTE1800 carrier. The average number of users connected to the LTE800 cell after the addition of the new carrier, has a 54% lower deviation in comparison with the LTE800 cell before the addition of the new carrier. On the other hand, the average number of users connected to the LTE1800 cell is 3% lower compared with the LTE800 cell (before the addition of the new carrier), being 2.11 times higher than the ones obtained for LTE800 cell after the addition of the LTE1800 carrier.

The average CQI index, for the LTE800 cell after the addition of the new carrier, suffers a 8% higher deviation in comparison with the LTE800 one before the addition of the new carrier. On the other hand, the average CQI index deviation for the LTE1800 is 47% lower compared with the LTE800 cell (before the addition of the new carrier), being also 51% lower than the ones obtained for LTE800 cell after the addition of the higher frequency carrier. At last, the average number of RBs used, for the LTE800 cell after the addition of the new carrier, suffers a 7% higher deviation in comparison with the LTE800 cell before the addition of the new carrier. On the other hand, the average number of RBs used deviation for LTE1800 is 14% lower when it is compared with the LTE800 cell (before the addition of the new carrier), being also 19% lower than the ones obtained for the LTE800 cell after the addition of the 1 800 MHz carrier.

4.6 Receiver Conditions Improvement

Beyond cell capacity improvement, operators can improve receiver conditions in order to provide a better quality of service to users. As stated before, all the analysis made in this thesis are based on a sample of measurements reported by UEs when they are indoors. However, an external antenna can be placed outdoors and connected to the UEs (which are indoors) in order to remove the extra attenuation that comes from the indoor penetration, providing an extra antenna gain, and increasing the UEs' height.

Thus, one can considerer that there are two distinct scenarios related with the UEs location: an indoor scenario, in which the UE antenna is integrated, or an outdoor scenario, in which the UE has an external/outdoor antenna, as shown in Figure 4.16. Only as curiosity, two examples of outdoor antennas are presented in Figure 4.17.

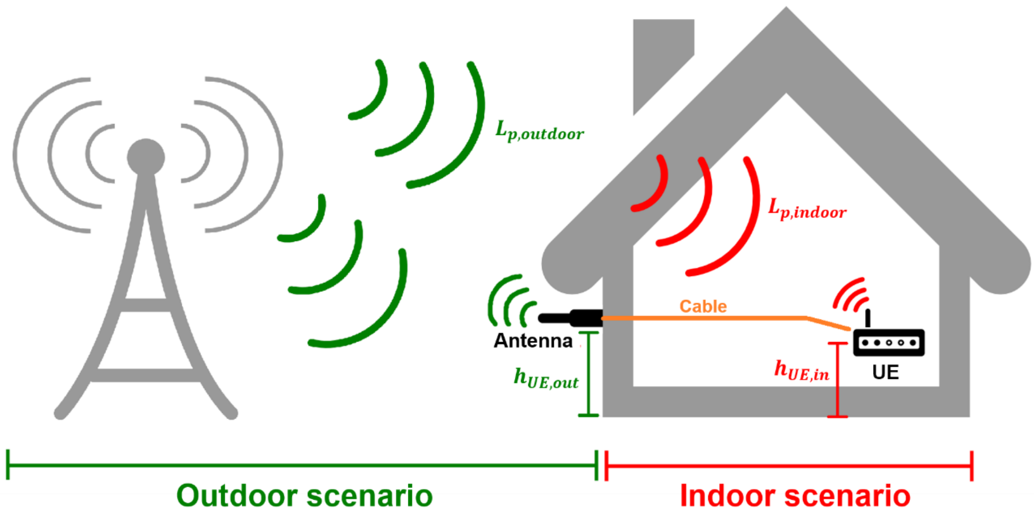

Figure 4.16 Representation of the indoor and outdoor scenarios under analysis.

(a) Outdoor antenna (b) Outdoor/Indoor antenna

Figure 4.17 Outdoor antennas used by NOS (extracted from [Dipo15] and [Pano15]).

Using radio link budget models, detailed in Section 3.1.1, the data rate models, presented in Section 3.1.4, and the scenarios specified in Table 4.11, one can analyse in these two distinct scenarios the (theoretical) influence of some parameters in the total path loss, the RSRP value and the data rate. It is important to notice that the additional outdoor antenna gains considered in this section already take cable losses (used to connect the external antenna and the UE) into account. Furthermore, it is also important to refer that with the addition of the extra antenna, the MIMO capability is lost – with the integrated antenna one can configure two antenna ports, however, with the external antenna it is only possible to configure one port.

Table 4.11 Configuration of parameters used for study the indoor and the outdoor scenarios in DL.

Parameter	Indoor scenario	Outdoor scenario
Distance between the BS and the UE [km]	5 – 10	5
Indoor penetration losses [dB]	12 – 20	0
BS height [m]	30	
UE height [m]	1.5	1.5 – 5.5
Additional outdoor antenna gain [dBi]	0	4 – 8
Number of configured antenna ports	2	1

Table 4.12 and Table 4.13 present the obtained theoretical results for the indoor scenario, for both LTE800 and LTE1800, taking an indoor penetration loss reference value of 16 dB and a distance between the BS and the UE reference value of 5 km into account, respectively. On the other hand, Table 4.14 and Table 4.15 presents the obtained theoretical results, for both LTE800 and LTE1800, taking the outdoor scenario into account. An additional outdoor antenna gain reference value of 5 dBi and a UE height reference value of 3.5 m were considered, respectively. The values were computed using MATLAB.

Table 4.12 Indoor scenario: influence of the distance between the BS and the UE in the total path loss, the RSRP value and the data rate, taking an indoor penetration loss of 16 dB into account.

Distance between the BS and the UE [km]	LTE800			LTE1800		
	Total path loss [dB]	**RSRP [dBm]**	**Data rate [Mbit/s]**	**Total path loss [dB]**	**RSRP [dBm]**	**Data rate [kbit/s]**
5	145.34	-113.39	4.64	150.99	-122.05	500.00
6	148.13	-116.18	2.07	153.78	-124.84	147.36
7	150.49	-118.54	0.95	156.14	-127.20	47.10
8	152.53	-120.58	0.45	158.18	-129.24	16.08
9	154.34	-122.39	0.22	159.98	-131.04	5.81
10	155.95	-124.00	0.11	161.59	-132.65	2.21

Analysing the results presented in Table 4.12, one can see that there are a 42.18 and a 226.24 times higher theoretical data rates when the distance between the BS and the UE is reduced from 10 to 5 km, for the LTE800 and the LTE1800 respectively. Thus, as expected, a user who is closer to the BS has higher throughputs than one who is farther away.

Considering now the results presented in Table 4.13, it is possible to see that there are an 8.40 and a 28.13 times higher data rate when the indoor penetration losses is reduced from 20 to 12 dB, for LTE800 and LTE1800, respectively. As expected, the characteristics of buildings materials, the floor where the user is, and the number of walls that the signal has to cross to reach the UE, have a lot of influence in the throughputs that can be achieved by users when they are indoors.

Table 4.13 Indoor scenario: influence of the path loss coming from indoor penetration in the total path loss, the RSRP value and the data rate, taking a 5 km distance between the BS and the UE into account.

Indoor penetration losses [dB]	LTE800			LTE1800		
	Total path loss [dB]	RSRP [dBm]	Data rate [Mbit/s]	Total path loss [dB]	RSRP [dBm]	Data rate [Mbit/s]
12	141.34	-109.39	11.76	146.99	-118.05	2.25
14	143.34	-111.39	7.64	148.99	-120.05	1.09
16	145.34	-113.39	4.64	150.99	-122.05	0.50
18	147.34	-115.39	2.64	152.99	-124.05	0.21
20	149.34	-117.39	1.40	154.99	-126.05	0.08

Table 4.14 Outdoor scenario: influence of the UE height in the total path loss, the RSRP value and the data rate, taking an additional outdoor antenna gain of 5 dBi into account.

UE height [m]	LTE800			LTE1800		
	Total path loss [dB]	RSRP [dBm]	Data rate [Mbit/s]	Total path loss [dB]	RSRP [dBm]	Data rate [Mbit/s]
1.5	124.34	-92.39	47.32	129.99	-104.06	53.46
2.5	121.85	-89.90	48.49	127.11	-101.18	69.37
3.5	119.36	-87.41	49.17	124.23	-98.30	81.62
4.5	116.86	-84.91	49.57	121.35	-95.42	89.70
5.5	114.37	-82.42	49.79	118.47	-92.54	94.51

Analysing the results presented in Table 4.14, one can see that there are a 5% and a 77% higher data rate when the UE height is increased from 1.5 to 5.5 m, for the LTE800 and the LTE1800 respectively. Thus, as expected, a user who has a higher UE antenna height has much higher throughputs.

Considering the results presented in Table 4.15, one can see that there are a 1% and a 16% higher data rate when the additional outdoor antenna gain is increased from 4 to 8 dBi, for LTE800 and LTE1800, respectively. Thus, as expected, a user who has an antenna with a higher additional gain has higher throughputs.

Table 4.15 Outdoor scenario: influence of the additional outdoor antenna gain in the total path loss, the RSRP value and the data rate, taking a 3.5 m UE height into account.

Additional outdoor antenna gain [dBi]	LTE800			LTE1800		
	Total path loss [dB]	RSRP [dBm]	Data rate [Mbit/s]	Total path loss [dB]	RSRP [dBm]	Data rate [Mbit/s]
4	120.36	-88.41	48.94	125.23	-99.30	77.86
5	119.36	-87.41	49.17	124.23	-98.30	81.62
6	118.36	-86.41	49.36	123.23	-97.30	84.87
7	117.36	-85.41	49.51	122.23	-96.30	87.63
8	116.36	-84.41	49.62	121.23	-95.30	89.96

Finally, comparing the difference between the two scenarios, if one considers for the indoor scenario a 5 km distance between the BS and the UE and an indoor penetration loss of 16 dB, and for the outdoor scenario an additional outdoor antenna gain of 5 dBi and a 3.5 m UE height, it is possible to see that:

- The total path loss decreases 18% when the outdoors antenna is added, for both LTE800 and LTE1800;
- The RSRP value increases 0.77 and 0.81 times when the outdoors antenna is added, for the LTE800 and the LTE1800, respectively;
- The data rate increases 10.6 and 163.2 times when the outdoors antenna is added, for the LTE800 and the LTE1800, respectively.

This means that there are a huge gain in the data rates when an extra outdoor antenna is connected to the UE (which is indoors), despite the loss of the MIMO capability.

Chapter 5

Conclusions

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

The main goal of this thesis was the study of the usage of LTE networks to provide “fixed” data services to users when they are at home. Although in terms of QoS cellular networks cannot compete with other fixed technologies, an LTE network can be designed or optimised in order to provide “fixed” data services. Thus, some performance parameters, like QoE, need to be evaluated in order to assess that possibility. In short, this report aimed to present some improvements guidelines, and to provide an assessment for this problem, taking distinct scenarios into account.

In the first chapter, a superficial description of the mobile communications systems evolution over time and of the growing consumer and traffic demand is presented, followed by an explanation about the motivation and contents of this thesis.

Chapter 2 provides a theoretical background on LTE’s network architecture, radio interface, and coverage and capacity aspects. It was possible to conclude that data rates decrease strongly with the reduction of the SNR/SINR, which leads to a reduction of the channel capacity. This problem is especially important in indoor scenarios, because of the extra attenuation that comes from the indoor penetration, which leads to a significant decline of the SNR. Furthermore, some information about performance parameters, mainly focusing on the services and applications and some QoE aspects are also presented in this chapter, as well as a brief state of the art.

Chapter 3 presents a description of the models used in this thesis, in which their mathematical formulation and implementation were detailed. One of the main problems addressed in this thesis was the analysis of cells performance, in order to assess the quality of the data services provided by them. Taking that into account, two simulators were developed in order to characterise and analyse a sample of experimental measurements, which were collected by some NOS’s costumers UEs. The simulators use the DL data rates and the RSRP values of each measurement to characterise the cells performance, in which that characterisation is made taking two different threshold approaches into account: the relative and the absolute. The first approach is based on the comparison between the obtained experimental measurements and the data rate theoretical values. On the other hand, the second approach is made taking specific thresholds for data rate and RSRP into account. According to NOS, and in order to ensure a minimum QoS associated with the relationship between the data rate and the RSRP value, the analysis of the measurements with bad performance was made using the absolute threshold approach. Considering that approach, the experimental measurements were analysed, taking the measurement frequency band (LTE800 or LTE1800) and time interval (off-peak or on-peak) into account, and characterised according to two different categories: normal, for the measurements outside the thresholds interval, or pessimistic, for the measurements within the thresholds interval.

Chapter 4 starts by providing a description of the scenarios used in this thesis, followed by the scenarios analysis. Seeing only the measurements reported in the off-peak scenario, the first insight that one can extract is that the performance is essentially limited by the network coverage and do not depend on the capacity. A total number of 31 881 and 11 189 measurements, for LTE800 and LTE1800 respectively, were analysed during these hours. Considering that the pessimistic measurements are the ones with high RSRP values and low data rates, a total number of pessimistic measurements of 6.97% and 1.76% were obtained, for the 800 and 1 800 MHz bands, respectively. The remaining measurements were classified as normal. In terms of cells, the LTE1800 had only 9.63% of cells with at least one pessimistic measurement against 46.53% for the LTE800. Knowing the measurements with a pessimistic performance it was possible to find the cells in which the users who are connected to them cannot have an acceptable quality of service (so called pessimistic cells). That cells were defined by having more than 30% of pessimistic measurements in a sample with, at least, a total of 20 measurements. LTE1800 did not have any cell with a pessimistic performance, however there were 14 cells with a pessimistic performance for the LTE800, which correspond to approximately 1% of all the 1 382 LTE800 cells. These results can be explained since the main constrain of higher frequency bands is the signal attenuation, which increases with the frequency. It is also important to recall that, in the first place, the analysis was made taking the measurements with high values of RSRP into account, so the attenuation was not the main topic under study – thus, one can expect this high performance for the LTE1800.

Analysing now the measurements reported during the on-peak hours, the first insight that one can extract is that the quality of service associated with each costumer does not depend only on the network characteristics. The amount number of users who are connected to the network, at the same time, has a direct influence on the quality of service which is provided to all of them – in other words, some customers with a high RSRP value and a high CQI index could be without service if there are no available RBs. In this scenario, a total number of 12 636 and 5 454 measurements, for LTE800 and LTE1800 respectively, were analysed during the busy-hours, in which, a total number of pessimistic measurements of 64.72% and 24.39% were obtained, for the 800 and 1 800 MHz bands, respectively. The remaining measurements were classified as normal. Analysing these results, one can see the higher performance of the LTE1800 when compared with the LTE800, as it already happens in the first scenario. Like it was expected, during the busy-hours both frequency bands had worst measurements comparatively with the ones performed during the off-peak hours. In terms of cells, the LTE1800 had 31.04% of cells with at least one pessimistic measurement against 73.35% for the LTE800. Considering only the pessimistic cells (already defined), one can highlight that the LTE1800 had 31 cells with a pessimistic performance, and there were 165 cells with a pessimistic performance for the LTE800, which correspond to approximately 2.84% and 12.49% of the total number of cells analysed, respectively. Thus, comparing these values with the ones obtained for the first scenario, they increase from 1.01% to 12.49% and from 0% to 2.84%, for the LTE800 and the LTE1800, respectively. It is also important to refer that around 6% of the LTE800 cells with pessimistic performance had 100% of pessimistic measurement. Once again, these results demonstrate the worst performance of the network during the on-peak time intervals and for the LTE 800 MHz frequency band.

Since the 1 800 MHz frequency band cells had a much better performance than the 800 MHz ones a more specific analysis was made taking only the cells with the lower frequency band into account. Thus, in order to study the LTE800 cells with a pessimistic performance a comparison between some of that cells and some cells with a normal performance were made. Some different LTE800 cells were arbitrarily selected and the following parameters, for each one of them, were analysed: average DL data rate per user, average number of users connected to a single cell, average CQI index and average number of RBs used. It is important to notice that the main conclusions of this work are made taking the manufacturer A into account. As it is expected, the data rates decrease as the daylight hours go by, since the off-peak hours occur during the early hours of the morning and the on-peak ones happens late at night, however, some occasional exceptions to this trend were observed. The normal cell users had on average 38% higher DL data rates than the ones obtained with the pessimistic cell, which is a relatively small difference. The differences between the normal and the pessimistic cells were more evident during the off-peak hours when usually the data rates per user reach their maximum values. Considering only the daily peak values of the data rates per user, the normal cell could achieve an average value of 27.04 Mbit/s, and the pessimistic cell could achieve an average value of 15.12 Mbit/s – the normal and the pessimistic cells had average peak values 3.45 and 3.11 times higher than their global average values, respectively. The number of users increase along the day, contrary to the trend that was observed for the data rate per user. The normal cell had on average 37.43 more users connected to them than the pessimistic cell, which is a 2.68 times higher value. Assuming that 80 is the maximum number of users who can be connected to the same cell in order to avoid capacity issues, the normal cell had some capacity problems during the on-peak hours. On the other hand, the pessimistic cell did not have any problem related with capacity constrains since it always had on average less than 40 users connected at the same time. Similarly to the data rates per user, the average CQI index suffer a great variation along the day, for both normal and pessimistic cells. Doing only a simple analysis, one could see that the CQI values decrease along the day, as it is expected. The normal cell had on average 61% higher CQI index in comparison with the values of the pessimistic cell. Assuming a minimum acceptable CQI index of 10, it was possible to conclude that both cells had interference problems – during all the time, they only reach a maximum index of 10.56. The percentage of used RBs increase a lot during the day. Analysing the obtained results, it was possible to see that the normal cell had on average 64.20% of RBs used and the pessimistic cell only had 57.3%. This means, that on average the normal cell had 10.49% more RBs used in comparison with the pessimistic cell. Together with the global average, the standard deviation of the considered parameters were also used to analyse the differences between the normal and the pessimistic cells. The normal cell data rates per user suffered a 90% higher deviation in comparison with the pessimistic cell, and the number of users connected to the normal cell had a 2.45 times higher deviation also in comparison with the pessimistic cell. On the other hand, the CQI index and the number of RBs used had a higher deviation in the pessimistic cell when compared with the deviation of the normal one: the CQI index deviation of the pessimistic cell was 23% higher when compared with the deviation of the normal cell, and the deviation of the number of RBs used in the pessimistic cell is 5% higher also when it is compared with the deviation of the normal cell.

LTE800 has lower capacity and may not always deliver reliable data rates when compared with higher frequency bands. Thus, in order to solve some capacity problems, the mobile operators can add a cell with a higher frequency band in sites which have this kind of problems. Using the Web Intelligence Rich Client platform [BuOb08] and some cell statistics collected in the NOS network, it was possible to study the impact of the addition of a new LTE1800 carrier in sites which had an LTE800 carrier with capacity issues. The users that stayed in the LTE800 cell increased on average 1.31 times their data rates, and the ones who changed for the LTE1800 cell increased on average 4.78 times. Comparing the LTE800 cell average number of users before the addition of the new LTE1800 carrier with the one obtained for the same cell after the addition of the new carrier, there were a 47% reduction of users connected to the lower frequency cell. Considering the LTE1800 cell, on average it had 2.17 times more users connected to them when compared with the average value of the LTE800 cell (after the new carrier been added). Analysing the average CQI index for the LTE800 cell during the first interval and comparing it with the index obtained for the same cell in the second interval, there were on average a 13% reduction of the CQI index after the addition of the new carrier. On the other hand, the users who changed from the LTE800 to the LTE1800 cell increased their index on average 25%. A user connected to the LTE1800 cell had on average a CQI index 44% higher than a user who was in the LTE800 after the addition of the new carrier. At last, comparing the LTE800 cell average number of RBs used before the addition of the new LTE1800 carrier with the one obtained for the same cell after the addition of the new carrier, there were a 43% reduction of the number of RBs used in the lower frequency cell. Analysing the LTE1800 cell, on average it had 10% less RBs used then the average value of the LTE800 cell after the new carrier addiction.

Beyond the cell capacity improvement, the network operators can improve the receiver conditions in order to provide a better quality of service to the users. All the analysis made in this thesis were based on a sample of experimental measurements reported by UEs when they are indoors, however an external antenna can be placed outdoors and connected to the UEs (which are indoors) in order to remove the extra attenuation that comes from the indoor penetration, provide an extra antenna gain, and increase the UEs height. In order to compare the difference between these two scenarios, one considered, for the indoor scenario, a 5 km distance between the BS and the UE, and an indoor penetration loss of 16 dB, and, for the outdoor scenario, an additional outdoor antenna gain of 5 dBi, and a 3.5 m UE height. Using that reference values, the theoretical total path loss decreases from 145.34 to 119.36 dB and from 150.99 to 124.23 dB when the outdoors antenna is added, for both LTE800 and LTE1800. The theoretical RSRP value increases from -113.39 to -87.41 dBm and from -122.05 to -98.3 dBm when the outdoors antenna is added, for the LTE800 and the LTE1800, respectively. Finally, the theoretical data rate increases from 4.64 to 49.17 Mbit/s and from 0.50 to 81.62 Mbit/s when the outdoors antenna is added, for the LTE800 and the LTE1800, respectively. Thus, there are a huge gain in the data rates when an extra outdoor antenna is connected to the UE.

Regarding future work, a more deep analysis of the experimental measurements could be made. For example, the measurements could be organised by costumers instead of by cells. With that different approach, one could characterise the quality of service associated with each one of the costumers, being a great complement to the network cells analysis made during this thesis. Another topic which could be addressed as future work is the usage of new LTE-Advanced functionalities, like Carrier Aggregation (CA), in order to improve the network capacity. The principle with CA is to extend the maximum bandwidth by aggregating multiple carriers. The use of CA benefits system performance in two ways: there is an increased peak data rate when enabling the aggregation of spectra from more than single frequency band, and the average user throughput is improved, especially when the number of users is not too high. Thus, it is expected that, in the end, the QoE could be widely improved. At last, the study of some network improvements achieved with the usage of some load balance algorithms is also a topic that could bring more value to this work.

Annex A

UE Categories in LTE

This annex presents the device-capability classes defined for the user equipment in LTE Releases 8, 9 and 10.

In practice it is important to recognise that the market for UEs is large and diverse, and there is therefore a need for LTE to support a wide range of categories of UE with different capabilities to satisfy different market segments. In a general way, each market segment attaches different priorities to aspects such as peak data rate, UE size, cost and battery life. An UE which supports the highest data rates generally requires a large amount of memory for data processing, which increases the cost of the UE. This is only one example of a typical trade-off related with these parameters.

The first release of LTE was designed to support a compact set of five categories of UE, ranging from relatively low-cost terminals with similar capabilities to UMTS HSPA, up to very high-capability terminals which exploit the LTE technology to the maximum extent possible. The five Release 8 UE categories are summarised in Table A.1.

Table A.1 Categories of LTE UE in Releases 8 and 9 (based on [SeTB11]).

<table>
<tr><th rowspan="2">Category</th><th colspan="2">Peak throughput [Mbit/s]</th><th colspan="2">MIMO layers supported</th><th colspan="2">Support for 64-QAM modulation</th></tr>
<tr><th>DL</th><th>UL</th><th>DL</th><th>UL</th><th>DL</th><th>UL</th></tr>
<tr><td>1</td><td>10</td><td>5</td><td>1</td><td rowspan="5">---</td><td rowspan="5">Yes</td><td rowspan="4">No</td></tr>
<tr><td>2</td><td>50</td><td>25</td><td rowspan="3">2</td></tr>
<tr><td>3</td><td>100</td><td rowspan="2">50</td></tr>
<tr><td>4</td><td>150</td></tr>
<tr><td>5</td><td>300</td><td>75</td><td>4</td><td>Yes</td></tr>
</table>

Additional three new UE categories were introduced in LTE-Advanced. These new Release 10 categories are detailed in Table A.2. It is important to notice that previous UE categories are reused and can support carrier aggregation in Release 10.

Table A.2 UE categories supported in Release 10 (based on [SeTB11]).

<table>
<tr><th rowspan="2">Category</th><th colspan="2">Peak throughput [Mbit/s]</th><th colspan="2">MIMO layers supported</th><th colspan="2">Support for 64-QAM modulation</th></tr>
<tr><th>DL</th><th>UL</th><th>DL</th><th>UL</th><th>DL</th><th>UL</th></tr>
<tr><td>6</td><td rowspan="2">300</td><td>50</td><td rowspan="2">2 or 4</td><td rowspan="2">1, 2 or 4</td><td rowspan="3">Yes</td><td rowspan="2">No</td></tr>
<tr><td>7</td><td>100</td></tr>
<tr><td>8</td><td>3 000</td><td>1 500</td><td>8</td><td>4</td><td>Yes</td></tr>
</table>

Annex B

Experimental Measurements

A brief explanation of the MeasurementsDataUpdated.xlsx file with a list of all the parameters, which characterise the experimental measurements, are presented in this annex. All the data processing that were made in the original file provided by NOS, in order to create its “Updated” version, are also detailed.

As it was already referred, the scenarios studied in this thesis are based on a sample of experimental measurements collected between 22nd of August, 2014 and 3rd of May, 2015 in the NOS network. Each measurement contains information about some parameters, which characterise a data service provided to a specific customer. The information about the experimental measurements were saved in an ACS after being reported by the UEs using the TR-069 protocol [DLSH15]. An Excel file (MeasurementsData.xlsx) with all the reported parameters, during the time interval considered in this work, were created by NOS. This Excel file is the main source of the data that are treated in this work. However some data processing and information selection were made in order to guarantee a better analysis. Furthermore, the original file contains information about 3G (15%) and LTE (85%) measurements, so all the 3G measurements and their specific parameters must be removed, since in this thesis only the 4G networks are considered. Thus, a new updated file was created (MeasurementsDataUpdated.xlsx) with the following parameters:

- **Master ID**: it is a 32 characters string defined by NOS, which is used to identify each one of the measurements. This parameter must be in the 2nd column of the first sheet in the updated Excel file.
- **ID:** it is an integer generated to identify each one of the measurements more easily than the “Master ID” parameter, which is a very complex identification. This parameter must be in the 1st column of the first sheet in the updated Excel file.
- **Client ID**: it is a 16 characters string used to identify the client. This parameter must be in the 3rd column of the first sheet in the updated Excel file.
- **Cell ID**: it is a number used to identify the cell. The last number represents the sector of the BS (sector 1, 2 or 3) and that the last but one represents the LTE frequency band associated with the cell (1 if LTE800 or 2 if LTE1800). This parameter must be in the 4th column of the first sheet in the updated Excel file.
- **Frequency**: it is the direct conversion of the “LTE Band” parameter provided in the original Excel file. It is 800 or 1 800 for band 20 or 3, respectively. This parameter must be in the 5th column of the first sheet in the updated Excel file.
- **Date**: it is the data in which the measurement was made. It is presented as “yyyymmdd”, in which “yyyy” is the year, “mm” is the month and “dd” is the day. This parameter must be in the 6th column of the first sheet in the updated Excel file.
- **Hour**: it is the hour in which the measurement was made. It is presented as “hh”. This parameter must be in the 7th column of the first sheet in the updated Excel file.
- **Time interval**: it is the conversion of the “Hour” parameter to one of the two time intervals considered in this work: off-peak (between 3 and 8 am) or on-peak (between 8 pm and 0 am). The intervals are presented using a text string. This parameter must be in the 8th column of the first sheet in the updated Excel file.
- **Time code:** it is an integer defined to identify each time interval, since it is easier to work with number than with strings in MATLAB. The number 1 are used to represent the on-peak hours and 0 to represent the off-peak ones. This parameter must be in the 9th column of the first sheet in the updated Excel file.

- **RSRP**: it is the value of the reference signal received power in dBm measured by the UE. This parameter must be in the 10th column of the first sheet in the updated Excel file.
- **RSRQ**: it is the value of the reference signal received quality in dB measured by the UE. This parameter must be in the 11th column of the first sheet in the updated Excel file.
- **DL data rate**: it is the value of the DL data rate in Mbit/s. This parameter must be in the 12th column of the first sheet in the updated Excel file.
- **UL data rate**: it is the value of the UL data rate in Mbit/s. This parameter must be in the 13th column of the first sheet in the updated Excel file.
- **Plan**: it is an integer, which is the conversion of the following plans to the maximum allowed DL data rate:
  - "Internet Fixa 100Mbps": maximum of 100 Mbit/s in DL;
  - "Internet Fixa 20Mbps" plan: maximum of 20 Mbit/s in DL;
  - "Internet Fixa 40Mbps" plan: maximum of 40 Mbit/s in DL;
  - "Net Fixa DTH" plan: maximum of 40 Mbit/s in DL;
  - "Net Fixa DTH 20Mbps" plan: maximum of 20 Mbit/s in DL.

  This parameter must be in the 14th column of the first sheet in the updated Excel file.
- **Antenna**: it is a text string with the information about the UE antenna. It can be defined as integrated (if the antenna is within the UEs) or external (if an extra antenna is connected outside the UEs). This parameter must be in the 15th column of the first sheet in the updated Excel file.

One should notice that all the parameters must be in the specified column of the first sheet in the MeasurementsDataUpdated.xlsx file to ensure the correct reading of their values in the simulator.

As it was detailed, the measurements are associated with a commercial plan, provided by the operator, which limits the maximum value of data rate according to three different plans:

- P1: 20 Mbit/s plan with a maximum data rate of 20 Mbit/s in DL and 2 Mbit/s in UL;
- P2: 40 Mbit/s plan with a maximum data rate of 40 Mbit/s in DL and 4 Mbit/s in UL;
- P3: 100 Mbit/s plan with a maximum data rate of 100 Mbit/s in DL and 10 Mbit/s in UL.

The measurements in which data rates are 10% higher than the limit of the plan (for DL and UL), are considered as P3 measurements. New clients have an initial period of some few days in which they have a trial service, which do not have limits for the allowed data rates. Thus for an analysis point of view they have a service equivalent to the ones that have the plan with the higher limit.

It is also important to refer that in some measurements of the original file the data were reported/received with errors (e.g. null frequency bands or blank spaces in some parameters), so that measurements are not considered in the updated file.

Annex C

Confidential Information

This annex presents some confidential information related with this thesis, namely the conversion of some normalised values to their absolute ones, the thresholds values used in the absolute threshold model, and the two distinct manufacturers analysed in this work.

Annex D

Cell Performance Analysis for Manufacturer B

This section presents additional results for Section 4.3, taking the manufacturer B into account.

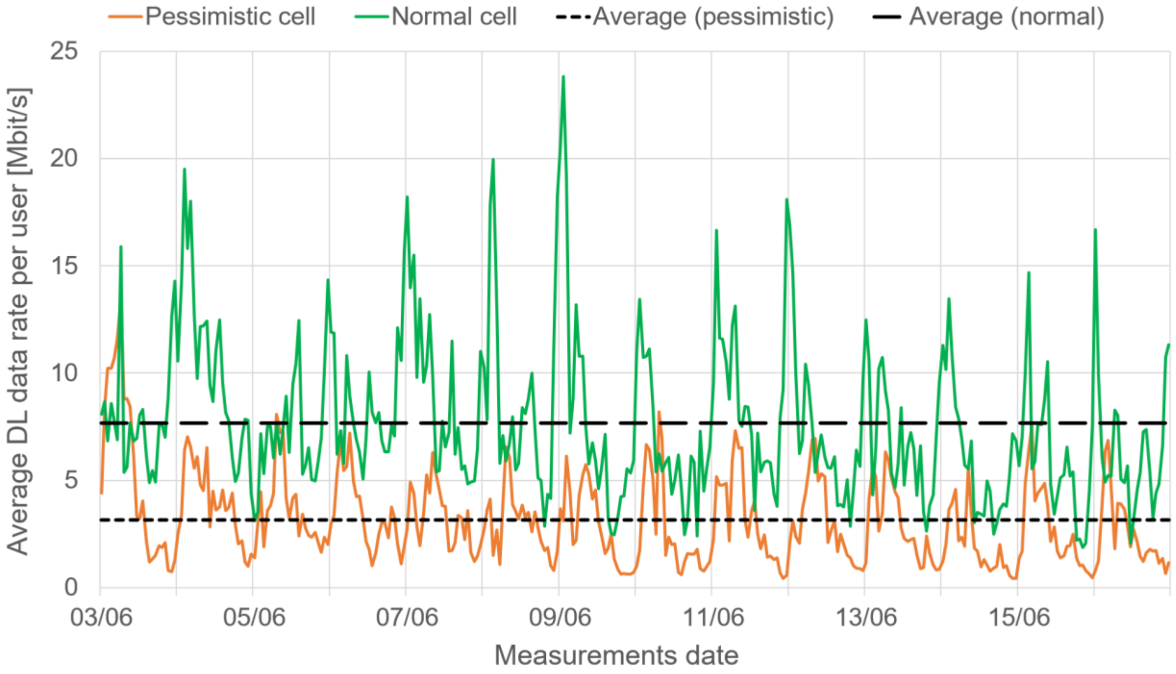

Figure D.1 Average DL data rates per user measured in each hour during 14 days, taking a normal and a pessimistic manufacturer B cell into account.

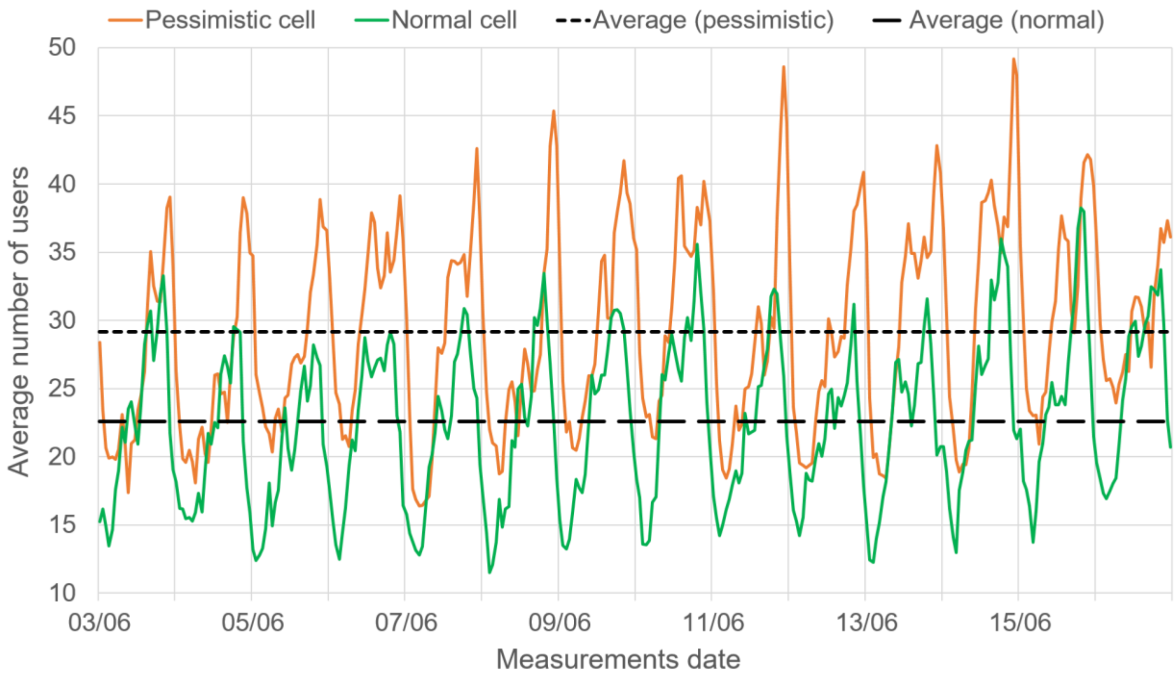

Figure D.2 Average number of users connected to a single cell measured in each hour during 14 days, taking a normal and a pessimistic manufacturer B cell into account.

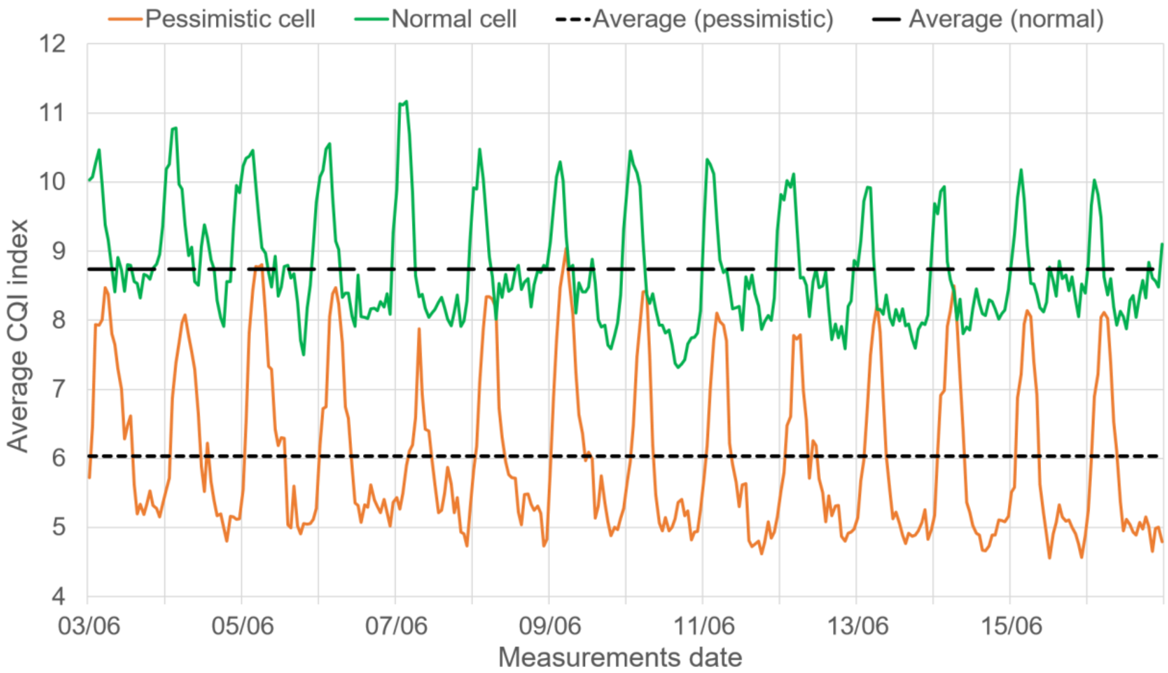

Figure D.3 Average CQI index measured in each hour during 14 days, taking a normal and a pessimistic manufacturer B cell into account.

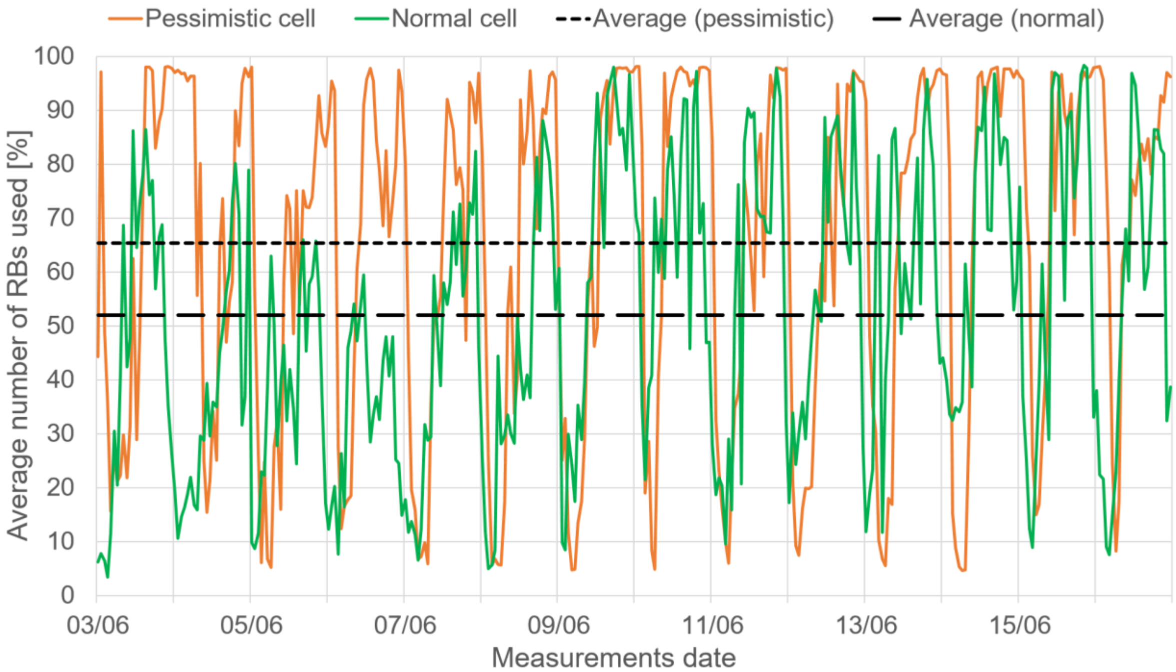

Figure D.4 Average number of RBs used in each hour during 14 days, taking a normal and a pessimistic manufacturer B cell into account.

Annex E

Cell Capacity Improvement for Manufacturer B

This section presents additional results for Section 4.5, taking the manufacturer B into account.

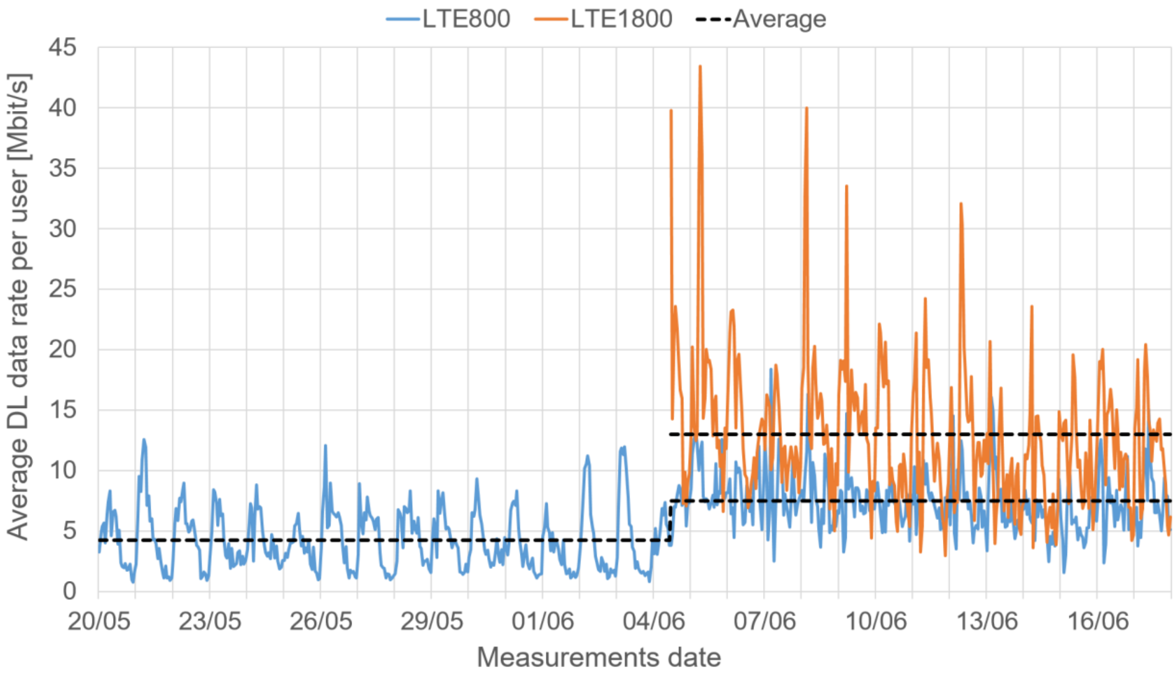

Figure E.1 Variation on the average DL data rates per user with the addition of a new LTE1800 carrier, taking the manufacturer B cells into account. Measurements collected between the 20th of May, 2015 and the 18th of June, 2015.

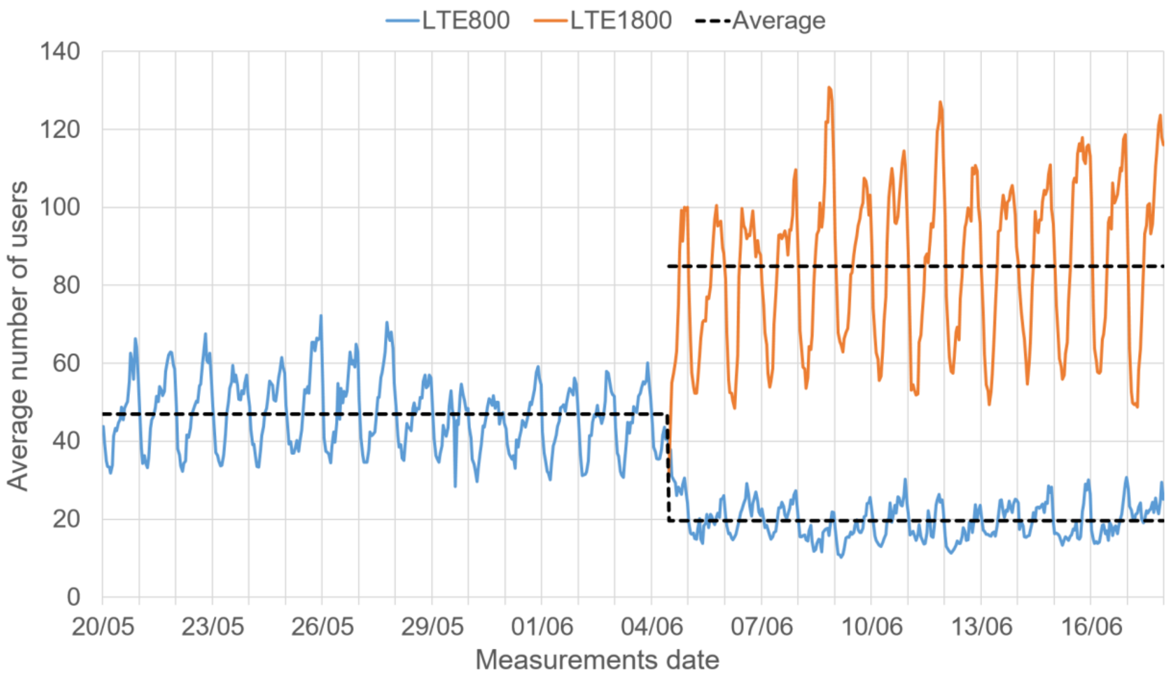

Figure E.2 Variation on the average number of users connected to a single cell with the addition of a new LTE1800 carrier, taking the manufacturer B cells into account. Measurements collected between the 20th of May, 2015 and the 18th of June, 2015.

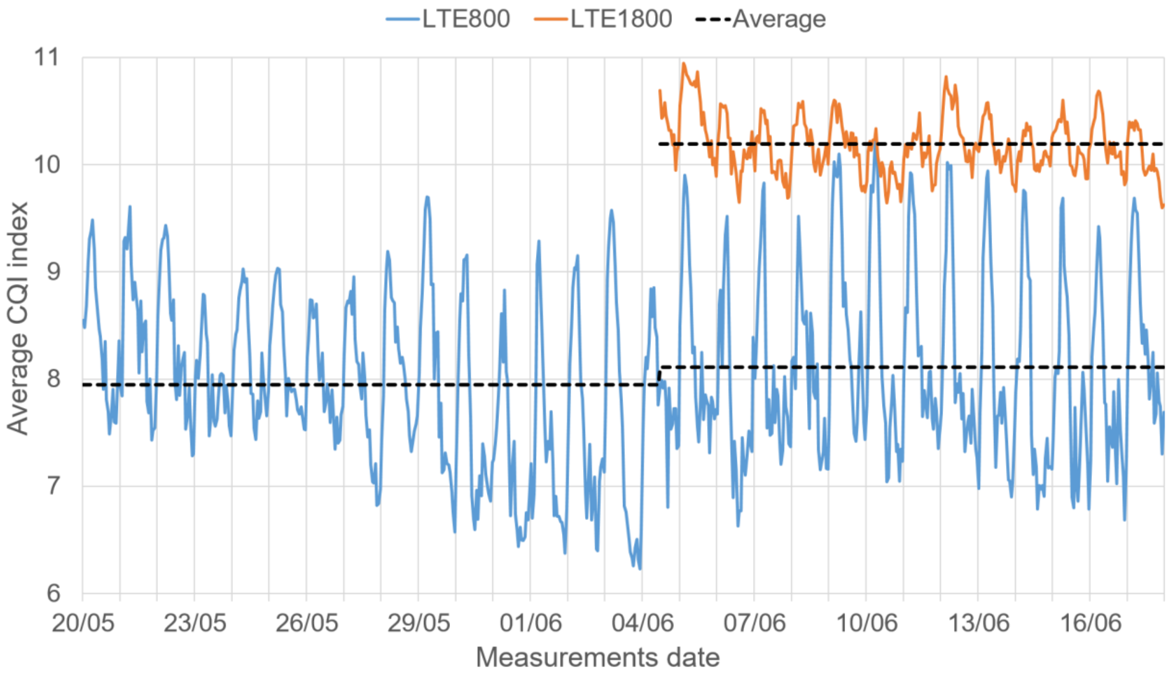

Figure E.3 Variation on the average CQI index with the addition of a new LTE1800 carrier, taking the manufacturer B cells into account. Measurements collected between the 20th of May, 2015 and the 18th of June, 2015.

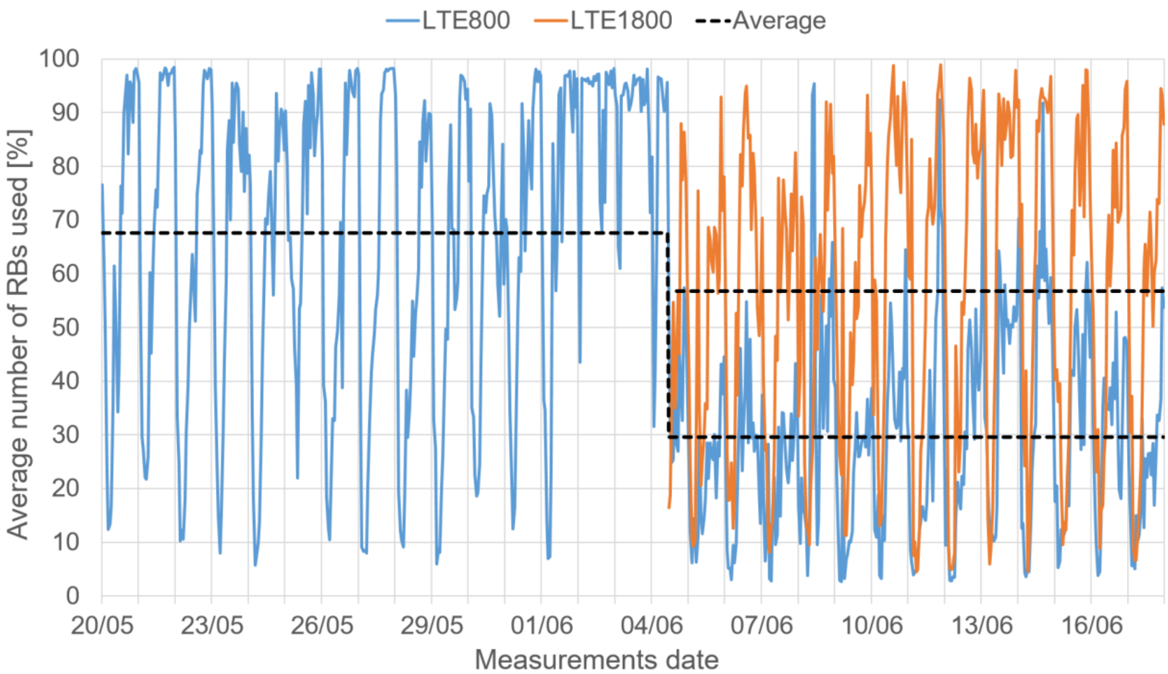

Figure E.4 Variation on the average number of RBs used with the addition of a new LTE1800 carrier, taking the manufacturer B cells into account. Measurements collected between the 20th of May, 2015 and the 18th of June, 2015.

Table E.1 Variation on a cell performance with the addition of a new LTE1800 carrier, taking the global average for the considered parameters into account. Values for Manufacturer B.

Cell parameter	LTE800 before	LTE800 after	LTE1800
$\overline{\overline{R_{b,u}^{hour}}^{days}}$ [Mbit/s]	4.26	7.49	12.98
$\overline{\overline{N_{u}^{hour}}^{days}}$	46.90	19.67	84.95
$\overline{\overline{I_{CQI}^{hour}}^{days}}$	7.95	8.11	10.19
$\overline{\overline{N_{RB}^{hour}}^{days}}$ [%]	67.62	29.63	56.77

Table E.2 Variation on a cell performance with the addition of a new LTE1800 carrier, taking the standard deviation for the considered parameters into account. Values for Manufacturer B.

Cell parameter	LTE800 before	LTE800 after	LTE1800
$\sigma_{\overline{R_{b,u}^{hour}}}^{days}$ [Mbit/s]	2.51	2.48	5.96
$\sigma_{\overline{N_{u}^{hour}}}^{days}$	9.15	4.78	20.63
$\sigma_{\overline{I_{CQI}^{hour}}}^{days}$	0.80	0.87	0.27
$\sigma_{\overline{N_{RB}^{hour}}}^{days}$ [%]	28.97	18.63	28.00

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