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Inter-Cell Interferences in LTE Radio Networks

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To the ones I love

“Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world.”

Albert Einstein (1879-1955)

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Abstract

The main scope of this thesis is to study the impact of frequency reutilisation schemes in the performance of an LTE MIMO 2x2 network, in terms of satisfied users, throughput and SINR, quantifying its key performance indicators in urban scenarios, regarding low and high network load, for 2600, 1800 and 800 MHz bands. This purpose was achieved through the development of a suitable model and a simulator for LTE DL, which recreates the users' allocation in a certain instant of time, implementing a real urban network, realistic users density for the city of Lisbon, using typical urban distributions of users along the pedestrian, vehicular and indoor scenarios, and six frequency reuse schemes, including Full Frequency Reuse. The low and high load results show that frequency reuse schemes improve the average user SINR between 5 to 10 dB, some even serving a similar number of satisfied users as Full Frequency Reuse. Nevertheless, there is always a penalty in the average user throughput, which is around 0.3 Mbit/s for a high loaded network, and even reaches 1 Mbit/s for a low one. As a consequence, from an operator's viewpoint, frequency reutilisation schemes may not be reliable interference mitigation technique.

Keywords

LTE, interference, frequency reutilisation schemes, urban scenario, Lisbon.

Resumo

O principal objectivo desta dissertação foi estudar o impacto dos esquemas de reutilização de frequências no desempenho de uma rede LTE MIMO 2x2, em termos de utilizadores satisfeitos, débito e SINR, quantificando os indicadores chave de desempenho em cenários urbanos, tendo em conta uma alta e uma baixa carga da rede, para as bandas de 2600, 1800 e 800 MHz. Este propósito foi atingido através do desenvolvimento de um modelo e de um simulador adequado para LTE DL, que recria a atribuição de canais aos utilizadores num dado instante de tempo, implementando uma rede urbana real, com uma densidade de utilizadores realística para a cidade de Lisboa, utilizando uma distribuição típica de utilizadores nos cenários pedonal, automóvel e interior, e seis esquemas de reutilização de frequências, incluindo *Full Frequency Reuse*. Os resultados para cargas da rede alta e baixa mostram que os esquemas de reutilização de frequências melhoram a SINR média por utilizador, entre 5 a 10 dB, e que alguns esquemas até servem um número de utilizadores satisfeitos semelhante ao *Full Frequency Reuse*. No entanto, o débito médio por utilizador sofre sempre uma penalização, que ronda 0.3 Mbit/s para uma carga da rede alta e chega até 1 Mbit/s para uma baixa. Consequentemente, do ponto de vista de um operador, os esquemas de reutilização de frequências não parecem ser técnicas de mitigação de interferência viáveis.

Palavras-chave

LTE, interferência, esquemas de reutilização de frequências, cenário urbano, Lisboa.

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List of Acronyms

3GPP	3rd Generation Partnership Project
AMC	Adaptive Modulation and Coding
CoMP	Coordinated Multi-Point
CP	Cyclic Prefix
DL	Downlink
eICIC	Enhanced Inter-Cell Interference Coordination
EPC	Evolved Packet Core Network
E-UTRAN	Evolved UTRAN
FDD	Frequency Division Duplexing
FFR	Fractional Frequency Reuse
FFRopa-R	FFR with frequency occupation ordering within its own sector preferred sub-band, power adaptation and reuse of 1 at sector level
FSFR	Fractional Sector Frequency Reuse
FSFR-F	FSFR taking into account frontier users
FSFR-IF	FSFR with independent frontier region
FSRopa-ISFA	Fractional sector reuse with frequency occupation ordering, power adaptation and inner sub-band frontier allocation
FSR	Frequency Reuse Schemes
HD	High Definition
IC	Interference Cancellation
ICI	Inter-Cell Interference
ICIC	Inter-Cell Interference Coordination
IP	Internet Protocol
IRC	Interference Rejection Combining
ISI	Inter-symbol Interference
ISIC	Inter-Sector Interference Coordination
LTE	Long Term Evolution
MIMO	Multiple-Input and Multiple-Output
MRC	Maximal Ratio Combining
MU-MIMO	Multi-User Multiple-Input and Multiple-Output
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAR	Peak-Average-Ratio
PBCH	Physical Broadcast Channel
PDCCH	Physical DL Control Channel
PDSCH	Physical DL Shared Channel
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PUCCH	Physical UL Control Channel
PUSCH	Physical UL Shared Channel
P-SCH	Primary Synchronisation Signals

RB	Resource Block
RE	Resource Element
Reuse-1	Full Frequency Reuse
RNTPI	Relative Narrowband Transmit Power Indicator
RS	Reference Signal
SAE	System Architecture Evolution
SAE-GW	System Architecture Evolution Gateway
SC-FDMA	Single Carrier Frequency Division Multiple Access
SFR	Soft Frequency Reuse
SINR	Signal to Interference plus Noise Ratio
SNR	Signal-to-Noise Ratio
SU-MIMO	Single-User Multiple-Input and Multiple-Output
S-SCH	Secondary Synchronisation Signals
TDD	Time Division Duplexing
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
UL	Uplink
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UP	User Plane
UTRA	Universal Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
VRB	Virtual Resource Block

List of Symbols

a_{pd}	Average power decay
α_{RB}	Allocated RB index
ρ_N	SNR
ρ_{IN}	SINR
d	Horizontal distance between the eNodeB and the UE
f	Carrier frequency
Δf	Bandwidth of the radio channel
F_N	Noise figure
G_r	Gain of the receiving antenna
G_t	Gain of the transmitting antenna
h_b	eNodeB height
h_m	UE height
H_B	Buildings height
I	Interference power
I_i	Interference power coming from transmitter i
k_a	Increase of path loss for the BS antennas below the rooftops of the adjacent buildings
k_d	Control of the dependence of the multi-screen diffraction loss versus distance
k_f	Control of the dependence of the multi-screen diffraction loss versus frequency
L_0	Free space propagation path loss
L_{bsh}	Loss due to the height difference between the rooftop and the antennas
L_c	Cable losses
L_{ori}	Street orientation loss
L_p	Path loss
$L_{p,environment}$	Environment losses
$L_{p,COST\ 231\ WI}$	COST 231 Walfisch-Ikegami path loss
L_{rm}	Loss between the BS and the last rooftop
L_{rt}	Loss between the last rooftop and the MT
L_u	User losses
m	Order of modulation
M_{SF}	Slow fading margin

N	Noise power
N_I	Number of interfering signals reaching the receiver
N_{RB}	Number of RB
N_{RB}^u	Number of RBs per user
N_{sc}^{RB}	Number of subcarriers per resource block
$N_{streams}$	Number of streams
N_{symb}^{SF}	Number of symbols per frame
N_u	Number of users served by a cell
N_Z	Number of samples
σ	Standard Deviation
P_r	Power available at the receiving antenna
$P_{r,min}$	Power sensitivity at the receiving antenna
P_{RX}	Receiver input power
P_t	Power fed to the antenna
${P_t}^{DL}$	Power fed to the antenna in DL
${P_r}^{UL}$	Power fed to the antenna in UL
P_{TX}	Transmission output power
R	Maximum cell radius
R_b	Resource Block Throughput
$R_{b,eNodeB}$	eNodeB throughput
$R_{b,teo}$	Theoretical user throughput
$R_{b,user}$	UE throughput
T_{SF}	Sub-frame period
μ	Average
w_B	Buildings separation distance
w_S	Street width
Z_i	Value of sample i

List of Software

Eclipse IDE for C/C++ Developers	C++ Integrated Development Environment software
MapBasic	Programming software and language to create additional tools and functionalities for the MapInfo
MapInfo	Geographic Information System software
Microsoft Excel	Calculation and Graphing software
Microsoft Word	Text editor software
OmniGraffle	Diagrams and flux charts design software

Chapter 1

Introduction

This chapter introduces the theme of this thesis, in particular, in a contextual and motivational perspective, while simultaneously providing an overview of the assumptions established for the work development. Furthermore, it establishes the scope for the work performed together with its main contributions, followed by the detailed presentation of the work’s structure.

1.1 Overview

In recent years, not only the number of mobile subscribers has increased tremendously, but also mobile communications have known great technological developments that had a great impact at social and economic levels. The great challenge for mobile communications has been to respond to the demand of data communications: not only the number of mobile users is constantly increasing, but with the introduction of smartphones, data traffic has incredible grown in the last years. In order to respond to this challenge, mobile broadband systems have been developed, namely Universal Mobile Telecommunications System (UMTS), marked as the 3rd Generation of mobile communications systems (3G), with the latest version, High Speed Packet Access Evolved (HSPA+), and Long Term Evolution (LTE), marked as the 4th Generation (4G), in which the Third Generation Partnership Project (3GPP) played an important role in their adoption.

Second generation systems, as Global System for Mobile Telecommunications (GSM), were initially design to carry only voice traffic, the data capability being introduced later; however, voice traffic was clearly dominant until the introduction of High Speed DL Packet Access (HSDPA), in 3G. HSDPA boosted the traffic in such a way that the paradigm totally changed, and shortly mobile communications networks evolved from voice to packet data dominant networks [HoTo11]. The predicted traffic growth for the next years in the different regions is presented in Figure 1.1, which predicts that 2013 doubles the traffic from 2012, and that traffic growth keeps an exponential curve over the next four years, 2014 to 2017. Smartphones provide a panoply of applications, such as web browsing, audio and video streaming, social networks, file sharing, mobile TV or multimedia online gaming. This panoply of applications, with different requirements together with traffic growth, is pushing operators to achieve higher data rates and lower latencies. As a curiosity, by the end of 2013, the number of mobile-connected devices will exceed the number of people on earth, and by 2017 there will be nearly 1.4 mobile devices per capita [Cisc13].

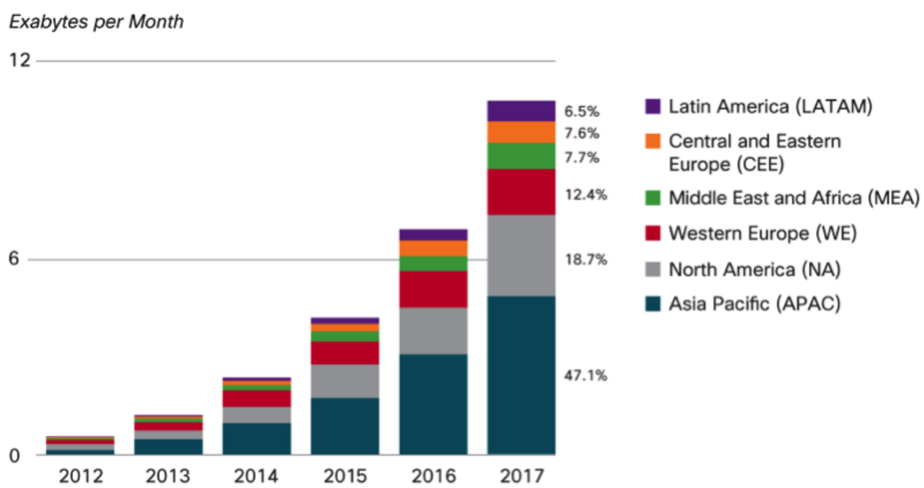


Figure 1.1 Global mobile data traffic forecast by region 2012-2017 (extracted from [Cisc13]).

Figure 1.2 shows that revenues do not follow the huge data growth over time, market competition between operators being one of the main reasons for this. In Portugal, one of the mobile operators always had the lowest number of subscribers, and in order to compete with the other two big operators, it has always been putting in the market innovative services and new special plans, e.g., one of the plans offers free voice calls for all operators and the other offers unlimited data traffic for the most popular applications, as Facebook, Viber or Whatsapp. By doing this, this operator forces the other two to offer similar services and plans with similar prices in order to keep their subscribers, which led to a smaller revenue per user, and with a perspective to stagnate. Nowadays, operators need to be innovative and search for more cost-efficient investments that provide a higher system capacity.

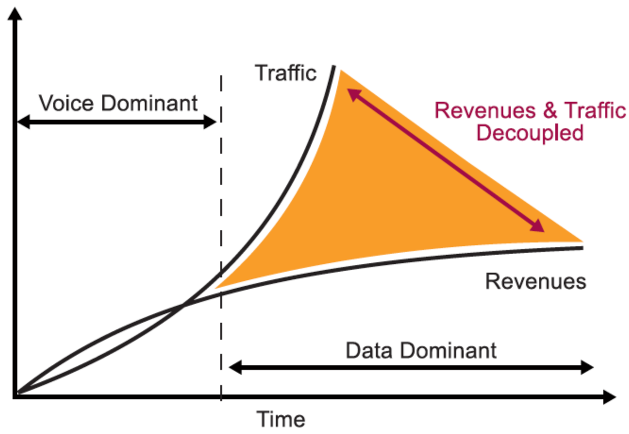


Figure 1.2 Traffic & Revenue: Mobile Data Gap (extracted from [Open13]).

Figure 1.3 shows the radio access milestone defined by 3GPP over the years, starting in 1999 with WDCMA and nowadays working in Release 11 and Release 12. As data increases, the latency becomes a more limiting factor, which is why LTE was defined to support an IP Multimedia System (IMS) and further evolved 3GPP packet core. 3GPP first LTE release was Release 8, which supports MIMO 2x2 and 4x4 and provides a high-data rate, low-latency and packet-optimised system, which supports theoretical peak data rates of 300 Mbit/s in Downlink (DL) and 75 Mbit/s in Uplink (UL). Some more features that were postponed from Release 8 were include in Release 9, mainly overall architecture enhancements and interoperability with UMTS. Release 10, most known as LTE-Advanced, increases peak data rates towards 1 Gbit/s in DL and 500 Mbit/s in UL, by including Carrier Aggregation, MIMO extension 8x8 in DL and 4x4 in UL, UL access enhancements, cell-edge performance improvements and backwards compatibility with Release 8. Regarding future releases, 3GPP's Release 12 is expected to be functionally frozen in 2014, however, it was emphasised by 3GPP that the start of new work in Release 12 will depend on the workload situation, as Release 11 completion takes priority [3GPP13].

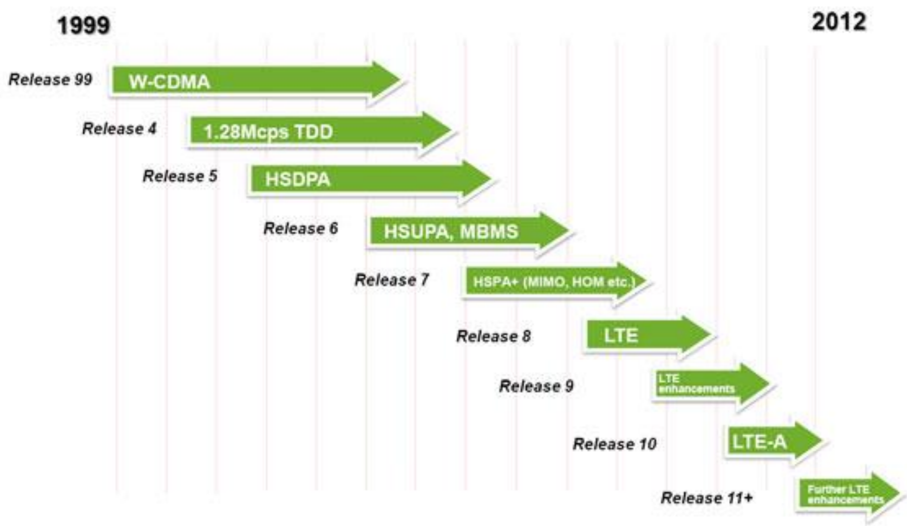


Figure 1.3 Radio Access Milestones (extracted from [3GPP13]).

1.2 Motivation and Contents

Due to high data rates, spectrum efficiency and system latency, LTE is a technology with a great potential. However, the great challenge for LTE is in the urban areas. In urban scenarios, not only the probability of a User Equipment (UE) being in Line of Sight (LoS) with an evolved Node B (eNodeB) is much lower, as there are much more indoor users, which add an even higher attenuation. In addition, urban environments usually have capacity limited cells, which lead to cell areas that are much smaller than in rural environments and to an increase of the overlapping coverage area between neighbouring cells, creating interference; this is a key issue for LTE, being one of the main performance limiting factors.

The main scope of this thesis is to study the performance of an urban LTE network for different frequency reutilisation mechanisms. Several frequency reutilisation mechanisms are analysed and compared, for different bandwidths and frequency bands, in terms of satisfied users, throughput and SINR. In order to perform this study, a model was developed and implemented in a simulator. The main results show the performance of the several frequency reutilisation mechanisms for high and low loaded LTE networks with MIMO 2x2.

This thesis was done in collaboration with Ericsson, which had the important role of providing assistance on several technical details and insights on the technologies. As Ericsson works directly with Vodafone Portugal, Vodafone Portugal agreed to give the required information about their network in Lisbon, in order to use it as the urban scenario in study.

The main output of this thesis is the developed simulator to implement the model, which recreates a mobile network in the city of Lisbon. The network has a wide number of eNodeBs spread throughout Lisbon, with a higher concentration in the centre of the city. Users can be outdoor or indoor, and are randomly spread through the network with a higher concentration in certain areas, in order to have a more realistic approach. Users ask for different services and throughputs, and have different locations, azimuths, and can be in LoS or NLoS. Users compete for resources and Quality of Service (QoS), being allocated according to the priority of their service and their SNR: the first user to be served is the one with the high priority service and best SNR.

The present thesis is composed of five chapters, including the present one, and by a group of annexes. Chapter 2 presents an introduction to LTE fundamental concepts and to the interference problem in LTE under study in this thesis. Initially, LTE basic concepts are presented, namely network architecture and radio interface. Then the problem of interference in LTE is introduced and the latest interference mitigation techniques are presented, followed by main aspects of capacity, coverage, services and applications. Finally, the state of the art is presented, containing the latest work developed related to this thesis.

Chapter 3 contains the full description of the used models, as well of the simulator that implements them. First, the models are presented, regarding Frequency Reuse Schemes (FRSs), propagation and throughput. Then one presents a detailed description of the simulator conceived to implement the models, including algorithms and important considerations and choices made. In the end, the simulator is assessed in order to guarantee the validity of the results.

Chapter 4 presents the description of the scenarios considered in this thesis and the analysis of results. In the first section, one presents the network under study, propagation parameters, user environments, specifications of each FRS considered, default parameters for reference scenario and services characterisation. In the next four sections, the analysis of results is presented, where the implemented FRSs are analysed for the 2600, 1800 and 800 MHz bands and for high and low loaded networks.

Chapter 5 summarises this thesis work, pointing out the main results and conclusions and addressing the future work.

At the end, a group of annexes is presented containing additional information. Annex A addresses the link budget used for the calculations regarding signal propagation between the UE and the eNodeB. Annex B presents the propagation model considered for the urban scenarios. Annex C addresses SINR and data rate models, including data rate models for LTE with MIMO 2x2 based of 3GPP trial measurements. Annex D describes with more detail the distribution of eNodeBs and users along the city area in the simulations. Annex E contains the user manual, describing how to configure and run the simulator.

Chapter 2

LTE Basic Concepts

This chapter provides an overview of LTE, mainly focussing on the network architecture, radio interface, interference, coverage and capacity, services and applications, and frequency reutilisation schemes.

2.1 Network Architecture

Data traffic on mobile networks is increasing year after year, in such a way that mobile operators have been forced to improve their networks in order to respond to this new requirement. The complexity and cost of creating a mobile network are quite high, which is one of the key factors that explain why current mobile networks are so complex and vary among operators, so it is obvious that operators require backward compatibility for all innovations that they will introduce in the network. This section is based on [HoTo11].

LTE responds to the needs of mobile operators by introducing the following improvements: higher spectral efficiency, peak rates exceeding 100 Mbit/s in DL and 50 Mbit/s in UL, round trip bellow 10 ms, optimised packet switched, higher level of mobility and security, optimised terminal power efficiency and frequency flexibility with allocations from 1.4 MHz up to 20 MHz. The amount of network elements has been reduced towards a flat architecture.

Figure 2.1 shows the division of the architecture into four main high-level domains: UE, Evolved UMTS Terrestrial Radio Access Network (E-UTRAN), Evolved Packet Core Network (EPC) and the Services domain. UE, E-UTRAN and EPC together represent the Internet Protocol (IP) Connectivity Layer, who provides IP based connectivity. All services are offered on top of IP, circuit switched nodes and interfaces not being present at all.

The LTE architecture development is limited to Radio Access (E-UTRAN) and Core Networks (EPC), UE and Services domains remaining architecturally intact.

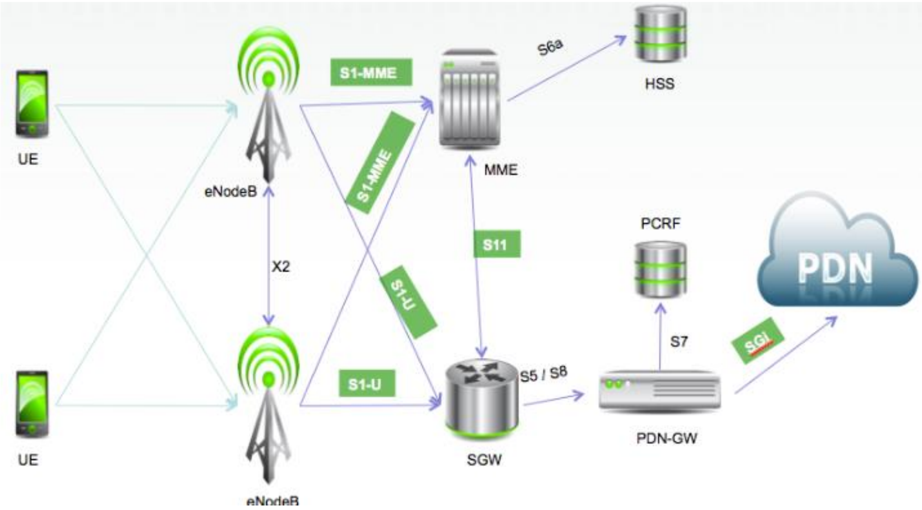


Figure 2.1 System architecture for 3GPP access networks (extracted from [Ixia13]).

Unlike other mobile systems, in LTE the only radio access node is the evolved NodeB (eNodeB). The eNodeB is a base station that encompasses all radio related functions, such as Radio Resource Management (RRM), Radio Link Control (RLC), Radio Resource Control (RRC) and Packet Data

Convergence Protocol (PDCP). In the eNodeB, radio bearer control, radio admission control, connection mobility control, dynamic resource allocation and measuring/reporting configurations are also performed. eNodeBs are interconnected, i.e., they have an X2 interface between them, this way they can communicate for radio handover purposes, eliminating the large flow of data through Radio Network Controllers (RNCs) as in UMTS.

The eNodeB is connected to the EPC through S1 interfaces. The EPC is equivalent to the packet switched domain of existing 3GPP networks, being composed of five elements: Mobility Management Entity (MME), Serving Gateway (S-GW), Packet Data Network Gateway (P-GW), Policy and Charging Resource Function (PCRF) and Home Subscription Server (HSS).

MME is the main control element in the EPC, responsible for Authentication and Security, Mobility Management, Managing Subscription Profile and Service Connectivity.

The S-GW high-level function is User Plane (UP) tunnel management and switching. The P-GW is the edge router between the EPC and the external packet data networks, usually acting as the IP point of the attachment for the UE and performing traffic gating and filtering functions as required by the services. The System Architecture Evolution Gateway (SAE-GW) is the combination of the two gateways, S-GW and P-GW, which are responsible for user plane handling in the EPC and both also handle the interoperability through other 3GPP radio systems.

PCRF is responsible for Policy and Charging Control (PCC), and HSS is the subscription data repository for all permanent user data.

PDN may include various sub-systems, such as IP Multimedia Sub-system (IMS) based operator services, Non-IMS based operator services and other services not provided by the mobile network.

2.2 Radio Interface

In LTE, two multiple access techniques are applied: Orthogonal Frequency Division Multiple Access (OFDMA) for DL and Single Carrier Frequency Division Multiple Access (SC-FDMA) for UL.

In OFDMA, multiple access is achieved by assigning each user a subset of subcarriers, this way users can transmit and receive at the same time within a single channel, through what can be called sub-channels. Unfortunately, as the number of subcarriers increases, the peak-average-ratio (PAR) will increase as well. Although this is not a problem for the eNodeBs, battery saving is a very important factor for the UE, which is one of the main reasons why SC-FDMA is used for UL instead of OFDMA.

SC-FDMA cleverly combines the low PAR of single-carrier systems with the multipath resistance and flexible subcarrier frequency allocation offered by Orthogonal Frequency Division Multiplexing (OFDM) [Rumn08]. Therefore, it is more power efficient than OFDMA, because the UE only needs to transmit one carrier at a time, maximising the UE’s battery life.

The primary advantage of OFDM is its resilience to fading, but without multipath protection, the symbols in the received signals will overlap in time, leading to Inter-Symbol Interference (ISI). ISI can be overcome by inserting a guard period, known as Cyclic Prefix (CP). This way, by sampling the received signal at an optimum time, the receiver can avoid the ISI caused by the delay spread up to the length of the CP.

In cellular communication systems, the quality of the signal received by an UE depends on the channel quality from the serving cell, the level of interference from other cells, and the noise level. To optimise system capacity and coverage for a given transmission power, the transmitter should try to match the information data rate for each user as the variations in the received signal quality. This is commonly referred to as link adaptation and is typically based on Adaptive Modulation and Coding (AMC) [SeTB09].

For LTE, in DL, scalable bandwidths are allowed, from 1.4 up to 20 MHz, with a subcarrier spacing of 15 kHz. As a result, system bandwidth can be adjusted according to the needs, i.e., Quality of Service (QoS), etc. The scalable bandwidths allocated for LTE and the differences between the parameters are presented in Table 2.1.

Table 2.1 Key Parameters for different bandwidths (extracted from [HoTo11]).

Bandwidth	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Sub-frame (TTI) [ms]	1					
Sub-carrier spacing [kHz]	15					
Sampling [MHz]	1.92	3.84	7.68	15.36	23.04	30.72
FFT	128	256	512	1024	1536	2048
Sub-carriers	72 + 1	180 + 1	300 + 1	600+1	900+1	1200+1
Symbols per frame	4 with short CP and 6 with long CP					
Cyclic Prefix	5.21 μs with short CP and 16.67 μs with long CP					

DL and UL are composed of physical channels and signals. Physical channels carry information from higher layers and are used to carry user data, as well as user control information. Physical signals do not carry information from higher layers and are used for cell search and channel estimation purposes. The main DL physical channels are the physical broadcast channel (PBCH), physical DL control channel (PDCCH), and physical DL shared channel (PDSCH). The main DL physical signals are the reference signal (RS), and the primary and secondary synchronisation signals (P-SCH, S-SCH). The main UL physical channels are the physical UL control channel (PUCCH) and the physical UL shared channel (PUSCH). The main UL physical signals are the demodulation RS and the physical random access channel (PRACH), [Tech07].

In order to support paired and unpaired spectrum, the LTE air interface supports both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD). According to the specifications, the LTE spectrum is constituted by 17 FDD bands and 8 TDD bands [3GPP12]. In Portugal, an auction has been made by ANACOM, [ANAC12], for 800 MHz, 900 MHz, 1800 MHz, 2.1 GHz and 2.6 GHz frequency bands.

Two radio frame structures are defined: frame structure type 1, which uses both FDD and TDD duplexing and is optimised to co-exist with 3.84 Mcps Universal Terrestrial Radio Access (UTRA) systems; frame structure type 2, which only uses TDD duplexing and is optimised to co-exist with 1.28 Mcps UTRA TDD systems (Time Division Synchronous Code Division Multiple Access (TD-SCDMA)). This thesis only focuses on FDD, due to its adoption by the majority of European operators [Tech07].

As one can see in Figure 2.2, the physical mapping of the DL physical signals are:

- RS is transmitted at OFDM symbol 0 and 4 of each slot. This depends on frame structure type and antenna port number.
- P-SCH is transmitted on symbol 6 of slots 0 and 10 of each radio frame; it occupies 72 sub-carriers, centred on the DC sub-carrier.
- S-SCH is transmitted on symbol 5 of slots 0 and 10 of each radio frame; it occupies 72 sub-carriers centred on the DC sub-carrier.
- PBCH physical channel is transmitted on 72 sub-carriers centred on the DC sub-carrier.

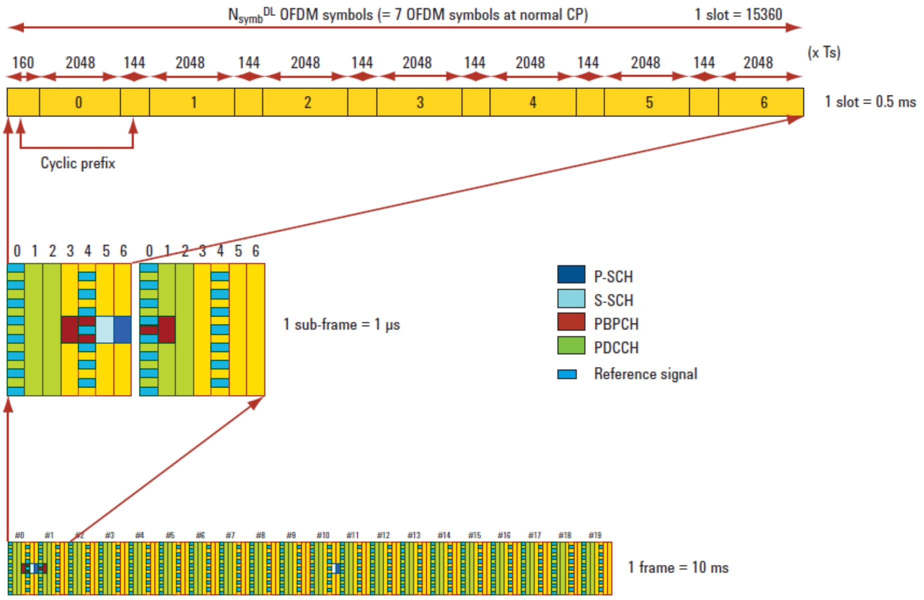


Figure 2.2 Frame structure type 1 (extracted from [Tech07]).

Figure 2.3 shows a 10 MHz LTE DL frame. The time frame consists of 10 sub-frames, each lasting 1 ms. Half of a sub-frame is called a slot. In frequency, each sub-frame is split into 50 Virtual Resource Blocks (VRBs) and each VRB is comprised of a pair of Physical Resource Blocks (PRBs). Each PRB is composed of 12 subcarriers in frequency and 7 symbols in time, being the smallest unit allocation in LTE, being called Resource Block (RB). Each element of the PRB is called a Resource Element (RE). An RE spans one subcarrier in frequency and one symbol in time, has a frequency width of 15 kHz and lasts approximately 70 µs [MiLV11].

For UL, the frame structure type 1 is the same as for DL in terms of frame, slot and sub-frame length.

However, the number of symbols in a slot depends on the CP length, i.e., for a normal CP, there are seven SC-FDMA symbols per slot, but for an extended CP, there are six SC-FDMA symbols per slot. The UL slot structure is shown in Figure 2.4.

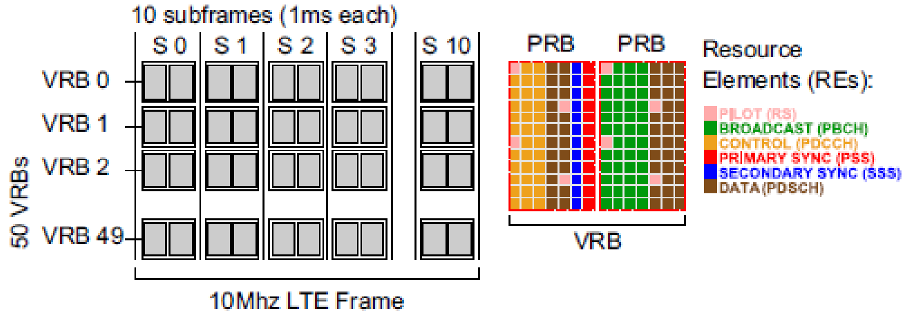


Figure 2.3 The essential components of a DL LTE frame (extracted from [MiLV11]).

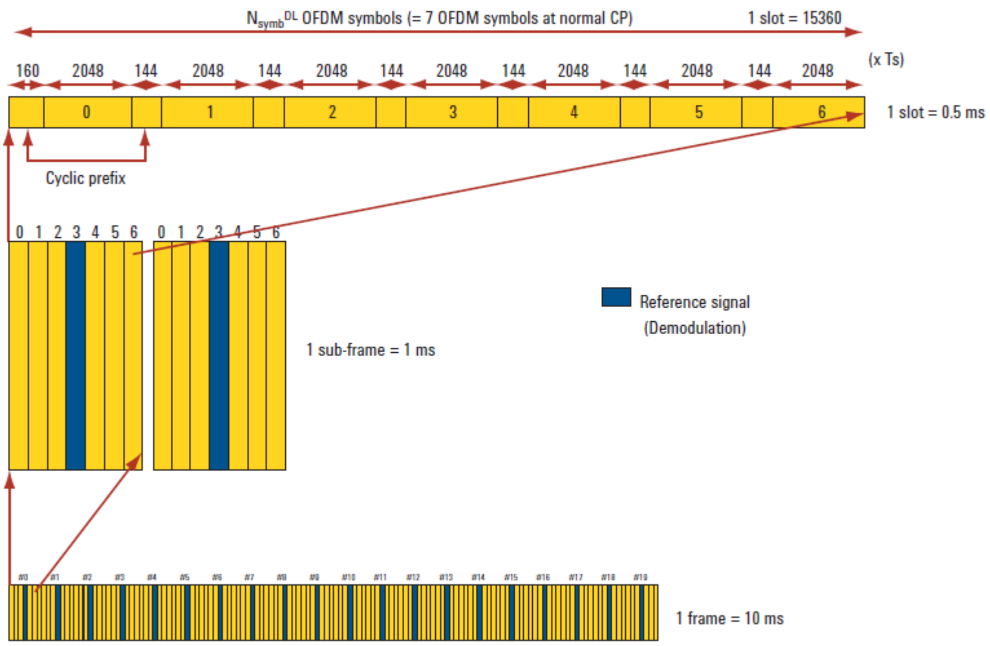


Figure 2.4 UL frame and slot format for frame structure type 1 (extracted from [Tech07]).

Additionally, to the optimisation in the time and frequency domains referred above, and in order to enable a high data rate, antenna optimisation through MIMO is definitely a key factor.

2.3 Interference

When LTE was defined, OFDMA networks were supposed to use frequency reuse of 1, i.e., each cell should use the whole spectrum for transmission. Obviously, that aggressive frequency reuse raised a lot of problems regarding interference.

Interference can be divided into two classes, Intra-Cell Interference (Adjacent-channel interference) and Inter-Cell Interference (ICI) (Co-channel interference). Intra-cell interference, as shown in Figure 2.5, appears when UE devices interfere with each other, but as the subcarriers in the intra-cell are orthogonal with each other, intra-cell interference can be avoided efficiently [XuZW11].

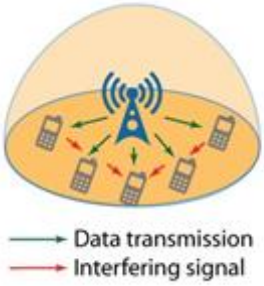


Figure 2.5 Intra-Cell Interference (extracted from [Senz12]).

As shown in Figure 2.6, ICI happens when UE receives interfering signals from neighbouring cells. Aggressive frequency reuse can offer higher system capacity but at the same time increases the interference from the other cells, in other words, increases ICI. This results in a degradation of the Signal to Interference plus Noise Ratio (SINR) for cell-edge users, which severely limits cell-edge spectrum efficiency [Yang12].

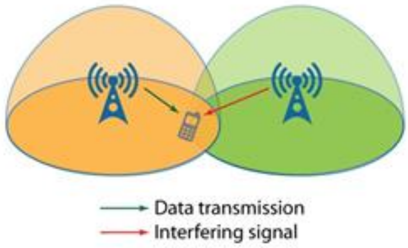


Figure 2.6 ICI between macro-cells (extracted from [Senz12]).

Moreover, the interference becomes more severe with the introduction of heterogeneous LTE networks, where low-power nodes, such as small cells, are deployed within the coverage of a macro-cell network to improve coverage and spectrum efficiency. Although the usage of this low-power nodes eliminates the coverage holes and increases capacity, it also rises significantly the ICI, [Yang12]. As shown in Figure 2.7, the UE also receives interfering signals from the small cells, which results in a degradation of SINR for users near to those small cells. ICI mitigation in Heterogeneous Networks led to a lot of research and a vast literature can be found on this issue.

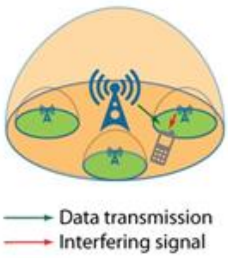


Figure 2.7 ICI between macro- and small-cells (extracted from [Senz12]).

Interference mitigation is one of the key issues currently under investigation in different standardisation bodies and fora. Based on the used approach, mitigation techniques are generally categorised into three major classes [RaYW09]:

- Interference cancellation: the basic principle is the receiver signal processing to estimate interference and subtract it from the desired signal component.
- Interference averaging: ensures UE to access a range of channels rather than a narrow set in a specific pattern, so that interference is averaged for all UEs, e.g., Frequency Hopping (FH).
- Interference avoidance: focuses on finding an optimal effective reuse factor, often achieved through restrictions on frequency and power allocations to accomplish network performance goals.

Several techniques to manage real-time ICI within LTE networks were developed, [Senz12], and they can work at three levels:

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

In the first level, all techniques use exclusively E-UTRAN elements to manage interference. Currently, there are three techniques that work on this level: Inter-Cell Interference Coordination (ICIC), enhanced ICIC (eICIC), which takes heterogeneous networks into account, and Coordinated Multi-Point (CoMP) transmission and reception.

In the second level, it is required that both E-UTRAN elements and UE devices have an active role in managing interference. Fundamentally, the main focus is multiple-input and multiple-output (MIMO) enhancements, including Multi-User MIMO (MU-MIMO) and Single-User MIMO (SU-MIMO).

In the third level, interference management takes place entirely within the UE, the most important techniques deployed until now being Maximal Ratio Combining (MRC), Interference Rejection Combining (IRC) and Interference Cancellation (IC).

2.4 Coverage and Capacity

As seen in the previous section, interference can lead to a severe degradation of SINR and spectrum efficiency. Obviously, this degradation decreases the overall capacity of the network, and the expected user’s throughput will not be achieved, especially regarding cell-edge users.

End-user throughput depends on parameters like the number of assigned RBs, modulation, MIMO configurations, CP size used, channel coding rate, overhead amount due to synchronisation and RS as well as control channels, among others. The theoretical throughput for a UE in DL can be obtained from, [Carr11]:

$$R_{b,teo_{[\text{Mbit/s}]}} = \frac{N_{sc}^{RB} \cdot N_{RB}^{u} \cdot N_{symb}^{SF} \cdot \log_2(m) \cdot N_{streams}}{T_{SF_{[\text{s}]}}} \quad (2.1)$$

where:

- N_{sc}^{RB}: Number of subcarriers per RB, 12 subcarriers for a 15 kHz spacing;
- N_{RB}^{u}: Number of RB per user;
- N_{symb}^{SF}: Number of symbols per frame, 14 symbols for normal CP and 12 symbols for an extended CP;
- m: Order of modulation;
- $N_{streams}$: Number of streams, in case of MIMO;
- T_{SF}: Sub-frame period, 1 ms.

One of the main limiting aspects for system throughput performance in cellular networks is inter-cell interference, especially for cell-edge users, being one of the main focuses of this thesis. The equations to calculate the throughput taking into account interference are described in Chapter 3.

The estimation of the total number of users served by a cell can be obtained from, [Gonç11]:

$$N_u = \frac{N_{sc}^{RB} \cdot N_{RB} \cdot N_{symb}^{SF} \cdot \log_2(m) \cdot N_{streams}}{R_{b\,[\text{Mbits/s}]} \cdot T_{SF_{[\text{s}]}}} \quad (2.2)$$

where:

- N_{RB}: Number of resource blocks

The theoretical calculation of cell coverage radius is obtained from the combination of the link budget expression with an adequate environment propagation model for path loss, [Pire12]:

$$R_{[\text{km}]} = 10^{\frac{P_{t\,[\text{dBm}]} + G_{t\,[\text{dBi}]} - P_{r,\min\,[\text{dBm}]} + G_{r\,[\text{dBi}]} - L_{p\,[\text{dB}]}}{10^{a_{pd}}}} \quad (2.3)$$

where:

- P_t: Power fed to the antenna;
- G_t: Gain of the transmitting antenna;
- $P_{r,min}$: Power sensitivity at the receiver antenna;
- G_r : Gain of the receiving antenna;
- L_p: Path loss;
- a_{pd}: Average power decay.

The number of resources allocated to users is limited, so the scheduling scheme directly influences user's throughput and overall capacity. Therefore, an algorithm that plans RB distribution has to be applied, in order to maximise the capacity along the time and frequency domains with reasonable fairness among users. The most important scheduling algorithms are described below, [DaPS11]:

- Maximum Rate: The scheduler takes the instantaneous radio-link conditions into account, scheduling the user with best radio-link conditions. Still, from a system capacity perspective, this scheduling strategy is not fair in all situations. The UEs experience differences in the average channel conditions, due to differences in distance and shadow fading between the eNodeB and the UE. In this case, the channel conditions experienced by one UE may be worse than for other UEs, for a relatively long time. A pure maximum rate strategy may “starve” the UE with bad channel conditions and it may never be scheduled.

- Round Robin (RR): This scheduling strategy lets users take turns in using the shared resources, without taking instantaneous conditions into account. It can be seen as fair scheduling in the sense that the same amount of radio resources is given to each communication link. In the case that more radio resources must be given to communication links with bad channel conditions, RR is not fair because it does not provide the same service quality to all communication links.
- Proportional Fair (PF): This strategy stays between maximum rate scheduling and RR scheduling, trying to use fast variations in channel conditions as much as possible while still satisfying some degree of fairness among users. In this strategy, the shared resources are assigned to the user with the better radio-link conditions.

In the above description of the scheduling algorithms, it was assumed that all radio resources in DL were assigned to a single user at a time, the scheduling was done purely in time domain using TDM between users. However, scheduling algorithms should not rely solely on TDM in the DL for two main reasons, [DaPS11]:

- If the amount of data to transfer to a user is not sufficiently large to utilise the full channel capacity, a fraction of resources could be assigned to another user, through FDM or CDM.
- The channel variations in the frequency domain can be exploited through FDM.

The scheduling strategies that take into account FDM or CDM can be seen as generalisations of the scheduling strategies presented above. For example, to handle small payloads, the scheduled user is selected according to maximum rate or any other scheduling strategy; once this user has been assigned resources matching the amount of data awaiting transmission, the second best user according to the scheduling strategy is selected and assigned a fraction of resources and so on, [DaPS11].

2.5 Services and Applications

One of the main factors for the deployment of LTE was the increasing trend for users to consume data in mobile environments. As users get used to access the Internet wherever they are, they also are expecting for better and faster services via a mobile communication system, similar to access to a triple play service by DSL or optical fibre. For them, this enriched user experience will be typified by the large-scale streaming, downloading and sharing of video and music, online gaming, among others. All these services will need significantly greater throughput to provide the QoS that users are expecting, especially with the growing popularity of High Definition (HD) services like HD TV [Foru08].

LTE incorporates all the services and applications of his predecessors and brings the characteristics of today's Web 2.0. This alongside with higher throughput and secure e-commerce will bring forward peer-to-peer applications like multiplayer gaming and file sharing in mobile systems.

LTE offers a new world of services and application opportunities. For example, with LTE it is possible to provide a much better mobile online gaming experience, high quality music and video streaming, true on-demand television, among much many others, [Foru08]. All this new services consist of several applications that may be very different from each other, as well as the quality requirements vary widely among them. Special attention should be paid to the different quality requirements of each service in order to guarantee the desired QoS.

To face all the challenges proposed by these services, for the development of System Architecture Evolution (SAE) bearer model and QoS concept, it was necessary to define parameters and quantify performance, and improvements compared to the existing 3GPP systems should be made. For UMTS, 3GPP has specified four QoS classes (also referred as traffic classes): conversational, streaming, interactive and background.

As shown in Table 2.2, there are many attributes that characterise these classes, but the main distinguishing attribute is delay. Conversational and streaming classes are the most sensitive to delay. An extensive set of QoS attributes is available, but it is not easy to configure attributes in the right way. In addition, the UE is responsible for setting the QoS attributes for a bearer and the bearer model has many layers, each signalling just about the same information. It has been agreed that only a reduced set of QoS parameters and standardised characteristics is specified. It has also been decided to turn the bearer set-up logic so that the network resource management is only network controlled, the network decides how the parameters are set, and the main bearer set-up logic consists of only one signalling transaction from the network to the UE and all interim network elements, [HoTo11].

The QoS parameters were optimised for SAE and only a limited set of signalled QoS parameters are included in the specification, [HoTo11]: QoS Class Identifier (QCI), an index that identifies a set of locally configured values for three QoS attributes (Priority, Delay and Loss Rate); Allocation and Retention Priority (ARP), that indicates the priority of the bearer compared to other bearers; Maximum Bit Rate (MBR), which identifies the maximum bit rate for the bearer; Guaranteed Bit Rate (GBR), that identifies the bit rate that will be guaranteed to the bearer; Aggregate Maximum Bit Rate (AMBR), which indicates the total maximum bit rate a UE may have for all bearers in the same PDN connection. The QoS parameters that define the QCI classes are, [HoTo11]: Resource Type, that indicates which classes will have GBR associated to them; Priority, used to define the priority for the packet scheduling of the radio interface; Delay Budget, which helps the packet scheduler to maintain sufficient scheduling rate to meet the delay requirements for the bearer; Loss Rate, that helps to use appropriate RLC settings, for example, helps to define the number of re-transmissions.

Ten pre-configured classes have been specified in two categories of bearers, GBR and Non-Guaranteed Bit Rate (Non-GBR) bearers, but mobile operators have the liberty to create their one classes and apply them within the network. The standard QCI classes and the QoS parameters associated to them are shown in Table 2.2.

Table 2.2 UMTS QoS classes (extracted from [Serr12]).

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

2.6 State of the art

This thesis addresses frequency reutilisation mechanisms with a focus on tri-sectored cells, in order to mitigate the inter-cell interference in DL. From the techniques presented in Section 2.3, the most important in the subject of this thesis is the ICIC. Note that ICIC mechanisms for UL are outside the scope of this thesis.

ICIC can be thought as a variety of mechanisms for controlling the interference between neighbouring cells. The standardised ICIC schemes for Release 8 rely on frequency domain sharing between cells and on adjustment of the transmitted powers. The X2 interface between eNodeBs includes standardised signalling for carrying interference and schedule information. This schemes can be categorised as, [HoTo11]:

- Reactive schemes: Methods based on measurements of the past, that are used to monitor performance and to take appropriate actions if the interference is too high;
- Proactive schemes: An eNodeB informs its neighbouring eNodeBs how it plans to schedule users in the future, so that the neighbouring eNodeBs can take this information into account.

Table 2.3 QoS parameters for QCI (extracted from [HoTo11]).

QCI	**Resource type**	**Priority**	**Delay budget [ms]**	**Loss ratio**	**Example applications**
1	GBR	2	100	10^{-2}	VoIP
2	GBR	4	150	10^{-3}	Video call
3	GBR	5	300	10^{-6}	Streaming
4	GBR	3	50	10^{-3}	Real time gamming
5	Non-GBR	1	100	10^{-6}	IMS signalling
6	Non-GBR	7	100	10^{-3}	Interactive gamming
7	Non-GBR	6	300	10^{-6}	
8	Non-GBR	8			Application with TCP: browsing, e-mail, file download, etc.
9	Non-GBR	9			

This thesis focuses on proactive schemes. Proactive DL ICIC schemes can use the standardised Relative Narrowband Transmit Power Indicator (RNTPI), which indicates the maximum anticipated DL transmit power lever per RB. RNTPI is signalled over the X2 interfaces to the neighbouring eNodeBs. With the information contained in the RNTPI, the neighbouring eNodeBs know at which RBs the cells from that eNodeB use more power, and can use different power patterns in their cells in order to improve the overall SINR conditions for the UEs, [HoTo11].

According to the different resource allocation techniques, the coordination schemes among cells can be, [HäSS12]:

- Static: The parameters do not change;
- Semi-static: With slow adaptation of the parameters based on signalling between eNodeBs.
- Dynamic: That relies on frequent adjustment of the parameters with the use of signalling between eNodeBs.

Dynamic coordination is not suitable for practice yet, because it requires too many signals and makes scheduling too complex, [XiSX07].

By setting different DL transmit powers per RB, it is possible to configure different reuse patterns, known as Frequency Reuse Schemes (FRS), [HoTo11]:

- Full Frequency Reuse (Reuse-1);
- Hard Frequency Reuse;
- Soft Frequency Reuse (SFR);
- Fractional Frequency Reuse (FFR).

In Full Frequency Reuse (Reuse-1), meaning that the entire spectrum is used to transmit, all RBs have equal transmit power. In Hard Frequency Reuse, shown in Figure 2.8, the frequency band is divided into sub-bands, each cell gives maximum power only to one sub-band and no power to the other ones, mitigating the ICI, but only using in each cell one third of the entire spectrum available.

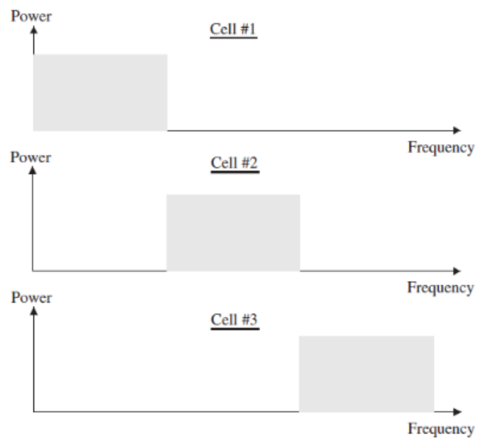


Figure 2.8 Example of DL transmission power settings for hard frequency reuse three (extracted from [HoTo11]).

FFR is the most popular frequency reutilisation technique, where the main idea is to divide the area of the cell into two regions, inner and outer ones, where the latter uses one third of the spectrum and is divided into three sectors. As shown in Figure 2.9, a part of the frequency band is dedicated to cell-centre users (used in the inner region of all cells) and the remaining part of the frequency band is divided in three sub-parts. As illustrated in Figure 2.10, each one of these sub-parts is assigned to a specific sector in the outer region of each cell in a way that neighbouring cells do not share the same sub-part of the spectrum.

SFR is illustrated in Figure 2.11, a variation of FFR, the difference being the scheduling of users over the entire bandwidth with different power levels. Cell-edge users are scheduled in the bandwidth with the highest power level and the users closer to the eNodeB are scheduled in the RBs with lower transmit power, [HoTo11].

However, traditional SFR and FFR overlook users near the frontier between sectors. In these schemes, the inner region of all sectors share some parts of the spectrum, the interference between sectors cannot be disregarded and Inter-Sector Interference Coordination (ISIC) has to be considered. In the SFR case, only half of the sub-band reserved for each sector inner region is shared with the other sectors, but in the FFR one, all sectors share the same part of the spectrum.

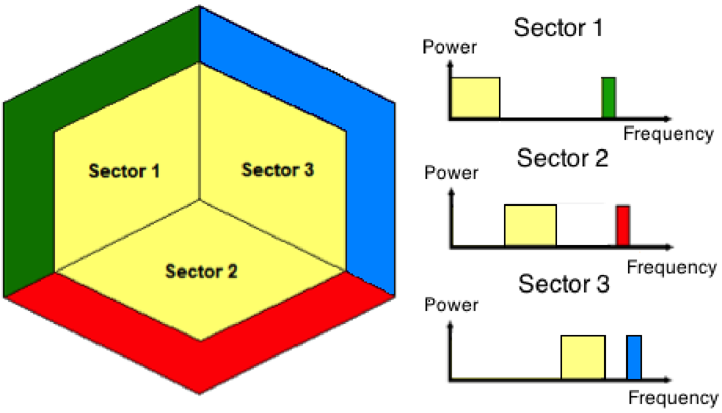


Figure 2.9 FFR applied in a tri-sectored cell, including frequency distribution.

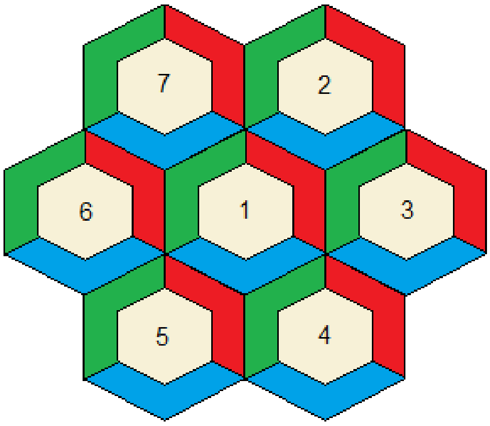


Figure 2.10 FFR applied in a system with 7 tri-sectored cells.

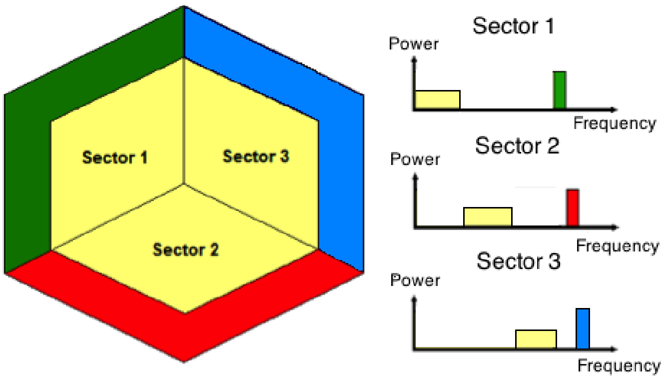


Figure 2.11 Example of SFR.

In [GuHC12], the authors propose new schemes, based on FFR and SFR, that take frontier users into account. The proposed schemes that have led to better results try to apply reuse of 1 at sector level:

- FFR with frequency occupation ordering within its own sector preferred sub-band, power adaptation and reuse of 1 at sector level (FFRopa-R). As shown in Figure 2.12, in this scheme, each sector has reserved for itself a part of the sub-band, but if it is totally allocated the sector starts reusing the parts reserved for the other sectors.

- Fractional sector reuse with frequency occupation ordering (FSRopa). As illustrated in Figure 2.13, frontier users are allocated in outer region resources.
- Fractional sector reuse with frequency occupation ordering, power adaptation and inner sub-band frontier allocation (FSRopa-ISFA). As illustrated on Figure 2.14, a new region is created and is called frontier region, and for each sector a specific part of the inner sub-band is reserved only to this region. In [GuHC12], several variations of this scheme are proposed.

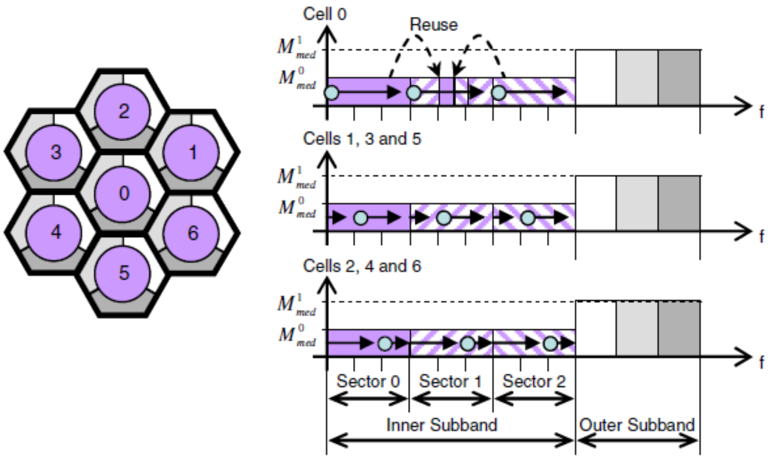


Figure 2.12 FFRopa-R (extracted from [GuHC12]).

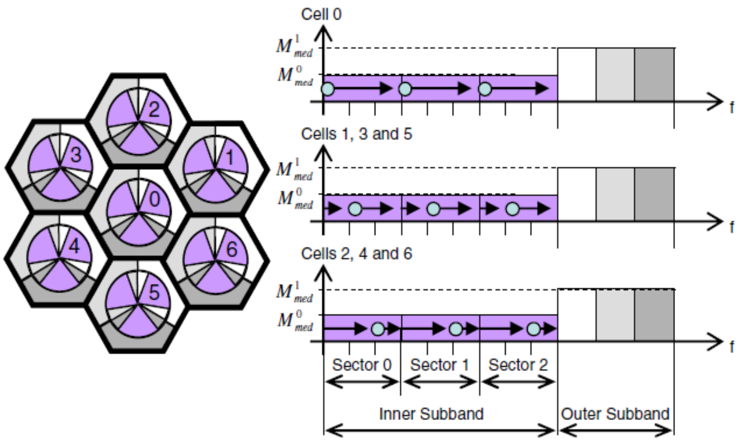


Figure 2.13 FSRopa (extracted from [GuHC12]).

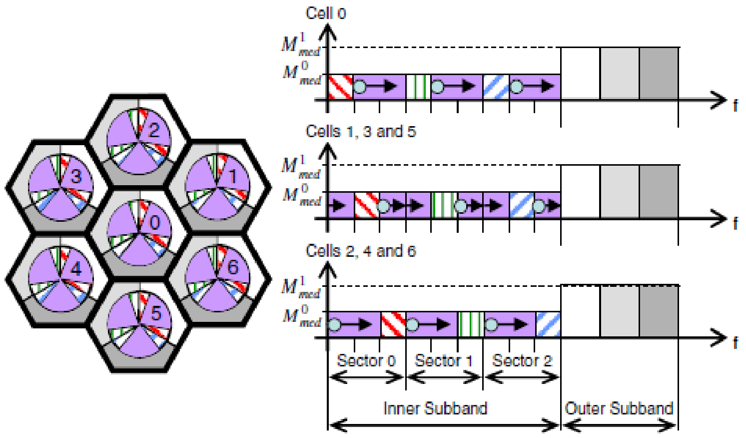


Figure 2.14 FSRopa-ISFA (extracted from [GuHC12]).

However, in these proposed schemes, which take frontier users into account, the relative location of the users among the sectors and among the primary and interfering eNodeBs is an important parameter, in order to correctly allocate the resources. This required location information can be obtained by a combination of location data obtained from positioning methods, such as GPS, and by performance measurements at the physical level [GuHC12]. In [Alca13], several location techniques to apply in LTE are shown.

A number of schemes have been proposed, for example, regarding static resource allocation, two FRSs were proposed by Ericsson and Alcatel, and for semi-static resource allocation Siemens proposed another scheme that led to better results than the static ones, [XiSX07].

In [KiCY09], a scheme called Whispering is proposed, where each six-sectored cell is composed of an inner and an outer regions. Based on Figure 2.15, in the first step resources are divided by 4 and the same resources are assigned for the inner region of cell 1 and S1, which will be 1/4 of all resources, the same is done to cell 2 and S2, etc. In the case of cell 1 and its neighbouring sectors, if a UE is located in a sub-sector S1, it is not greatly affected by interference, since eNodeB of cell 1 transmits at reduced power. Comparing to the Siemens scheme mentioned above, the Whispering method is superior in fairness and performance, but each UE must feed back channel quality to other eNodeBs and each eNodeB requires constantly updated resource allocation standard. This scheme could be applied to small area scenarios with a several users, such as venues like stadiums or music festivals. However, since the author neglected the users near the frontiers between sectors, if ISIC is considered, this scheme will probably lead to even better performance.

A lot of research has been done regarding inter-cell interference, and various techniques, which significantly decrease the ICI, have been developed. Some semi-static and dynamic schemes are being developed, the main scope being to reduce their complexity, in order to apply them in existing LTE networks. Nevertheless, the continued increase of traffic demand and the introduction of heterogeneous networks continue to make the ICI a key issue in LTE radio networks.

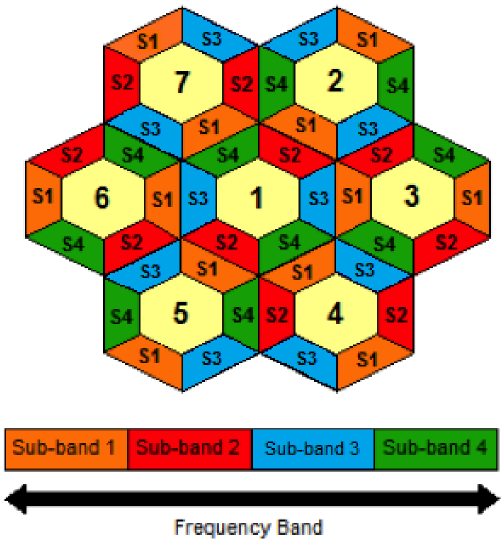


Figure 2.15 Whispering scheme.

Chapter 3

Models and Simulator Description

This chapter provides an overview of the developed and implemented model, in order to study the impact of frequency reutilisation mechanisms in an LTE network. First the model is presented, then the implementation is fully described, and in the end the simulator is assessed to guarantee the validity of the results.

3.1 Models

3.1.1 Frequency Reuse Schemes

One of LTE's objectives is the use of Full Frequency Reuse. However, this technique leads to an undesirable increase of ICI. The focus of this thesis is the mitigation of ICI using different frequency reuse mechanism. FRSs are able to mitigate interference by limiting the spectrum that is used in each sector of the eNodeB. The most popular frequency reutilisation techniques are FFR and SFR. Both divide the sectors into two regions, inner and outer regions, and they are able to mitigate ICI by controlling the use of resources in the two regions. For the outer region 1/3 of all resources are reserved and the remaining ones are only reserved for the inner region. Although, as in FFR and SFR, sectors cannot share the same resources, and users near the frontier between sectors are being neglected, three new schemes, FFRopa-R, FSRopa and FSRopa-ISFA, which deal with these issues have been introduced in Section 2.6. FFRopa-R introduces the reuse of 1 at sector level, meaning that the three sectors share the inner resources, using 2/3 of all resources available for the inner region. FSRopa and FSRopa-ISFA take the users near the frontiers between sectors into account. FSRopa considers frontier users as outer region ones, allocating them with outer region resources. On the other hand, FSRopa-ISFA reserves resources only for the frontier region, frontier region users being allocated to these resources.

Based on the work presented in Section 2.6, six FRS are compared in terms of performance:

1. Reuse-1: sectors are not limited at spectrum level, meaning that all RBs are available in each sector.
2. FFR: each sector is divided to in two regions, inner and outer ones. The outer region has 1/3 of all resources available, which are divided among the three sectors. These resources are only allocated to cell-edge users, which are at least at a certain defined distance to the eNodeB, referred to as inner region limit. The remaining resources are divided among the three sectors inner region and allocated to inner region users.
3. SFR: this technique is very similar to FFR, the difference being that the resources reserved to a sector outer region are transmitted at higher power than those transmitted in its inner region.
4. Fractional Sector Frequency Reuse (FSFR): based on the FFRopa-R scheme, similarly to SFR, the resources allocated to a sector's outer region are transmitted at a higher power than those transmitted in its inner region. The resources reserved to the inner region are divided into three groups and each sector reserves one of these groups to it, the same happening for the outer region resources. Users are preferably allocated to the RBs intended for their serving sector, hence, in low-load conditions this FRS behaves exactly like SFR. However, when the reserved bandwidth is fully allocated, the sectors can start reusing inner RBs from their neighbouring sectors of its serving eNodeB, following this order: sector 1 first reuses RBs from sector 2 and then from sector 3; sector 2 first reuses RBs from sector 3 and then from

sector 1; sector 3 first reuses RBs from sector 1 and then from sector 2.

5. FSFR with frontier users (FSFR-F): based on FSFR and FSRopa, this scheme takes into account the users near the frontier with the neighbouring sectors. A user is defined as frontier user if the difference between the powers received from the neighbouring sectors of the same eNodeB is smaller than a defined power difference limit. Each sector of a cell is divided in three regions, inner, outer and frontier region. However, in this FRS, the outer region will share its resources with the frontier region, and the resources reserved for these two regions are 1/3 of all available bandwidth.
6. FSFR with independent frontier region (FSFR-IF): based on FSFR and FSRopa-ISFA, it is similar to the FSFR-F scheme, but in this case, the frontier region has a part of the inner resources reserved only for it, not sharing resources with any region. Based on the assumptions taken on [GuHC12], it is considered that the frontier region represents approximately 30% of the inner region and uses 1/3 of inner region resources. In conclusion, the resources are distributed by the three regions as follows:
   - 1/3 of all resources are reserved to the outer region, which means that each sector outer region has 1/9 of all resources reserved.
   - 2/3 of all resources are reserved for inner region, which mean that each sector inner region has 2/9 of all resources. However, the frontier region has to be considered, so in reality each sector inner region has only 4/27 of all resources.
   - Finally, each sector frontier regions has 2/27 of all resources. The two frontiers regions of each sector use the same resources.

3.1.2 Interference and SINR

Interference being one of the most important parameters in this thesis, an accurate calculation has to be done, in order to get more relevant results. When the interference is known, it is possible to obtain the SINR, which is one of the main parameters to assess the performance of the six FRSs.

In Annex A, the equations used for link budget are presented, such as SINR, SNR, noise power and power at the receiver. To calculate the power at the receiver, it is necessary to know the path loss; as this thesis analyses the impact of frequency reutilisation mechanisms in an urban scenario, the COST-231 Walfisch-Ikegami propagation model was considered and is fully described in Annex B. Note that users are organised by higher priority services and higher SNR.

In terms of simulation, two types of interference are considered, ICI and ISI, as illustrated in Figure 3.1. The interference experienced by a user in a specific RB is calculated from (3.1), being the sum of all powers received by the user from the neighbouring sector's antennas, of the serving eNodeB or the neighbouring eNodeBs, that are transmitting that specific RB at the same time. For example, if the serving antenna is the only one allocating a specific RB, the user will not experience interference. But if two neighbouring sectors are allocating that specific RB too, the interference experienced by the UE is the sum of the two interfering signal powers received at the UE.

$$I_{[mW]} = \sum_{n=1}^{N_I} I_{i\,[mW]} \tag{3.1}$$

where:

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

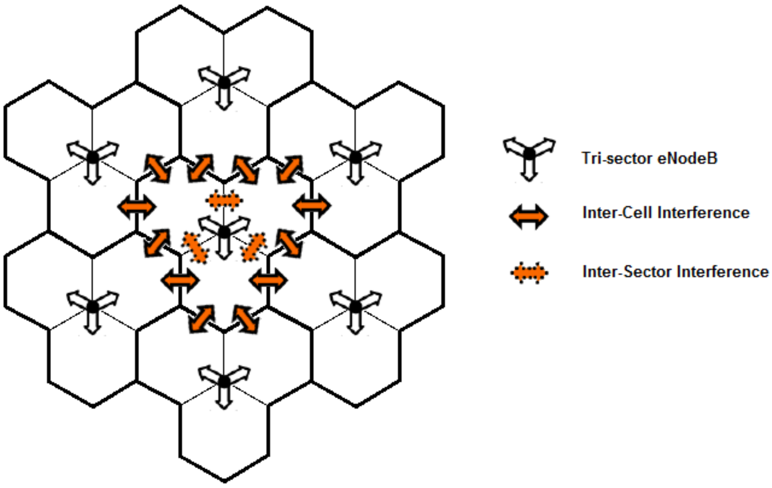


Figure 3.1 ICI and ISI.

As shown in Subsection 3.1.3, the equations considered for the throughput calculation give throughput as a function of SINR for one RB, which is why all link budget calculations are done per RB. Users are organised by higher priority services and higher SNR. Each time an RB is allocated to a user its SNR and throughput are calculated. When the interference experienced in an RB is known, its SINR and the real throughput are calculated. This way, when the interference experienced by a user in all RBs allocated to him is known, it is possible to calculate the user SINR and real throughput. A user is considered to be satisfied only if its real throughput is equal or better than the minimum throughput defined by its service.

3.1.3 Throughput and Capacity

In GSM, the capacity of a cell is normally considered as the number of users a cell can serve, largely due to voice being the most important and utilised service. In UMTS, with the introduction of data, this reality changed, and even more in LTE with the variety of services and the high throughput offered to the user. So, nowadays, the higher throughput that a cell can achieve for the considered circumstances is of key importance, regarding the cell capacity.

A good approximation to calculate the throughput of an RB is described in Annex C, taking into account specific channel modes, modulation, coding rate and multiple antenna systems. Regarding specifically MIMO 2x2, adopted in the network under study, the equations presented in Annex C for QSPK, 16-QAM and 64-QAM modulations are based on the latest measurements done by 3GPP. In [Alme13], the author describes how these equations were obtained. These equations give the throughput of one RB as a function of its SNR or SINR. The user throughput is given by (3.2) being the sum of the throughputs from all RBs allocated to him/her. Note that when calculating the throughput for one RB, the modulation is the one that enables to achieve the best throughput.

$$R_{b,user_{[Mbps]}} = \sum_{i=1}^{N_{RB,user}} R_{b,RB\ i_{[Mbps]}} \quad (3.2)$$

where:

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

The total throughput of a sector can be obtained from (3.3), being the sum of the instantaneous throughputs for active users in a cell, [Pire12]. Obviously, the total throughput of an eNodeB is the sum of the throughputs of all sectors that belong to it.

$$R_{b,eNodeB_{[Mbps]}} = \sum_{i=1}^{N_u} R_{b,user_{[Mbps]}} \quad (3.3)$$

where:

- N_u: Number of users to be served by the sector.

Note that a user is considered to be allocated when the RBs reserved to him/her guarantee the service maximum throughput, or, if there are no more free RBs, the service minimum throughput. After the interference calculation, the SINR and real throughput of each RB are calculated through the throughput equations presented above.

The number of satisfied users served by a cell is an important parameter regarding the capacity of a cell. Users are classified as satisfied if the minimum throughput is guaranteed, being unsatisfied otherwise. The variety of services offered by LTE needs to be taken into account for simulation. For example, it is possible to obtain the number of satisfied users served for a given service or user type, which are some of the parameters that are used assess performance of the six FRSs under study.

3.2 Simulator

3.2.1 Simulator Overview

The ICI simulator developed in this thesis in order to study the impact of FRS is composed of several parts, the results being the work of former students, namely by [SeCa04], [Card06], [LaCo06], [Duar08], [Salv08] and [Pire12], which in turn were adapted from an UMTS simulator made by former students. This simulator works on a snapshot basis, which is like a picture of the network in a certain time instant, recreating user’s allocation for specific conditions. The simulator main structure is presented in Figure 3.2 and consists of three modules: user generation, network deployment and LTE DL Analysis modules.

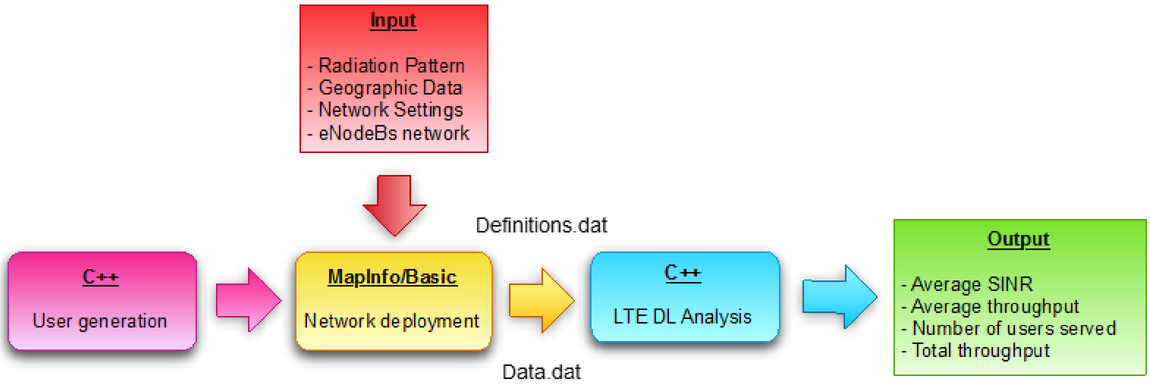


Figure 3.2 Simulator's main structure.

The users generation module is described in detail in [Lope08] and [Salv08]. A file is created as output with user information, including location and service. Note that users are randomly distributed throughout the service area and that services are randomly allocated to users, according to a service penetration percentage. The input data for the traffic distribution, the services penetration percentage and QoS priority number, needed for user's generation, are described in Section 4.1.

Regarding the network deployment module, only minor changes were done in the user interface to integrate the necessary network settings input for this thesis. When running this module, the antennas' radiation pattern and geographical data of the scenario are the first parameters loaded, followed by the user profile and network settings. Then, the users' output file generated in the user generation module and the eNodeBs from the considered network are loaded and placed in the map. Before running the LTE DL analysis module, two files are generated by the network deployment module, one containing the network settings (Definitions.dat) and the other (Data.dat) containing which are the sectors that are in the range of each user, and also the necessary information about all eNodeBs and users, such as the users and eNodeBs geographical positions, in latitude and longitude.

The main work for this thesis was the development of the LTE DL analysis module. There was an old LTE DL analysis module developed by former students, but it was decided to reformulate the whole module. Only some functions from the old module were exploited, as the one to calculate the received power per RB. Also, some old classes were implemented in the new module, having been adapted to the needs of the new module, where useless methods and variables were removed. Basically, this module is divided in four parts: read of input parameters, user allocation, interference calculation and output generation. The first part reads the two files generated by network deployment module, Definitions.dat and Data.dat. All required information is stored, including which sector and eNodeB should serve each user. When the users are registered in a sector, they are organised first by the priority of their service and then by their SNR, meaning that the first user to be served is the one with the higher priority service and higher SNR. In the user allocation part, in each sector the maximum number of users is served until there are no free RBs. If possible, users are served for their maximum throughput, unless that are no more free RBs and the user is only served if the minimum throughput for his service is guaranteed. After all possible users are served, the interference experienced by the served users is calculated. Note that the other sectors that the user is in range are considered as interfering sectors and are considered for interference calculation. For each user's RB, one calculates the interfering power coming from the interfering sectors and the neighbouring sectors to the serving eNodeB. After the interference power for each RB allocated to the user is known, SINR and real throughput is calculated for all RBs and the sum of all real throughputs gives the real user throughput. After the real throughputs for all users are obtained, the output parameters are generated, such as the average number of satisfied users and average user throughput.

3.2.2 Implementation Analysis

The LTE DL analysis module is structured as shown in Figure 3.3, and it is mainly constituted by four parts: read input parameters, user allocation, interference calculation and output generation. The user manual is presented in Annex E.

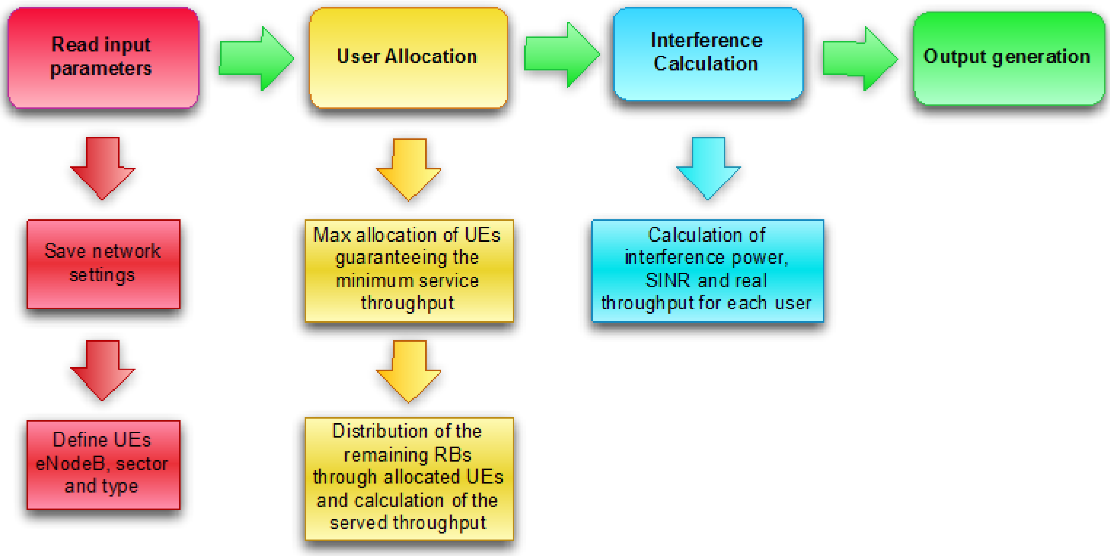


Figure 3.3 LTE DL analysis module structure.

The input parameters include the Kathrein antennas radiation pattern file, which is the one used by [Duar08] and [Jaci09], which contains the antenna gain value for each user orientation, from 0º to 359º, and is used to calculate azimuth and power received. The input files that come from MapInfo include the Definitions.dat, which contains the network settings parameters defined through the user interface in MapInfo, listed below:

- COST-231 Walfisch-Ikegami parameters (building height, street width, among others);
- User scenario (pedestrian, vehicular, indoor low-loss and indoor high-loss);
- Antenna's transmission power;
- Bandwidth;
- Frequency;
- Total number of users;
- Minimum and maximum service throughput;
- Noise factor;

- Cable losses;
- User losses;
- FRS;
- Inner region radius;
- Maximum difference between powers received in frontier region.

Note that one has considered that all eNodeBs are tri-sectorised and that the three sectors are orientated to 0º, 120º and 360º.

The MapInfo input files also include the Data.dat, which indicates which eNodeB sectors is the user in range, and contains information about eNodeB and UE longitudes, latitudes, IDs, sector orientation, user distance from eNodeB, and also the user scenario and service. With the information contained in this file, it is defined which eNodeB and sector should allocate each user; the criterion is based on the received power from each sector that the user is in range. Basically, the decision to which sector the user should be allocated is based on the highest received power. The algorithm flow chart is shown in Figure 3.4, and the possible actions that occur are summarised below:

- UE does not exist: if necessary the eNodeB and sectors are created, the UE is put in the sector's non-allocated users list and the user type is defined.
- UE already exists: the received power from the old and new sectors is compared, then, if the new sector is better, the UE is put in its list of non-allocated users, removed from the old sector's list and the user type is defined again.

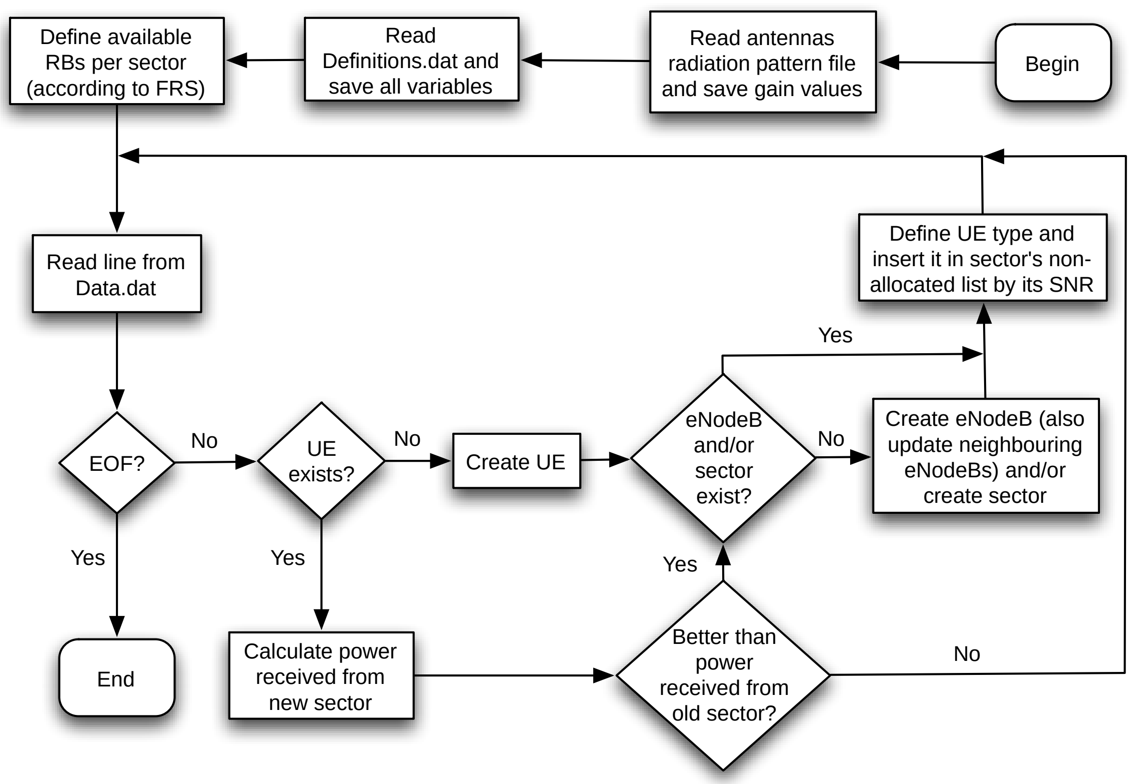


Figure 3.4 Read input parameters algorithm.

As said before, there are up to three types of users: inner, outer and frontier region ones, as shown in Figure 3.5, green, red and yellow users, respectively. Reuse-1 only considers inner region users, FFR, SFR and FSFR consider inner and outer region ones, and FSFR-F and FSFR-IF, inner, outer and frontier region ones. When defining the type of each user, if the frontier region is considered, the first verification is to check whether the UE is a frontier region user, by comparing the difference between the received power from the serving sector and the received powers from the two neighbouring sectors from the same eNodeB. If the difference between the powers received from the serving sector and one of the neighbouring sectors is below the power difference limit, then the UE is considered a frontier region user, i.e., a yellow one. If not, the distance between the UE and the serving eNodeB is checked, and if it is longer within the inner region radius limit, the UE is defined as an outer region user, i.e., a red one. Otherwise, the UE is considered an inner region user, i.e., a green one.

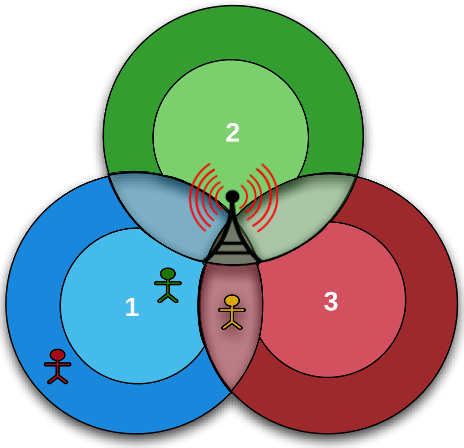


Figure 3.5 User types.

The scheduling algorithm considered for this thesis is the Proportional Fair. However, as the simulator is in a snapshot basis, meaning that it tries to recreate the network in a certain instant of time, each sector has a non-allocated user list that is in fact a priority list, where the first user is the one with the higher priority service and best SNR. This way, when a user is registered in a new sector, the user SNR for the RB with the central frequency is calculated, and he/she is registered in a specific position in the non-allocated list according to his/her SNR.

In order to calculate interference, it is necessary to know the neighbouring eNodeBs for each user. When the data.dat file is read in the read input parameters algorithm, every time a new line is read and the user is already registered in a sector, after comparing the received powers from the two sectors, the one with higher power should serve the user and the other one, with lower power, is defined as a neighbouring sector for that user.

In the user allocation part, the first user to be served is the one with the best SNR and each user is allocated only if the minimum throughput for the service is guaranteed. The user allocation algorithm flow chart is shown in Figure 3.6. The allocation starts in the first sector of the first eNodeB of the network. The first user of the non-allocated users list is picked, and RBs are given until the minimum throughput for the service is satisfied. If the minimum throughput is satisfied, the user is registered in the allocated users list, the RBs assigned are marked as occupied and the next user is picked. If not, the user remains registered in the non-allocated users list and the next user is picked. This process is repeated until there are no more users to allocate or free RBs, and subsequently, the next sector is picked and the allocation process is repeated all over again. After all sectors are analysed and all possible users allocated, the remaining free RBs in the sectors are distributed among the allocated users.

For the analysis under the scope of this thesis, 75% of the users are considered to be in NLoS with their serving eNodeB, and 90% of the users in NLoS with the neighbouring eNodeBs of their serving eNodeB.

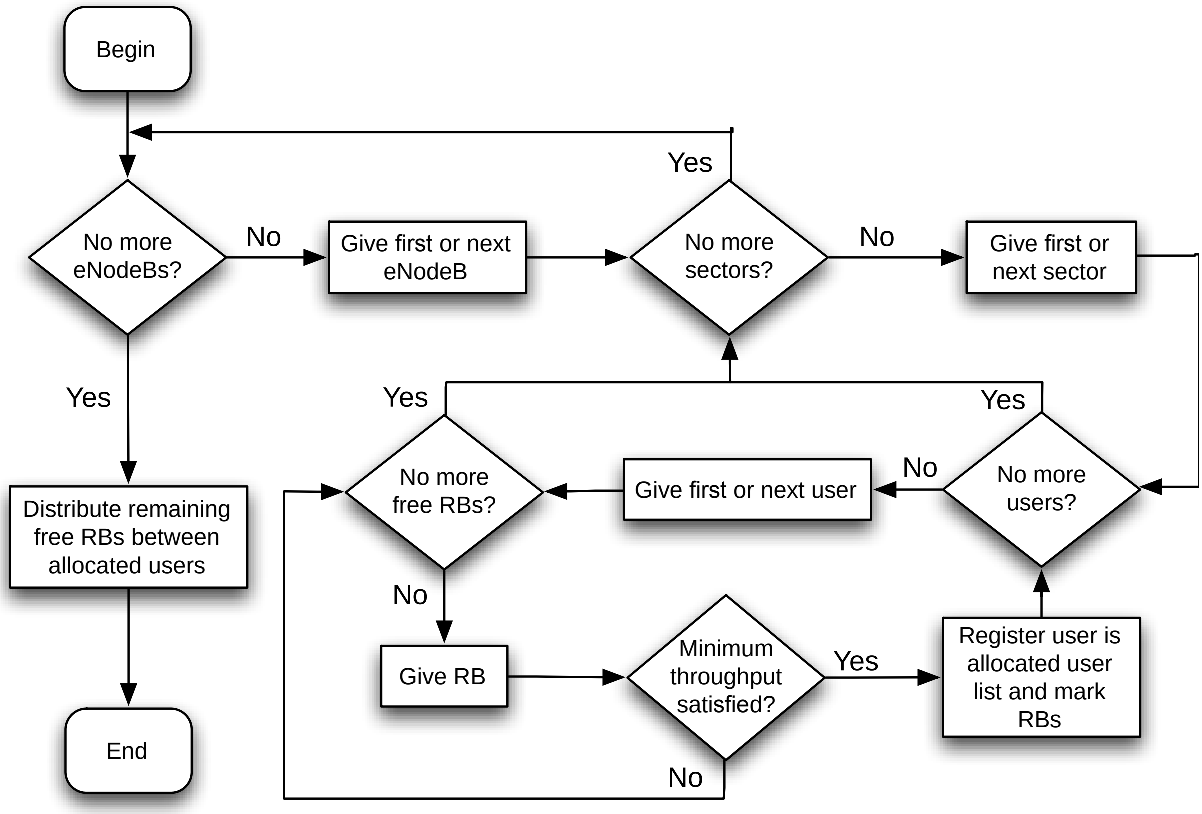


Figure 3.6 User's allocation algorithm.

After the user's allocation, the interference experienced by each user, SINR and real throughput is calculated. The interference calculation algorithm flow chart is shown in Figure 3.7. Similarly to the user allocation algorithm, the allocation starts in the first sector of the first eNodeB of the network. The first user of the allocated users list is picked up and, for each RB allocated to that user, the interfering power coming from the neighbouring eNodeBs and serving eNodeB's neighbouring sectors, SINR and real throughput are calculated. If the real throughput is below the minimum throughput defined for the user's service, the user is defined as unsatisfied. This process is repeated until all allocated users have been analysed.

After interference, SINR and real throughput are calculated for all users, the key output parameters for this thesis are calculated, i.e., average SINR per user, average throughput per sector and per eNodeB, number of satisfied and unsatisfied users, among others.

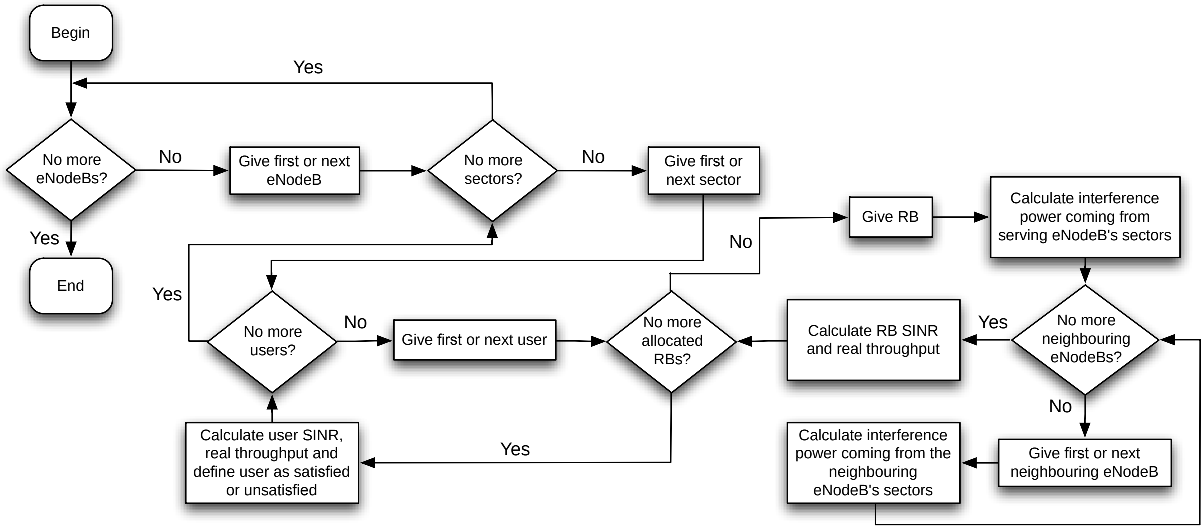


Figure 3.7 Interference calculation algorithm

3.2.3 Input, Output and Debugging Files

During the simulation, firstly, the Network Deployment module is called, with the following input parameters:

- Ant65deg.TAB: eNodeB's antennas radiation pattern;
- Dados_Lisboa.TAB: contain information regarding the city of Lisbon and its districts;
- ZONAS_Lisboa.TAB: contains area characterisation;
- users.txt: contains the user's information, as position, service, among others. This file is generated with the User Generation module;
- Vodafone Network.TAB: contains the location of the eNodeBs in the network.

The output files that come from Network Deployment module and enter as input in the LTEDL ICI Analysis module are:

- Definitions.dat: contains general information about the network, as number of users and eNodeBs, frequency, bandwidth, frequency reuse scheme, among others;
- data.dat: contains information about which eNodeBs can serve each user in the network.

When the simulation is completed, the LTEDL ICI Analysis module gives as output the file OUTPUT.txt, containing all the important output parameters considered in this thesis, as average throughput or SINR per user.

The tests and debugging performed on the simulator is addressed in the next section. The simulator developed for this thesis had to be validated, thus, the most important output variables were analysed. The output files considered for debugging are described below:

- debug_user.txt: List of non-allocated users per sector, with eNodeB, sector and user ID, and SNR for the RB with the central frequency. This file was already analysed to check the validity of the users' attribution to sectors.
- debug_n_user_type.txt, debug_n_user_service.txt: List with the number of covered, allocated,

non-allocated, satisfied and unsatisfied users per service and user type. This file was analysed to validate the user's service penetration and the user types for each frequency reuse scheme.

- debug_eNodeB_neigh.txt: List of neighbouring eNodeBs per eNodeB. This file was used to debug the neighbouring eNodeBs for each eNodeB.
- debug_N_RB.txt: List of allocated users with RBs information. This file was used to check the validity of the user's allocation and the interference calculation algorithms. It contains the information of which users are allocated in each sector, and also which RBs are allocated to each user, including the SNR, throughput served (without interference), SINR and real throughput, all per allocated RB, and also, SNR, throughput served, SINR and real throughput per user.
- debug_RB_Map.txt: List of occupied RBs per sector. This file was used to check if the frequency reuse schemes were being applied correctly, by analysing which RBs were allocated in each sector. For example, to check if the RBs reserved for each sector inner and outer region are not being incorrectly used by other sectors or to check if the reuse RBs per sector are being correctly chosen.
- debug_average_parameters.txt, debug_average_BS.txt, debug_average_sector.txt: Lists of average parameters for network, eNodeBs and sectors. These files were used to debug the interference calculation and to adjust some parameters to improve the network, as the inner region limit or power difference limit for frontier region. These files contain system average parameters, like total network throughput or average SINR per user, and most important, the number of satisfied or unsatisfied users per service and per type, with average throughput and SINR for each service and for each user type.

3.3 Simulator Assessment and Model Evaluation

Before analysing the obtained results, the simulator had to be assessed in order to guarantee the output validity, always with the necessary number of simulations that ensure statistical relevance of the results. For these purpose, some statistical parameters, as the average and standard deviation, were used to analyse the output data. The average and standard deviation for the output results were calculated by (3.4) and (3.5), respectively.

$$\mu = \frac{\sum_{i=1}^{N_Z} Z_i}{N_Z} \quad (3.4)$$

where:

- N_Z: Number of samples;
- Z_i: Value of sample i.

$$\sigma = \sqrt{\frac{1}{N_Z}\sum_{i=1}^{N_Z}(Z_i - \mu)^2} \quad (3.5)$$

During the programming phase of the C++ module, several tests and debugging were done to enssure the correct performance of the module for all implemented frequency reuse schemes. Regarding the performed tests, an extensive analysis of the output files was done for several simulations, in order to validate the output data. The debugging process was done with the Eclipse's debugger tool, and all the important variables were checked during the execution of the algorithms for each frequency reuse scheme.

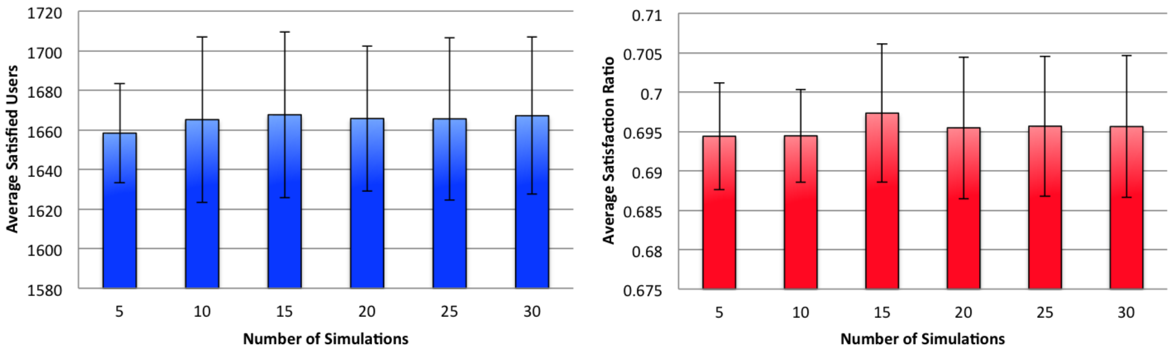
To test the LTE peak data rate for a sector with MIMO 2x2, being theoretically 150 Mbit/s, a scenario using Full Frequency Reuse with one eNodeB, one user in LoS very near to that eNodeB, without suffering any type of interference, and with 100 RBs allocated to him/her, was considered. Regarding the equations in Annex C that are used to calculate the throughput for MIMO 2x2 through SNR or SINR, the achieved peak data rate is 148.067 Mbit/s with a 64-QAM modulation, and a 3/4 coding rate, this value being very close to the theoretical peak rate.

The whole simulation time depends on the number of users and eNodeBs considered, and also on the characteristics of the computer, being a 2.5 GHz Intel Core i5 with 4GB RAM. Considering approximately 8000 users, and Lisbon's mobile network with almost 300 eNodeBs, for the C++ module, the simulation runtime can go up to 10 s. However, the MapInfo module is the one that has the biggest impact on the simulation runtime, where, considering the same scenario, the simulation runtime can take up to 1 hour.

Furthermore, to validate the models, a result analysis is required, regarding the important output parameters. The scenario uses the Vodafone mobile network in Lisbon, consisting of approximately 280 eNodeBs and 5500 covered users. The considered scheme is the Full Frequency Reuse, with 2600 MHz and 20MHz of bandwidth. It is important to refer that all frequency reuse schemes have been fully tested to guarantee their validity, several simulations were done with different scenarios and users.

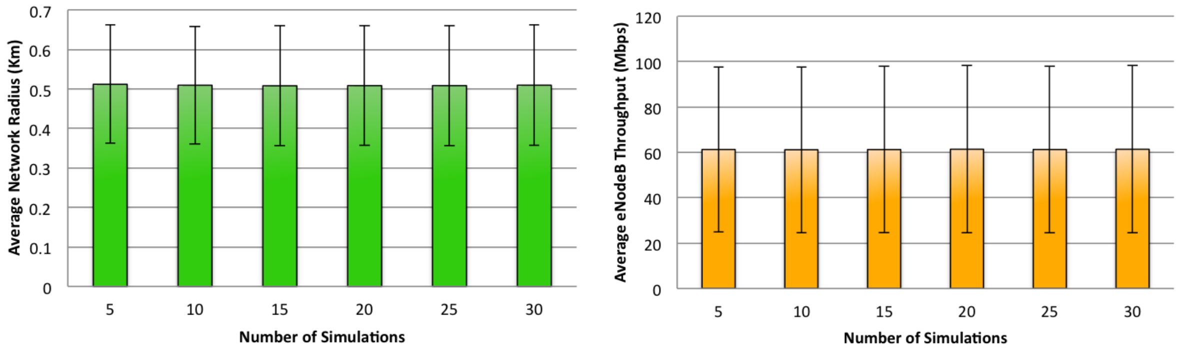
Concerning the position, LoS and service of the users vary, the output parameters may be somewhat different for each simulation made. Thus, for statistical relevance, 30 simulations were performed, with an average simulation runtime of 30 minutes. To ensure the validity of the models, the average and standard deviation for the number of satisfied users, satisfaction ratio for served users taking into account interference, throughput per eNodeB, sector and user, network radius, SNR and SINR were analysed.

Concerning the analysis of results, the number of simulations was estimated based on the results presented in Figure 3.8, Figure 3.9, Figure 3.10 and Figure 3.12 a). In Figure 3.11 and Figure 3.12 b), it is possible to examine the ratio between standard deviation and average for each one of the analysed parameters. As the variation of the users' LoS, position and service are random, and the average and standard deviation for the considered parameters with the increase in the number of simulations is minimal, the results analysis in Section 4 will be made considering 5 simulations, which last at least 30 minutes each.



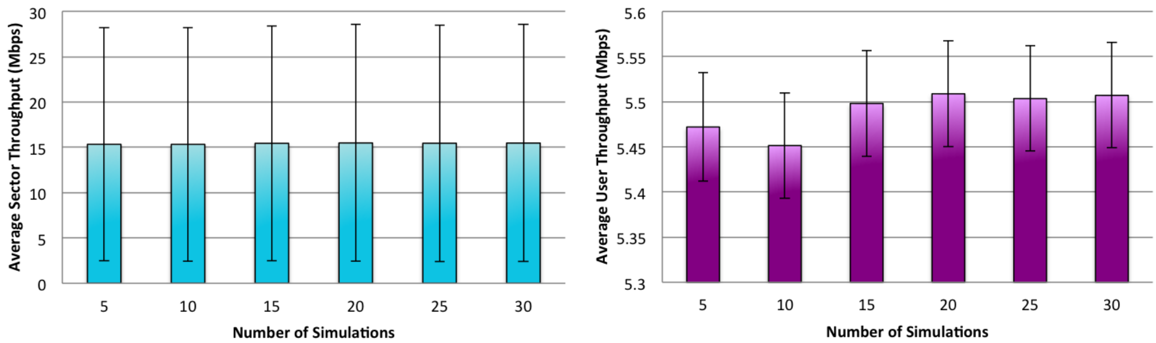
a) Satisfied Users b) Satisfaction Ratio

Figure 3.8 Evolution of the average number of satisfied users and average satisfaction ratio with the number of simulations.



a) Network Radius b) eNodeB Throughput

Figure 3.9 Evolution of the average network radius and average eNodeB throughput with the number of simulations.



a) Sector Throughput b) User Throughput

Figure 3.10 Evolution of the average sector throughput and average user throughput with the number of simulations.

From Figure 3.11, one can see that the network radius, eNodeB throughput and sector throughput have a high standard deviation over average ratio when compared to the other analysed parameters. In addition, as one can see from Figure 3.12, the standard deviation over average ratio for SNR and SINR is also high.

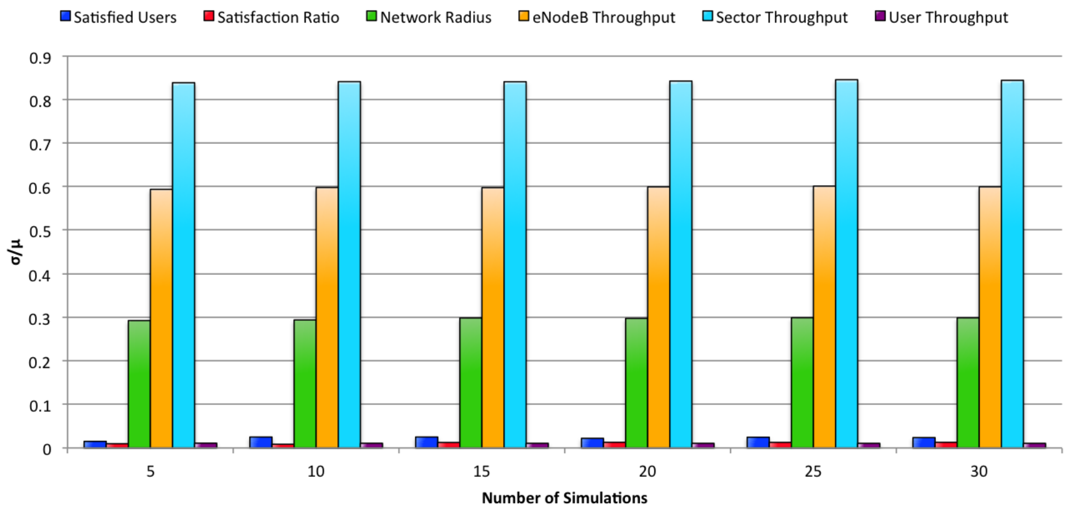
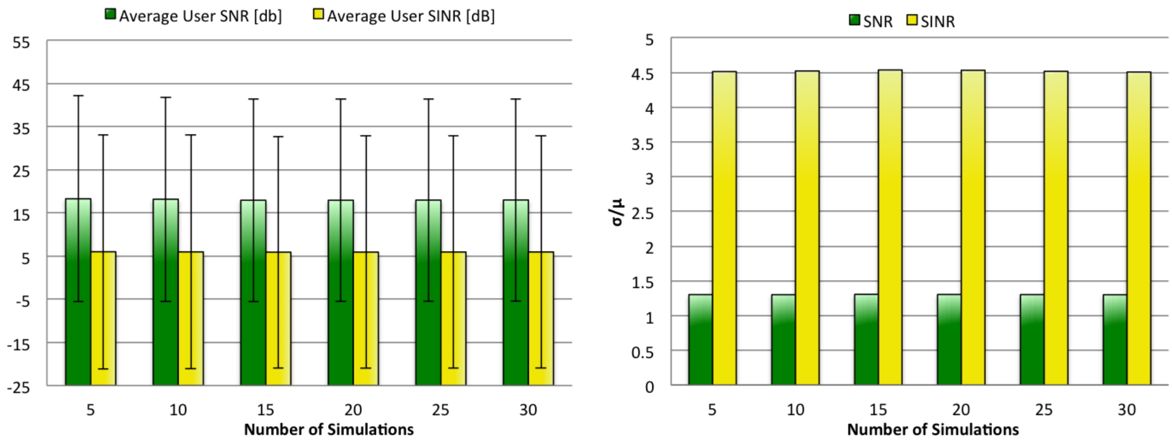


Figure 3.11 Standard deviation over average ratio with the number of simulations.



a) Average SNR and SINR

b) Standard Deviation over average ratio

Figure 3.12 Evolution of the average SNR and SINR per user and standard deviation over average ratio of SNR and SINR with the number of simulations.

Although these ratios have high values, they can be considered as normal, since these results are for a network with approximately 280 eNodeBs, considering interference, and with users being distributed over the network in one of the most populated zones of Lisbon during the day. Also, not only these parameters depend on the distance and LoS of their allocated users, but the number of users in some sectors varies drastically. Moreover, the users are allocated through a priority of services, taking into account only SNR to give the maximum throughput for their services if possible. So, when interference is considered, the real throughput and SINR for each user can be very different, explaining the high standard deviations for these parameters.

In Figure 3.13, one can observe that from approximately 5500 until 8000 covered users, the number of satisfied users does not increase much. Nevertheless, for more realistic results, it was considered that 8000 users is a good approximation for the number of users to be served by the network in Lisbon during the day.

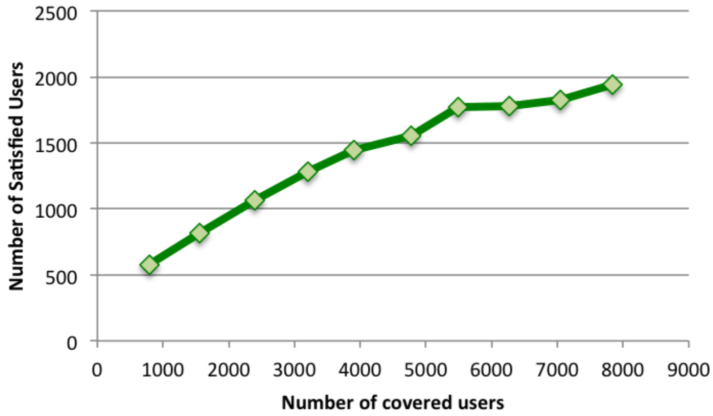


Figure 3.13 Evolution of satisfied users for different numbers of covered users.

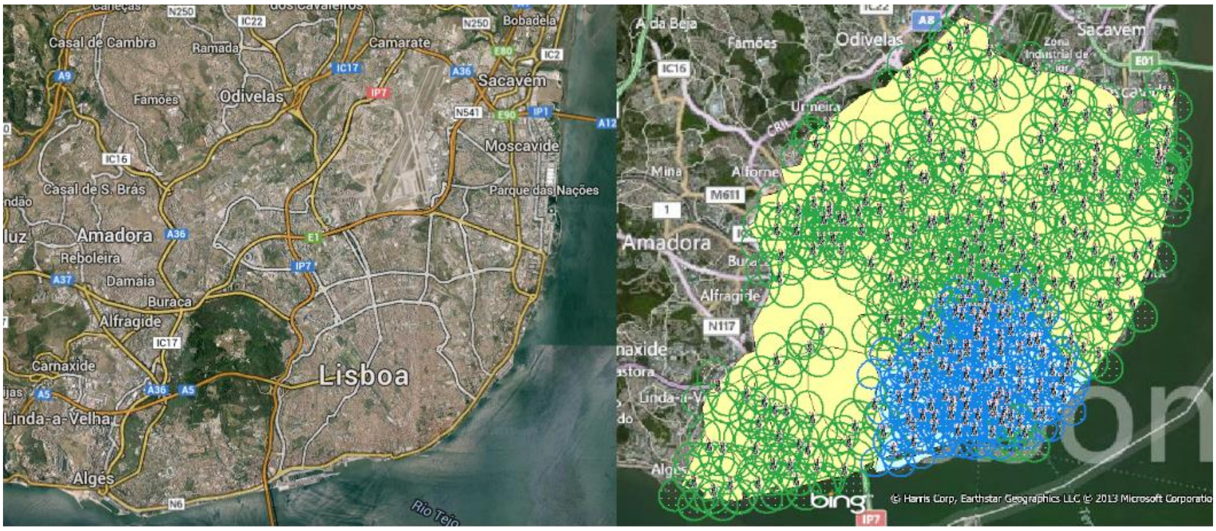
Chapter 4

Results Analysis

This chapter contains the scenarios descriptions used for high and low load simulations, and their results analysis. Firstly, a brief description of the parameters and environments used is done, and afterwards, high and low load scenarios results are presented, for the 2600, 1800 and 800 MHz bands, regarding the impact of the six FRS considered in terms of number of satisfied users, throughput and SINR.

4.1 Scenarios Description

The Vodafone network in Lisbon is considered, which is illustrated in Figure 4.1. As explained in Annex D, to obtain more realistic results, Lisbon was divided in two zones, centre and off-centre, and each region has different density and distribution of users and eNodeBs. As it can be seen in Figure 4.1 b), the yellow area is the one considered for simulation, where the blue eNodeBs are in the centre zone and the green ones in the off-centre zone.



a) Map b) Map with the network

Figure 4.1 City of Lisbon.

The propagation model considered to calculate path loss was the COST-231 Walfisch-Ikegami one, which is explained in Annex B. The parameters considered for this propagation model are shown in Table 4.1, where Dense Urban is considered for the centre zone, and Urban for the off-centre one. The density of users and eNodeBs is higher in the centre zone and lower in the off-centre one, in order to realistically recreate the network load.

Four different environments were considered by assigning additional path loss to the user in order to characterise outdoor, vehicular and indoor users: the pedestrian environment consists of a user at the street level with low attenuation margins; the vehicular one considers users performing services moving at high speed; the indoor environment has two variants and characterises users performing services inside buildings. Regarding the indoor environments, they are distinguished by the low and high losses, where the latter is used for users in deep indoor locations with higher penetration attenuation, L_{int}. Indoor environments represent around half of the overall percentage, since nowadays several users perform data services indoors, as during work time or at home. However, the number of users using data services outdoors has increased, for example, when users are walking on the street or in a public transport and need to occupy their time. The values for percentage of users, slow fading and indoor margin defined for the environments are shown in Table 4.2. The type of MT considered for the reference scenario is a smartphone.

Table 4.1 COST 231 Walfisch-Ikegami parameters

Propagation model parameter	Urban	Dense Urban
eNodeB height (h_B) [m]	26	26
Buildings height (H_B) [m]	24	24
MT height (h_m) [m]	1.70	1.70
Streets widths (w_s) [m]	35	30
Inter buildings distance (w_B) [m]	75	50
Departing angle from the closest building (Φ) [m]	90	90

Table 4.2 Slow fading, penetration margin and percentage values.

	Environment			
	Pedestrian	**Vehicular**	**Indoor Low-Loss**	**Indoor High-Loss**
Percentage [%]	30	15	20	35
M_{SF} [dB]	8.8	8.8	8.8	8.8
L_{int} [dB]	0	11	11	21

Six scenarios are considered, each one corresponding to one of the six FRS described in Subsection 3.1.1. For each FRS, the number of RBs and transmission power per RB for each region is shown in Table 4.3, for 20 MHz of bandwidth, and in Table 4.4, for 10 MHz of bandwidth. In Reuse-1 scheme, all RBs are used in each sector, due to the sectors' area not being divided in regions for this scheme. FFR and SFR divide the sector's area into two regions, inner and outer one, and the sectors of the same eNodeB do not share RBs, thus, for each sector, only 1/3 of all RBs available are available. Note that when dividing the RBs by the sectors and their respective areas, there are some remaining RBs that can be used for any region, and they are transmitted with the transmission power defined for the region where the user is located. SFR, FSFR, FSFR-F and FSFR-IF schemes apply different transmission powers to each region: a smaller transmission power per RB for the inner regions, and a bigger one for the remaining regions. FSFR, FSFR-F and FSFR-IF schemes consider the reuse of RBs for inner region, this means that the sectors from the same eNodeB share the RBs from the inner region. In FSFR-F scheme, frontier users are served with the outer region RBs. In FSFR-IF, a new region is considered, the frontier one, which will serve frontier users and has its own reserved RBs, which previously belonged to the inner region.

Table 4.3 Number of RBs reserved and transmission power per RBs for each region of a sector, for each one of the six FRS, considering 20 MHz of bandwidth.

FRS	**Inner Region**		**Outer Region**		**Frontier Region**		**Remaining RBs**	
	Number of RBs	$T_{X_{RB}}$ **[dBm]**	**Number of RBs**	$T_{X_{RB}}$ **[dBm]**	**Number of RBs**	$T_{X_{RB}}$ **[dBm]**	**Number of RBs**	$T_{X_{RB,MAX}}$ **[dBm]**
Reuse-1	100	26	-	-	-	-	-	-
FFR	22	30.68	11	30.68	-	-	1	26
SFR	22	30	11	31.76	-	-	1	31.76
FSFR	66	26.9	11	28	-	-	1	28
FSFR-F	66	26.9	11	28	-	-	1	28
FSFR-IF	42	26.9	11	27.9	7	28.8	4	28.8

Table 4.4 Number of RBs reserved and transmission power per RBs for each region of a sector, for each one of the six FRS, considering 10 MHz of bandwidth.

FRS	**Inner Region**		**Outer Region**		**Frontier Region**		**Remaining RBs**	
	Number of RBs	$T_{X_{RB}}$ **[dBm]**	**Number of RBs**	$T_{X_{RB}}$ **[dBm]**	**Number of RBs**	$T_{X_{RB}}$ **[dBm]**	**Number of RBs**	$T_{X_{RB,MAX}}$ **[dBm]**
Reuse-1	50	27.78	-	-	-	-	-	-
FFR	10	31.76	5	31.76	-	-	5	31.76
SFR	10	31.46	5	32.04	-	-	5	32.04
FSFR	30	28.45	5	29.54	-	-	5	29.54
FSFR-F	30	28.45	5	29.54	-	-	5	29.54
FSFR-IF	21	29.03	5	30	3	28.8	5	30

For the reference scenario, the Reuse-1 scheme was chosen, considering 2600 MHz and MIMO 2x2, and its parameters regarding radio interface and algorithms are specified in Table 4.5. The transmission power and bandwidth values considered are 46 dBm and 20 MHz, respectively, except when 800 MHz is being analysed, in this case the values considered being 44.77 dBm and 10 MHz of bandwidth. This scenario was chosen as a reference scenario, because it is the most similar to the current network implemented in Lisbon. Two main analyses were performed, trying to evaluate performance of the schemes by the users' and operators' perspectives. One is done with few users in the network, which better represents the current situation in the network, where the cells load is still very low. The other one is done with the network highly loaded, with much more users than the ones that can be served at an instant, where schemes take place to share the bandwidth along the users and according to QoS criteria. For low load analysis, one considered approximately 1000 covered users in the whole network, and for high load analysis, approximately 8000 users covered.

Table 4.5 Default parameters for reference scenario.

Parameters	DL Values for a 20 MHz bandwidth	DL Values for a 10 MHz bandwidth
eNodeB DL Transmission Power [dBm]	46	44.77
Frequency [MHz]	2600	
Bandwidth [MHz]	20	10
MIMO Configuration	2x2	
Modulation	QPSK, 16QAM, 64QAM	
Maximum eNodeB Antennas Gain [dBi]	17.6	
UE Antenna Gain [dBi]	0	
User Losses [dB]	1	
Cable Losses [dB]	3	
Users Noise Figure [dB]	7	
Slow Fading Margin [dB]	8.8	
FRS	Reuse-1	
Inner Region Limit [m]	300	
Max. Power Difference for Frontier Region [dB]	3	
Scheduling Algorithm	Proportional Fair	

Users are served according to their service priority and SNR, hence, the first users to be served are the ones with the higher service priority and the higher SNR. Services minimum and maximum throughputs are presented in Table 4.5, with the respective QoS priority and penetration. Users were specified as covered or served, and the served users were classified as satisfied or unsatisfied after the interference calculation. When a user is being allocated, the first step is to try to give him the maximum throughput for his service, and if that is not possible, to guarantee the minimum throughput, and for this case, the user is marked as served. The minimum throughputs defined are the ones that can guarantee a minimum QoS for each service. Regarding the maximum throughputs for each service, the maximum values could be higher, but as the maximum bandwidth is 20 MHz, which corresponds to 100 RBs, and as this particular mobile network is much influenced with interference, if higher values were chosen for maximum throughput, the number of users served would drastically drop. Although the maximum values considered try to guarantee a high QoS, for example, for streaming, 6 Mbit/s throughput is considered in order to guarantee a high QoS, i.e., to guarantee if HD streaming is possible.

Table 4.6 Smartphone services characterisation.

Service	QoS Priority	Penetration [%]	Minimum Throughput [Mbit/s]	Maximum Throughput [Mbit/s]
Streaming	1	36	1.024	6
Chat	2	5.5	0.064	0.384
Web Browsing	3	25	1.024	20
FTP	4	9.5	1.024	21.5
Email	5	6	1.024	8
P2P	6	18	1.024	5

4.2 High Load Analysis for a Bandwidth of 20 MHz

This section presents the analysis of the six FRS under study in high load conditions, considering a 20 MHz bandwidth, in the 2600 MHz and 1800 MHz bands. Note that the 2600 MHz band was chosen as reference band in all analysis performed, i.e., in high and low loads analysis. This section is divided into three sub-sections: Users, Throughput and Interference. In each sub-section the FRS are analysed and compared for the 2600 MHz and 1800 MHz bands.

4.2.1 Users

In this subsection, the six FRS are analysed and compared in terms of average number of satisfied users, average number of satisfied users per RB, and average satisfaction ratio for the 2600 MHz and 1800 MHz bands, considering a 20 MHz bandwidth.

In Figure 4.2, the average number of satisfied users, considering the 2600 MHz band is presented. One can see that the FFR and SFR serve much less satisfied users than the other 4 schemes, less than 400 satisfied users for the centre of Lisbon and more than 800 for the off-centre zone. This is due to the fact that, for FFR and SFR, each sector only uses 1/3 of the all available bandwidth, hence, the limitation of RBs in each sector may improve the SINR, although this severely affects the number of satisfied users. For the centre zone, FSFR, FSFR-F and FSFR-IF serve more users than Reuse-1, FSFR-F being the best one, with around 630 satisfied users. For the off-centre zone, Reuse-1, FSFR, FSFR-F and FSFR-IF serve a similar number of satisfied users, FSFR being the best one, serving a little more than 1200 satisfied users, and FSFR-F the worst, serving approximately 1120 ones.

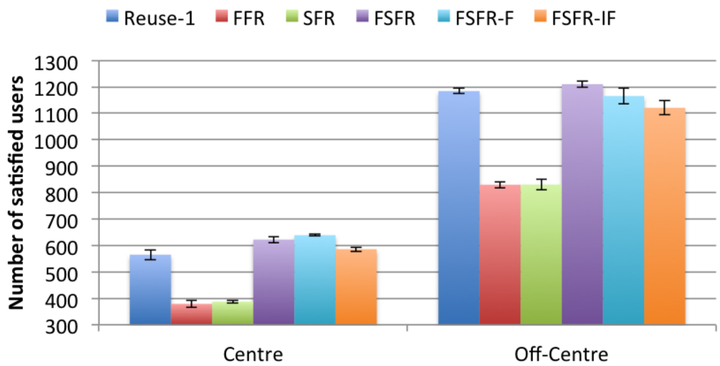


Figure 4.2 Average number of satisfied users for centre and off-centre zones, considering high load, 20 MHz bandwidth, in the 2600 MHz band.

In Figure 4.3, the average satisfied users per eNodeB for the centre and off-centre zones is shown. At first glance, the average number of satisfied users per eNodeB may seem lower than expected. Still, one has to remember that the implemented user allocation algorithm allocates users with the higher priority services first, Web Browsing being one of the services with a defined maximum throughput of 20 Mbit/s. Taking into account that the algorithm tries to allocate users for the maximum throughput of their services, giving them the amount of RBs needed, in some cases the sector resources may starve, explaining the low average number of satisfied users per eNodeB. Overall, for all FRSs the standard deviations are high, which means that there are eNodeBs with much less satisfied users per eNodeB than the average, and that at same time there are eNodeBs with much more satisfied users per eNodeB than the average, which is expected, due to the considered network.

The average user satisfaction ratio considering the 2600 MHz band is illustrated in Figure 4.4. FFR and SFR have the worst satisfaction ratio, with less than 69% of the served users satisfied. These results are also related to the limitation of RBs in each sector, because, for these two schemes, the average number of RBs per user and average user throughput are lower than for the other four schemes, as can be seen in Figure 4.5. FSFR, FSFR-F and FSFR-IF have a better satisfaction ratio than Reuse-1 for the two considered zones. FSFR-F has best average satisfaction ratio, with slightly more than 80% for the centre and 82% for the off-centre, which is 10% better for the centre and around 4% better for the off-centre, comparing to Reuse-1 scheme.

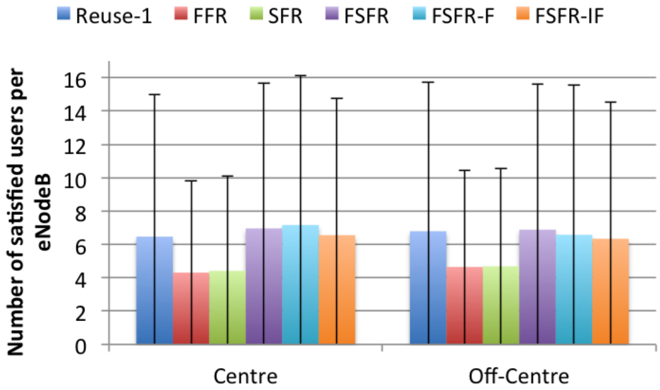


Figure 4.3 Average number of satisfied users per eNodeB for centre and off-centre zones, considering high load, 20 MHz bandwidth, in the 2600 MHz band.

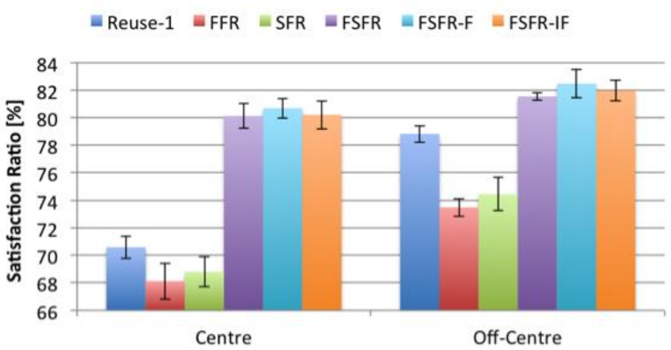


Figure 4.4 Average satisfaction ratio users for centre and off-centre zones, considering high load, 20 MHz bandwidth, in the 2600 MHz band.

The average number of satisfied users is shown in Figure 4.5, considering the 1800 MHz band. One can see that for all FRSs, the average number of satisfied users is higher than in the 2600 MHz band, as expected. As in the 2600 MHz band, the FFR and SFR schemes serve a much lower number of satisfied users than the other four schemes. For the centre zone, FSFR and FSFR-F schemes serve more satisfied users than Reuse-1 and FSFR-IF, FSFR being the one that serves more users, with approximately 680 satisfied users, and FSFR-F serves around 670 users. For the off-centre zone, Reuse-1, FSFR and FSFR-F are the schemes that serve more users, Reuse-1 being the best of these three schemes, serving around 1290 satisfied users, while FSFR and FSFR-F serve approximately 1280 ones.

The average users' satisfaction ratio considering the 1800 MHz band is illustrated in Figure 4.6; as one can see, the average satisfaction ratio for all schemes is worse than for the 2600 MHz band. Reuse-1 scheme has the worst average satisfaction ratio of all schemes, around 65% for the centre zone and 74% for the off-centre zone, followed by FFR and SFR. For the centre zone, the average satisfaction ratio for FSFR, FSFR-F and FSFR-IF schemes is approximately 9% better than in Reuse-1 scheme, where FSFR provides the best average satisfaction ratio, more than 74%. For the off-centre zone, the FSFR, FSFR-F and FSFR-IF schemes continue to have a better average satisfaction ratio than Reuse-1 scheme, but only around 5% better. The FSFR and FSFR-F schemes are the ones that present a better average satisfaction ratio for the off-centre zone, approximately 79%.

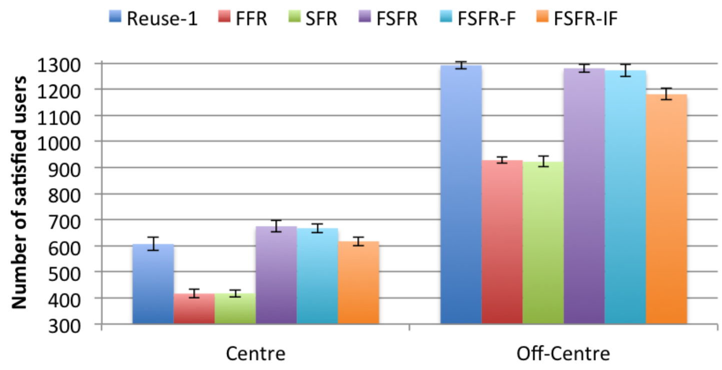


Figure 4.5 Average number of satisfied users for centre and off-centre zones, considering high load, 20 MHz bandwidth, in the 1800 MHz band.

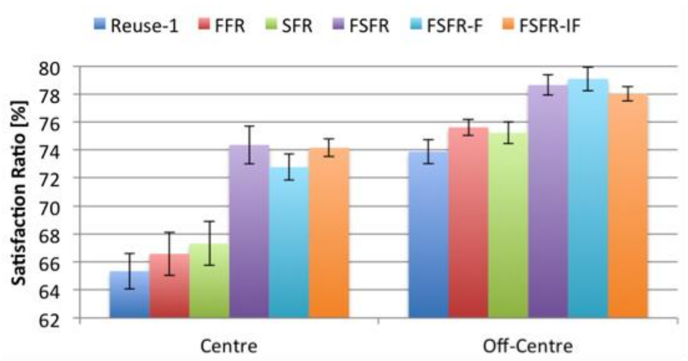


Figure 4.6 Average satisfaction ratio users for centre and off-centre zones, considering high load, 20 MHz bandwidth, in the 1800 MHz band.

4.2.2 Throughput

In this subsection the six FRS are analysed and compared in terms of average user throughput for the 2600 MHz and 1800 MHz bands, considering a 20 MHz bandwidth.

The difference between the average user throughput with no interference and with interference is analysed for the reference band. Therefore, for the 2600 MHz band, the average user throughput without taking interference into account is presented in Figure 4.7, and by taking interference into account, in Figure 4.8. From the analysis of Figure 4.7, one can see that Reuse-1 scheme presents the best average user throughput for the two considered zones, 10 Mbit/s for the centre zone and more than 8.5 Mbit/s for the off-centre one. FSFR is the second scheme with the higher average user throughput, with almost 8.5 Mbit/s for the centre zone and more than 7.5 Mbit/s for the off-centre one. In Figure 4.8, one can see that, similarly to Figure 4.7, Reuse-1 has the higher average user throughput, but as expected the average user throughput significantly drops when the inference is taken into account. For Reuse-1, the average user throughput is very similar, slightly more than 5 Mbit/s, for both centre and off-centre zones. FSFR continues to have the second higher average, which for the centre is slightly more than 4.7 Mbit/s, and than 4.9 Mbit/s for off-centre. FFR and SFR present the worst average user throughput, approximately 4.3 Mbit/s for the centre zone and between 4.4 and 4.5 Mbit/s for the off-centre one.

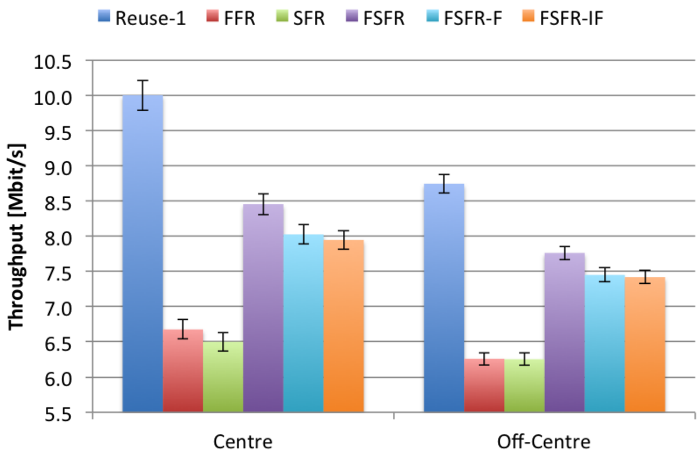


Figure 4.7 Average user throughput, not taking interference into account, considering high load, 20 MHz bandwidth, in the 2600 MHz band.

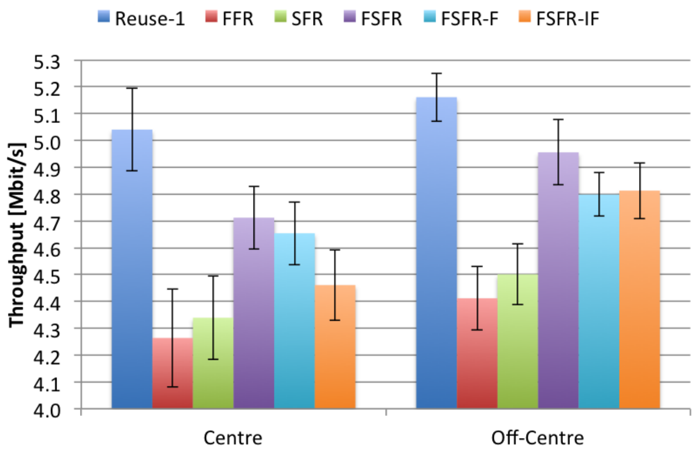
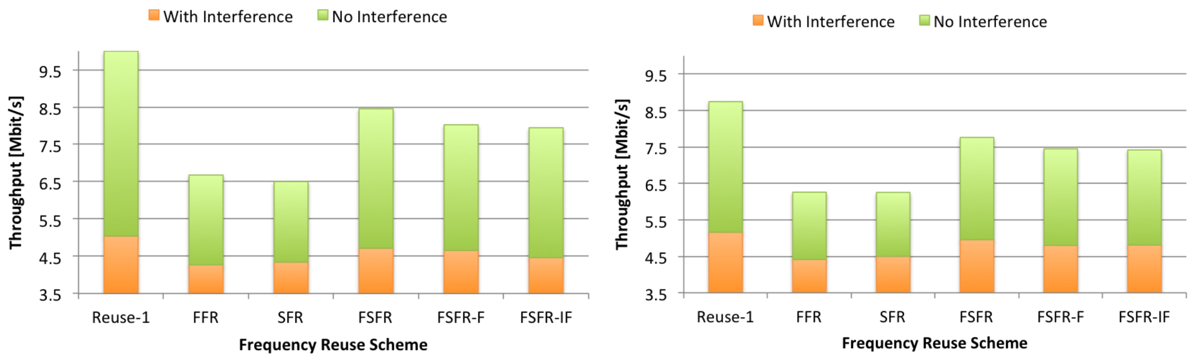


Figure 4.8 Average user throughput, taking interference into account, a considering high load, 20 MHz bandwidth, in the 2600 MHz band.

Figure 4.9 shows the degradation of the average user throughput after interference calculation considering the 2600 MHz band. As users are being firstly allocated according to their priority, and then according to SNR, no interference margin being considered, the difference shown between the average user throughput without interference and with interference was expected. In addition, the sectors azimuths are the same for all eNodeBs, meaning that all sectors 1 have the same azimuth, as well as all other sectors. This leads to an excessive overlapping of sectors, namely in the centre region, contributing to a higher interference felt by users and a higher degradation of throughput. One can see that Reuse-1 scheme has the higher degradation in the average user throughput, which causes that, in this scheme, users suffer more with interference than on other schemes. Even so, as shown in Figure 4.8, Reuse-1 is the scheme with the higher average user throughput. The FFR and SFR schemes have the smaller degradation of average user throughput, although, as seen before, they have the worst average of all FRSs. FSFR, FSFR-F and FSFR-IF have a similar degradation in average user throughput, however the FSFR scheme is the one that has the closest value to the Reuse-1 scheme, followed by FSFR-F.



a) Centre b) Off-Centre

Figure 4.9 Degradation of average user throughput when taking into account interference, considering high load, 20 MHz bandwidth, in the 2600 MHz band.

The average user throughput taking interference into account for the 1800 MHz band is presented in Figure 4.10. Reuse-1 scheme has the higher average user throughput for the centre and off-centre zones, 4.75 Mbit/s and 4.85 Mbit/s, respectively. The FSFR scheme has the second higher average user throughput, approximately 4.4 Mbit/s for the centre zone and 4.7 Mbit/s for the off-centre one, followed by FSFR-F with almost 4.4 Mbit/s for the centre zone, and more than 4.6 Mbit/s for the off-centre one. FFR and SFR have the worst average user throughput, 4.1 Mbit/s for the centre zone and 4.25 Mbit/s for the off-centre one. As expected, the average user throughput for all FRSs considering the 1800 MHz band is smaller than when considering the 2600 MHz band, which follows the behaviour of the number of satisfied users, supporting that the higher bands are better in terms of capacity and the lower ones in terms of coverage. The two better schemes, Reuse-1 and FSFR, are approximately 0.3 Mbit/s lower, for the centre zone, and 0.2 Mbit/s lower, for the off centre one, comparing with the results for the 2600 MHz band.

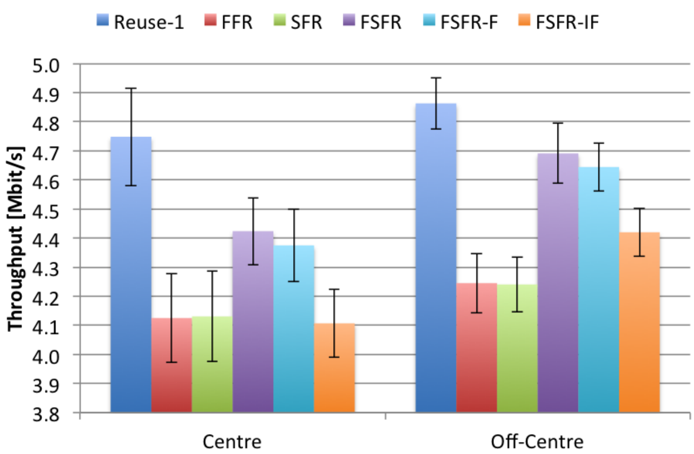


Figure 4.10 Average user throughput, taking interference into account, considering high load, 20 MHz bandwidth, in the 1800 MHz band.

4.2.3 Interference

In this subsection the six FRS are analysed and compared in terms of SINR for the 2600 MHz and

1800 MHz bands, considering a 20 MHz bandwidth.

Considering the 2600 MHz band, Figure 4.11 and Figure 4.12 illustrate average user SNR and SINR for satisfied users; however, as one can see, the standard deviations are significant. This is due to the differences among users in terms of position, distance to the eNodeB, LoS and interfering eNodeBs, leading to a high difference between users' SNR and SINR.

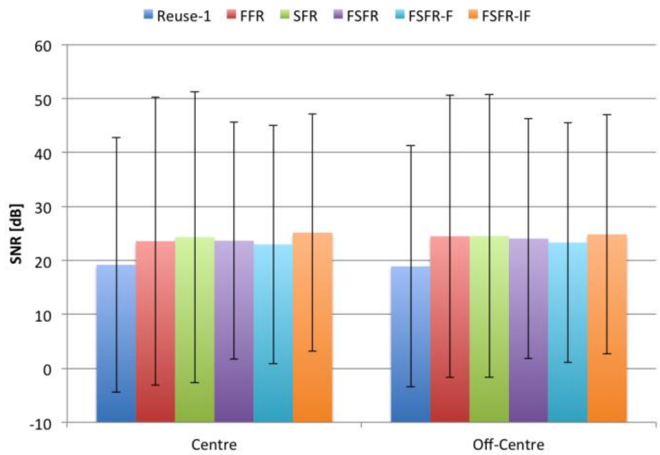


Figure 4.11 Average SNR for satisfied users, considering high load, 20 MHz bandwidth, in the 2600 MHz band.

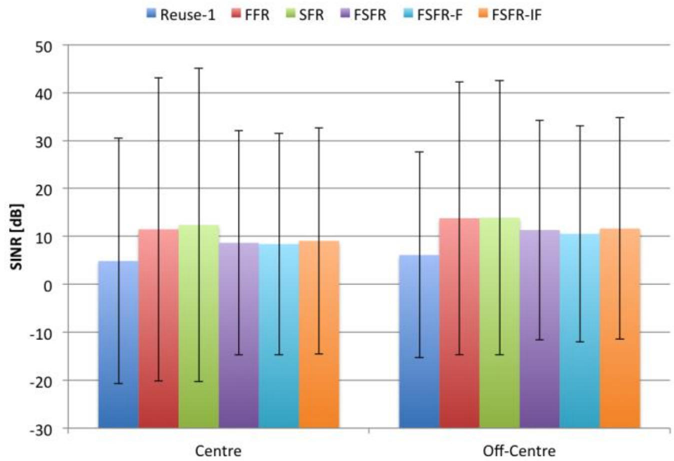


Figure 4.12 Average SINR for satisfied users, considering high load, 20 MHz bandwidth, in the 2600 MHz band.

As it is difficult to draw conclusions from Figure 4.11 and Figure 4.12 due to the high standard deviations, only the users with good channel conditions are considered, meaning users with a SINR higher than 5 dB. Note that differences between average user SNR and SINR are only analysed for the reference band (2600 MHz). Figure 4.13 presents the average user SNR for satisfied users with a SINR higher than 5 dB, for the centre and off-centre zones, where Reuse-1 scheme has the worst SNR and SFR the best. The difference between the obtained values for average user SNR for Reuse-1 and the other five schemes is due to the fact that Reuse-1 has a lower transmission power per RB than the other schemes. The FFR, FSFR, FSFR-F and FSFR-IF schemes have a similar SNR, which is around 1 dB smaller than in SFR scheme.

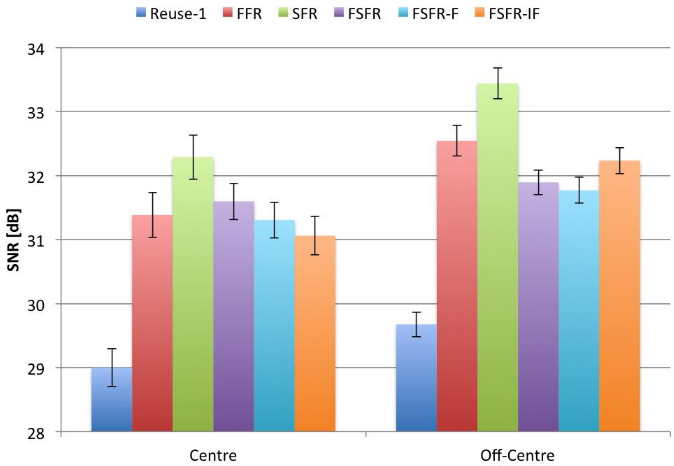


Figure 4.13 Average SNR for satisfied users with SINR higher than 5 dB, considering high load, 20 MHz bandwidth, in the 2600 MHz band.

The average user SINR for satisfied users with SINR higher than 5 dB is shown in Figure 4.14, and the difference between average user SNR and average user SINR for the six FRSs is presented in Figure 4.15. As expected, Reuse-1 has the worst average user SINR and the bigger difference between average SNR and average SINR, which is around 10 dB. SFR and FFR schemes present the best average user SINR, approximately 26 dB for the centre zone and 29 dB for the off-centre. The FSFR, FSFR-F and FSFR-IF schemes have a similar average user SINR, approximately 21 dB for centre zone and 24 dB for off-centre one, which is approximately 5 dB above Reuse-1 and 5 dB below FFR and SFR. The differences between average user SNR and average user SINR are bigger than in FFR and SFR but smaller than Reuse-1 scheme. The results presented in Figure 4.14 show that when the number of RBs available per sector is limited, and the RBs are given to each user accordingly to their type, the average user SINR increases, although, as seen in Sub-section 4.2.2, FFR and SFR have the worst average user throughput. It is true that by limiting the RBs on each sector, the interference experienced by users decreases, and that FSFR, FSFR-F and FSFR-IF have a better satisfaction ratio, serve more or almost the same satisfied users as Reuse-1, but with a cost concerning the average user throughput, around 0.3 Mbit/s less than Reuse-1 for FSFR.

The average user SINR for satisfied users with SINR higher than 5 dB for the 1800 MHz band is presented in Figure 4.16. One can see that the average user SINR for all FRS in this band is smaller than for the 2600 MHz band, which is due to the fact that lower bands enable covering more users, however with an overall interference penalisation. In the case of the 2600 MHz bandwidth, the Reuse-1 scheme presents the worst average user SINR, 16 dB for centre zone and 17 dB for off-centre one. The SFR scheme has the best average user SINR, approximately 26 dB for the centre zone and 29 dB for the off-centre. FSFR, FSFR-F, and FSFR-IF schemes have a similar average user SINR of approximately 21 dB for centre zone and 24 dB for off-centre zone. FSFR-IF scheme has a slightly better average user SINR than FSFR and FSFR-F.

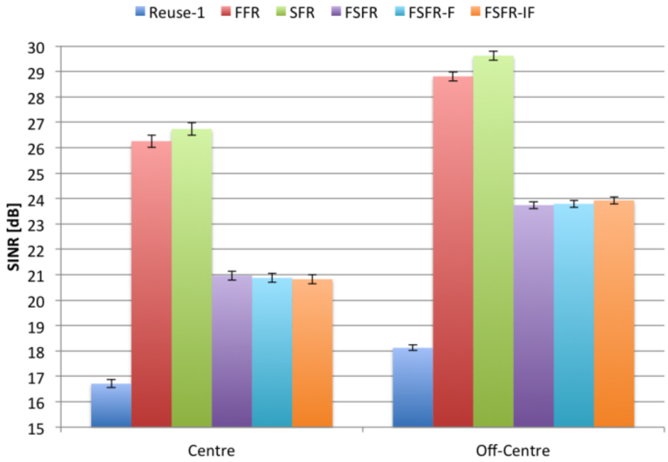
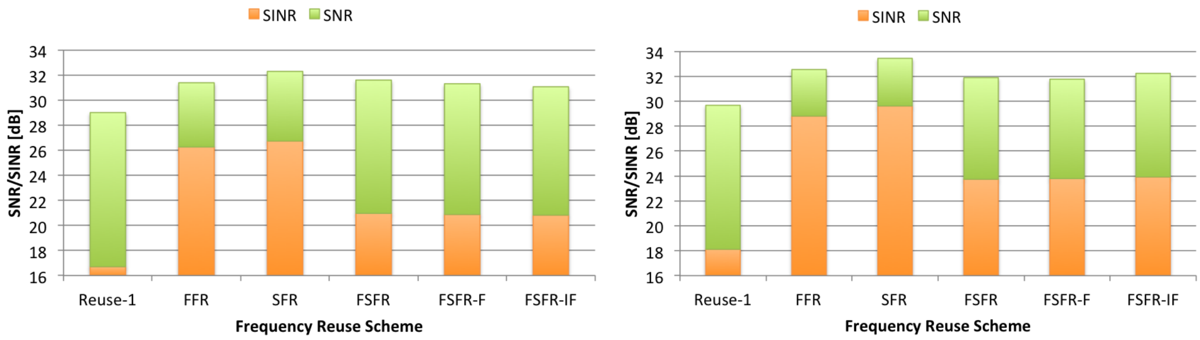


Figure 4.14 Average SINR for satisfied users with SINR higher than 5 dB, considering high load, 20 MHz bandwidth, in the 2600 MHz band.



a) Centre b) Off-Centre

Figure 4.15 Differences between SNR and SINR when taking into account interference, considering high load, 20 MHz bandwidth, in the 2600 MHz band.

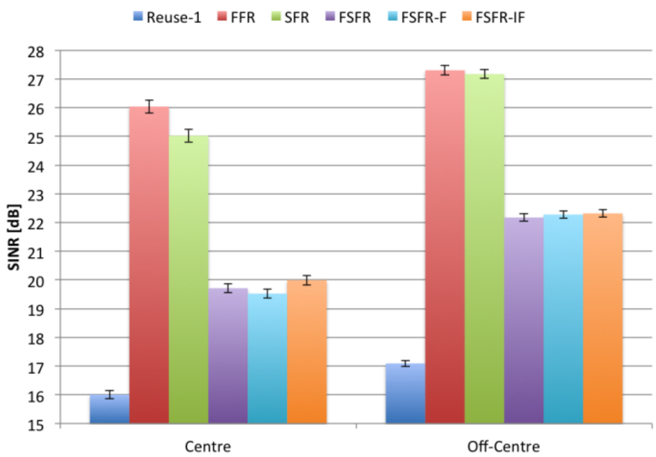


Figure 4.16 Average SINR for satisfied users with SINR higher than 5 dB, considering high load, 20 MHz bandwidth, in the 1800 MHz band.

4.3 High Load Analysis for a Bandwidth of 10 MHz

This section presents the influence of the six FRSs in high load conditions, considering the 2600 MHz and 800 MHz bands, and for a 10 MHz bandwidth. This section is divided in three sub-sections: Users, Throughput and Interference. In each sub-section the FRS are analysed and compared for the 2600 MHz and the 800 MHz bands.

4.3.1 Users

In this subsection the six FRS are analysed and compared in terms of average number of satisfied users and average satisfaction ratio for the 2600 MHz and 800 MHz bands, considering a 10 MHz bandwidth.

Regarding the 2600 MHz band, the results from Figure 4.17 show that the FFR and SFR schemes have the smaller number of satisfied users, similarly to subsection 4.2.1 where the 20 MHz bandwidth was considered. For the centre zone, FSFR and FSFR-F schemes serve about 460 satisfied users, which is slightly more than for Reuse-1. However, the FSFR-IF scheme serves significantly less satisfied users than Reuse-1. For the off-centre zone, FSFR and FSFR-F schemes serve fewer satisfied users than Reuse-1, which serves around 930 users, and FSFR-IF serves approximately less 100 satisfied users than Reuse-1. In addition, one can see that, as expected, when considering a 10 MHz bandwidth, the average number of satisfied users is much smaller than for a 20 MHz bandwidth.

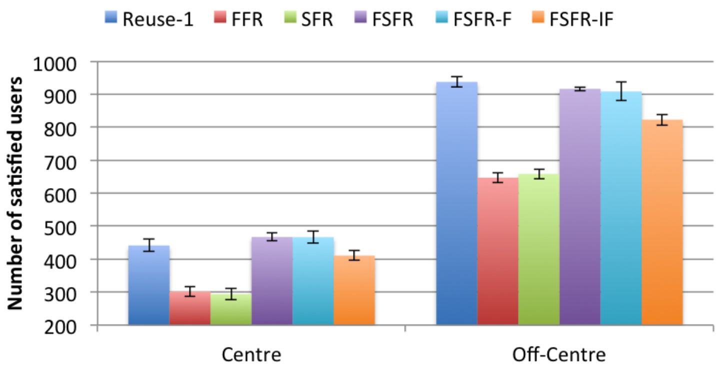


Figure 4.17 Average number of satisfied users for centre and off-centre zones, considering high load, 10 MHz bandwidth, in the 2600 MHz band.

The average number of satisfied users per eNodeB for the 2600 MHz band is presented in Figure 4.18. As explained is subsection 4.2.1, the lower average number of users per eNodeB is due to the user allocation algorithm implemented, which tries to allocate users for the maximum throughput of their service and for some cases may starve the sectors' resources. As expected, the average number of satisfied users per eNodeB is smaller when considering a 10 MHz bandwidth instead of 20 MHz.

The average users' satisfaction ratio for the six FRSs considering the 2600 MHz band is presented in Figure 4.19. For the centre zone, the SFR scheme presents the worst average satisfaction ratio, where less than 64% served users are satisfied, followed by Reuse-1 and FFR, with around 65% and

66%, respectively. For the off-centre zone, FFR scheme has the worst average satisfaction ratio, of approximately 70%, followed by FFR and Reuse-1, with around 73% and less than 72% served users satisfied, respectively. The scheme with the best average satisfaction ratio for the two zones is FSFR, with approximately 76% for centre zone and 78% for off-centre one.

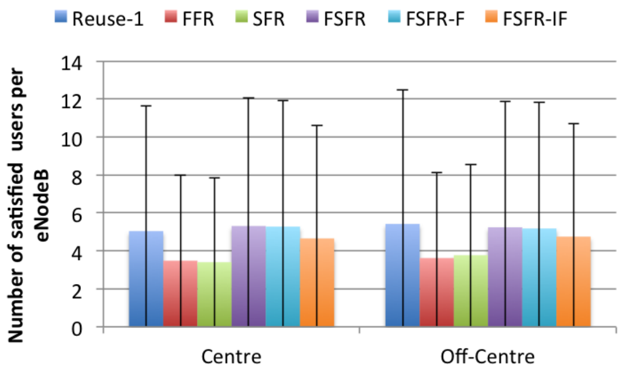


Figure 4.18 Average number of satisfied users per eNodeB for centre and off-centre zones, considering high load, 10 MHz bandwidth, in the 2600 MHz band.

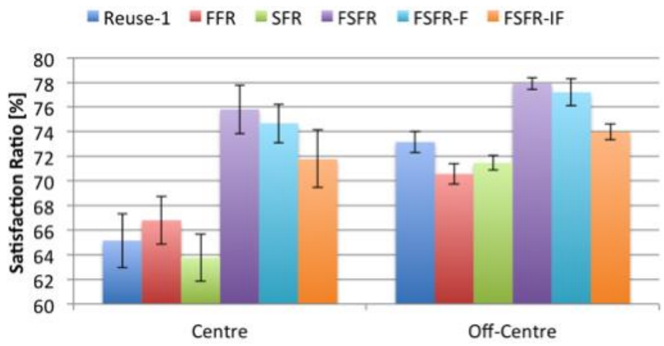


Figure 4.19 Average satisfaction ratio users for centre and off-centre zones, considering high load, 10 MHz bandwidth, in the 2600 MHz band.

This is due to the fact that, for FFR and SFR, each sector only uses 1/3 of all available bandwidth, hence, the limitation of RBs in each sector may improve the SINR, although this severely affects the number of satisfied users.

Regarding the 800 MHz band, the results presented in Figure 4.20 show that, as in the 2600 MHz band, the FFR and SFR schemes serve much less satisfied users than the other 4 schemes, around 400 satisfied users for the centre and almost 1000 for off-centre. For the centre zone, Reuse-1, FSFR and FSFR-F schemes serve almost 600 satisfied users, and FSFR-IF scheme serves approximately 500. For the off-centre zone, Reuse-1 scheme is the one that serves more satisfied users, around 1400 satisfied users, which is more 500 satisfied users in comparison with the 2600 MHz band. FSFR and FSFR-F schemes serve approximately 1200 and FSFR-IF scheme around 1100, which is more 300 satisfied users in comparison with the 2600 MHz band. As one can observe in Figure 4.20, the number of satisfied users in the six FRSs for the centre zone is significantly smaller than for the off-centre one. This is due to the high density of eNodeBs and users in the centre zone, and also due to the overlapping of sectors being much more severe in this zone.

The average users' satisfaction ratio when considering the 800 MHz band is illustrated in Figure 4.21. As in the 2600 MHz band, Reuse-1 has the worst average satisfaction ratio, with 55% for the centre zone and around 69% for the off-centre zone. For this band, the schemes that consider inner reuse, as FSFR, FSFR-F and FSFR-IF are penalised, having a lower average satisfaction ratio than FFR and SFR, which means that, although these three schemes serve more satisfied than FFR and SFR, they also serve more users that end up unsatisfied, i.e., with a throughput below the minimum throughput for their service.

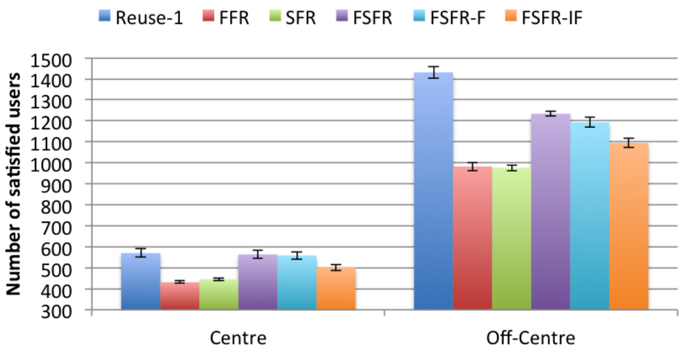


Figure 4.20 Average number of satisfied users for centre and off-centre zones, considering high load, 10 MHz bandwidth, in the 800 MHz band.

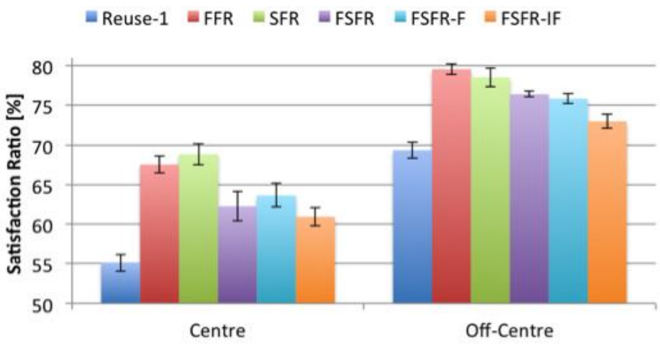


Figure 4.21 Average satisfaction ratio users for centre and off-centre zones, considering high load, 10 MHz bandwidth, in the 800 MHz band.

4.3.2 Throughput

In this subsection the six FRSs are analysed and compared in terms of average user throughput for the 2600 MHz and 800 MHz bands, considering a 10 MHz bandwidth.

As in the high load analysis for a 20 MHz bandwidth, the average user throughput for the reference band, 2600 MHz band, without taking interference into account is illustrated in Figure 4.22, and in Figure 4.23 taking into account interference. From Figure 4.23, the Reuse-1 scheme has the higher average user throughput, with almost 4.1 Mbit/s for the centre zone and 4.3 Mbit/s for the off-centre one. The FSFR scheme has the second higher average user throughput, with more than 3.9 Mbit/s for the centre zone and more than 4.2 Mbit/s for the off-centre one. When considering a 10 MHz bandwidth, the FSFR scheme has a smaller difference to Reuse-1 scheme in terms of average user throughput, having a difference of approximately 0.1 Mbit/s for the centre zone and of approximately 50 kbit/s for off-centre. As expected, the average user throughput is smaller when considering a 10 MHz bandwidth.

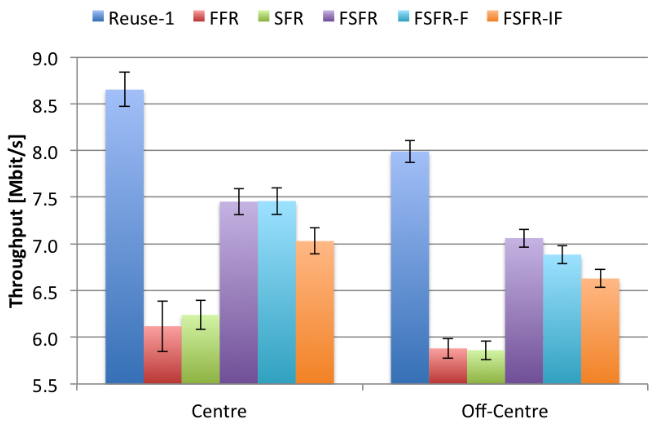


Figure 4.22 Average user throughput, not taking interference into account, considering high load, 10 MHz bandwidth, in the 2600 MHz band.

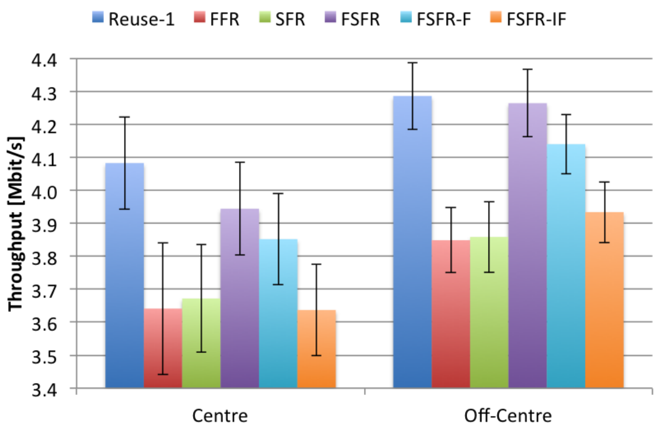


Figure 4.23 Average user throughput, taking interference into account, considering high load, 10 MHz bandwidth, in the 2600 MHz band.

In Figure 4.24, the degradation of the user throughput with interference is presented. The Reuse-1 scheme is the one where the average user throughput is worst, even so, it is also the one with the higher user throughput. The FFR and SFR schemes have the smaller degradation of users' throughput, although they have the worst average user throughput of all FRS. FSFR, FSFR-F and FSFR-IF schemes have a similar degradation in terms of average user throughput. However, the FSFR scheme is the one that has the closest average user throughput to the Reuse-1 scheme.

In Figure 4.25, the average user throughput taking interference into account for the 800 MHz band is presented. The Reuse-1 scheme has the higher average user throughput, more than 3.5 Mbit/s for the centre zone and more than 3.9 Mbit/s for the off-centre one. Although, for the centre zone, the SFR scheme has almost the same average user throughput as Reuse-1 scheme, the FFR scheme has a slightly lower and FSFR has a 0.1 Mbit/s lower average user throughput. For the off-centre zone, the FSFR and FSFR-IF schemes are the ones with the second best average user throughput, however they have an average user throughput more than 0.1 Mbit/s lower than Reuse-1. One can see that the scheme with the best average user throughput, Reuse-1, for the 800 MHz band has a lower average user throughput than for the 2600 MHz band, with less 0.5 Mbit/s for the centre zone and approximately less 0.35 Mbit/s for the off-centre one, which was expected, as the higher bands offers a better capacity.

a) Centre b) Off-Centre

Figure 4.24 Degradation of average user throughput when taking into account interference, considering high load, 10 MHz bandwidth, in the 2600 MHz band.

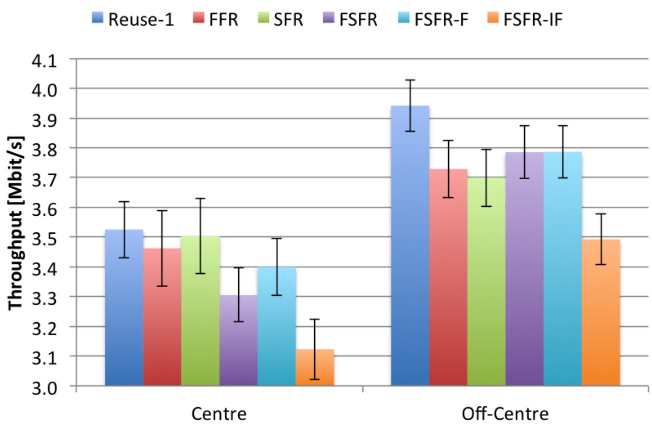


Figure 4.25 Average user throughput, taking interference into account, considering high load, 10 MHz bandwidth, in the 800 MHz band.

4.3.3 Interference

In this subsection the six FRSs are analysed and compared in terms of SINR for the 2600 MHz and 800 MHz bands, considering a 10 MHz bandwidth.

Considering the reference band, 2600 MHz band, in Figure 4.26 and Figure 4.27, average SNR and SINR for satisfied users, respectively, are presented. As argued before when considering a 20 MHz bandwidth, it is difficult to take conclusions from Figure 4.26 and Figure 4.27 due to the high standard deviations, and so it was decided to consider only the users with a SINR higher than 5 dB, i.e., good channel conditions.

Figure 4.28 presents the average user SNR for satisfied users with a SINR higher than 5 dB, for the centre and off-centre zones, where the Reuse-1 scheme has the worst SNR. The difference between values of average user SNR for the Reuse-1 scheme and of the other schemes is again due to the transmission power per RB being lower in Reuse-1 than in the other schemes. For the centre zone, SFR is the scheme that presents the better average user SNR, followed by FSFR-IF. For the off-centre zone, FFR and SFR schemes have the better average user SNR, followed by FSFR, FSFR-F and FSFR-IF, which have similar average user SNR.

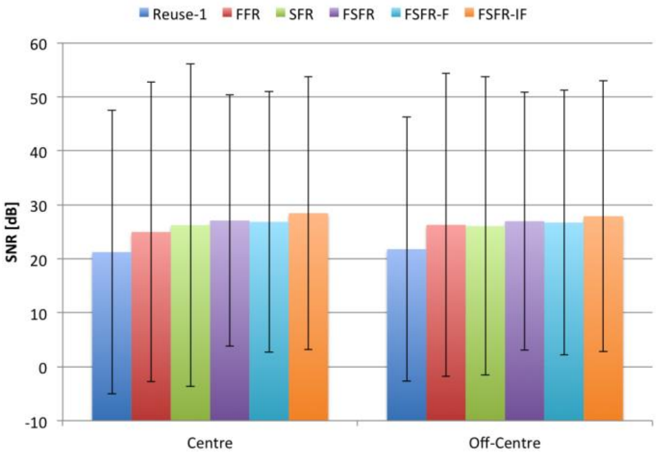


Figure 4.26 Average SNR for satisfied users, considering high load, 10 MHz bandwidth, in the 2600 MHz band.

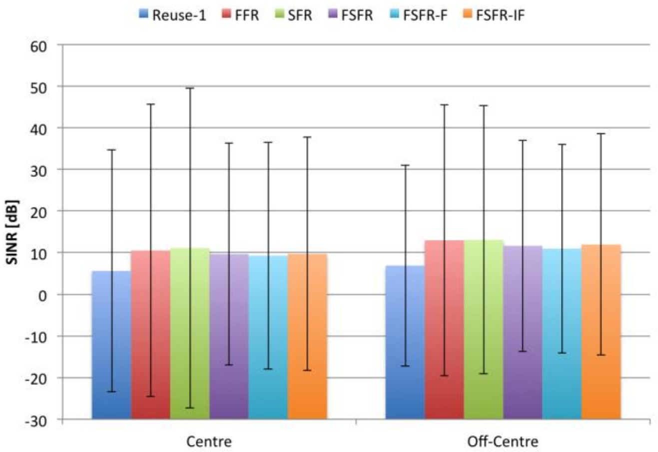


Figure 4.27 Average SINR for satisfied users, considering high load, 10 MHz bandwidth, in the 2600 MHz band.

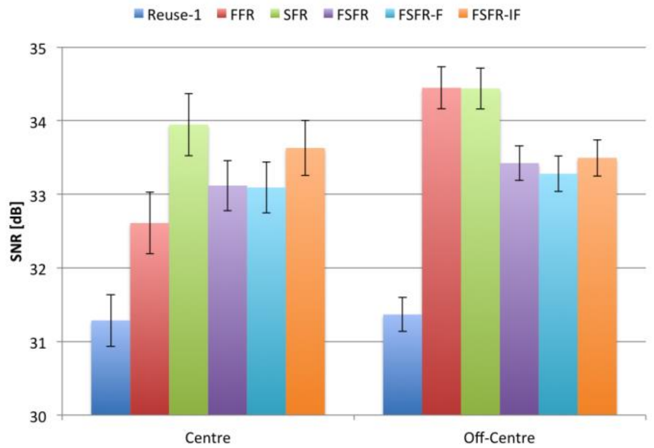


Figure 4.28 Average SNR for satisfied users with SINR higher than 5 dB, considering high load, 10 MHz bandwidth, in the 2600 MHz band.

The average user SINR for satisfied users with SINR superior to 5 dB is shown in Figure 4.29, and the difference between average user SNR and average user SINR for the six FRSs is presented in Figure 4.30. As expected, the Reuse-1 scheme has the worst average user SINR and the bigger difference between average user SNR and average user SINR, which is around 14 dB. SFR and FFR schemes present the best average user SINR, being SFR the better scheme for the centre zone of Lisbon, with approximately 26 dB, and FFR for the off-centre, with approximately 29 dB. The FSFR, FSFR-F and FSFR-IF schemes have a similar average user SINR, approximately 21 dB for centre zone and 24 dB for off-centre zone, and the differences between average user SNR and average user SINR are bigger than FFR and SFR schemes but smaller than Reuse-1 scheme. Although FSFR, FSFR-F and FSFR-IF schemes have a worst average user SINR, they serve more satisfied users and have a bigger average user throughput than FFR and SFR schemes. These schemes also have a 5 dB higher SINR comparing to Reuse-1.

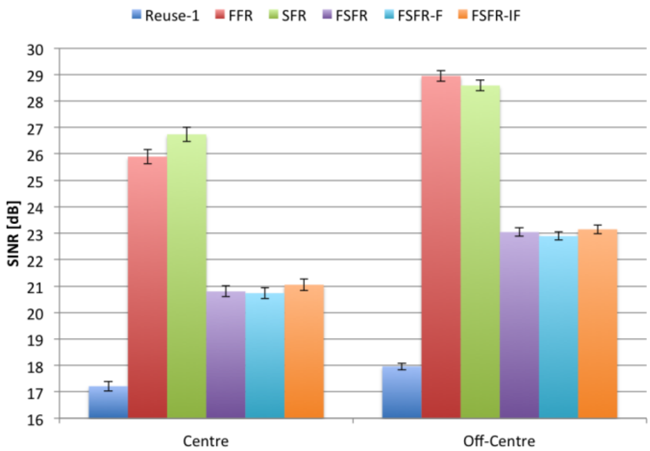
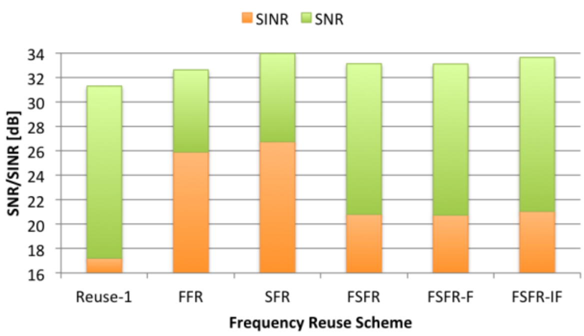
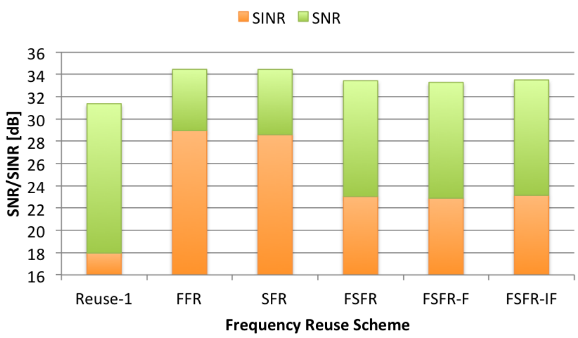


Figure 4.29 Average SINR for satisfied users with SINR higher than 5 dB, considering high load, 10 MHz bandwidth, in the 2600 MHz band.



a) Centre



b) Off-Centre

Figure 4.30 Differences between SNR and SINR when taking into account interference, considering high load, 10 MHz bandwidth, in the 2600 MHz band.

The average user SINR for satisfied users with SINR higher than 5 dB in the 800 MHz band is presented in Figure 4.31. As expected, the average user SINR for the six schemes is worse than when considering the 2600 MHz band. Reuse-1 scheme has the worst average user SINR, approximately 16 dB for centre and off-centre zones of Lisbon, which is around 2 dB worse than when considering the 2600 MHz band. SFR and FFR schemes have best average user SINR, approximately 26 dB for the both zones, where the SFR scheme has a slightly better average user SINR for the centre zone. As in the 2600 MHz band, the FSFR, FSFR-F and FSFR-IF schemes have a similar average user SINR, approximately 19 dB for centre zone and 21 dB for off-centre one, FSFR-F being scheme the best one from these three. In the overall, the three schemes that consider inner reuse, FSFR, FSFR-F and FSFR-IF, give a better satisfaction ratio and SINR, they serve almost the same number of satisfied users as Reuse-1, except in off-centre zone when considering the 800 MHz band. However the average throughput per user suffers a penalty comparing to Reuse-1, for the best scheme, FSFR, the average throughput per user suffers a penalty between 0.1 and 0.2 Mbit/s. The 800 MHz band serves a higher number of users, approximately more 100 satisfied users for centre-zone and 400 for the off-centre one. However, the average user SINR decreases and the average user throughput suffers a severe penalty.

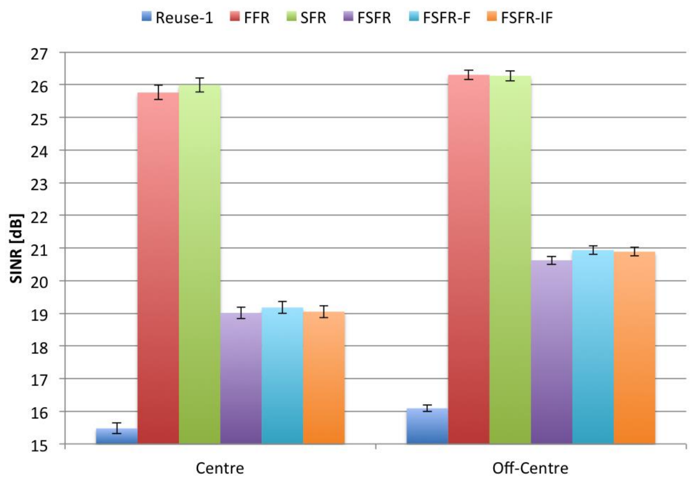


Figure 4.31 Average SINR for satisfied users with SINR high than 5 dB, considering high load, 10 MHz bandwidth, in the 800 MHz band.

4.4 Low Load Analysis for a Bandwidth of 20 MHz

This section presents the effects of the six FRSs in low load conditions, considering a 20 MHz bandwidth and 2600 MHz and 1800 MHz bands. Note that the 2600 MHz band is the reference band. This section is divided in three sub-sections: Users, Throughput and Interference. In each sub-section the FRS are analysed and compared for the 2600 MHz and the 1800 MHz bands.

4.4.1 Users

For the 2600 MHz band, the results from Figure 4.32 show that, for the centre zone the six schemes serve a similar number of satisfied users, which is expected due to the low load of the network. FFR is the scheme that has the higher average satisfied users, serving more than 160 satisfied users, and FSFR-IF the worst, serving less than 150 satisfied users. For the off-centre zone, Reuse-1, FFR and SFR serve approximately 275 satisfied users and FSFR, FSFR-F and FSFR-IF serve less than 250 satisfied users.

In Figure 4.33 the average satisfaction ratio for the 2600 MHz band is shown, where in high load, FSFR, FSFR-F and FSFR-IF present the better satisfaction ratio of approximately 90%. On the one hand, FSFR scheme is the one with the best average satisfaction ratio of 90% for the centre zone. On the other hand, Reuse-1 scheme has a 74% average satisfaction ratio. For the off-centre zone, the scheme with the best average satisfaction ratio is FSFR-F, with approximately 90%, being the Reuse-1 scheme satisfaction ratio around 83%.

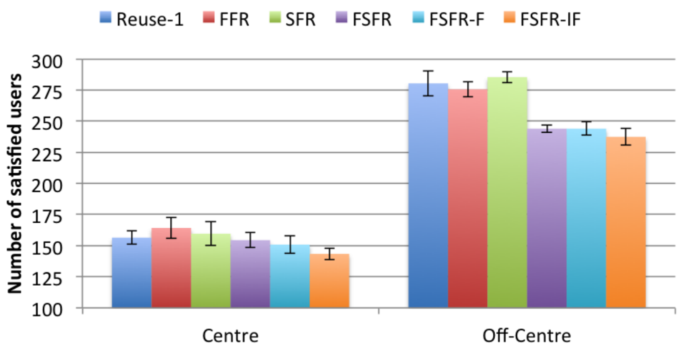


Figure 4.32 Average number of satisfied users for centre and off-centre zones, considering low load, 20 MHz bandwidth, in the 2600 MHz band.

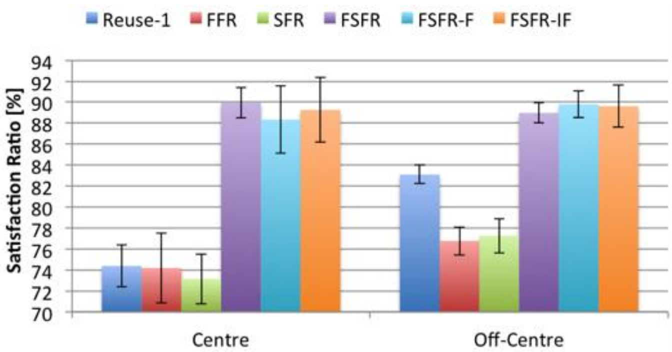


Figure 4.33 Average satisfaction ratio users for centre and off-centre zones, considering low load, 20 MHz bandwidth, in the 2600 MHz band.

Regarding the 1800 MHz band, the results presented in Figure 4.34 show that the number of satisfied users does not vary much between FRSs, although a higher number of satisfied users is served compared to 2600 MHz band, around 50 users more for the centre zone and 75 for the off-centre one. The Reuse-1 scheme is the one that serves the bigger number of satisfied users for the centre and off-centre zones, more than 200 satisfied users for the centre zone and more than 350 for the off-centre one. In detail, for the centre zone, FFR, SFR, FSFR and FSFR-F serve almost the same satisfied users, slightly less than 200 satisfied users, and FSFR-IF is the one that serves less. For the off-centre zone, the difference between Reuse-1, FFR and SFR schemes and FSFR, FSFR-F and FSFR-IF scheme is more visible, where the first ones serve around 350 satisfied users and the second ones serve between 300 and 350 satisfied users.

Regarding the 1800 MHz band, the average users satisfaction ratio for the six FRSs is shown in Figure 4.35, and in the overall is worse than for the 2600 MHz band. For the centre and off-centre zones, the FFR scheme has the worst average satisfaction ratio of all schemes, 76% for the centre zone and approximately 81% for the off-centre one. For the centre zone, the scheme that has the best average satisfaction ratio is FSFR-F, with 81%, followed by FSFR, with 80%. For the off-centre zone, FSFR-IF scheme as the best average satisfaction ratio, more than 84%, followed by Reuse-1 with almost 84%.

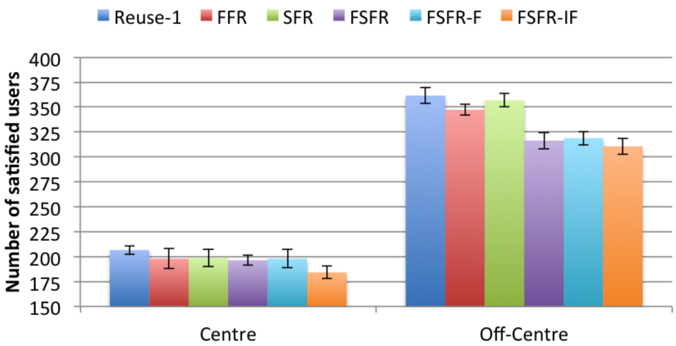


Figure 4.34 Average number of satisfied users for centre and off-centre zones, considering low load, 20 MHz bandwidth, in the 1800 MHz band.

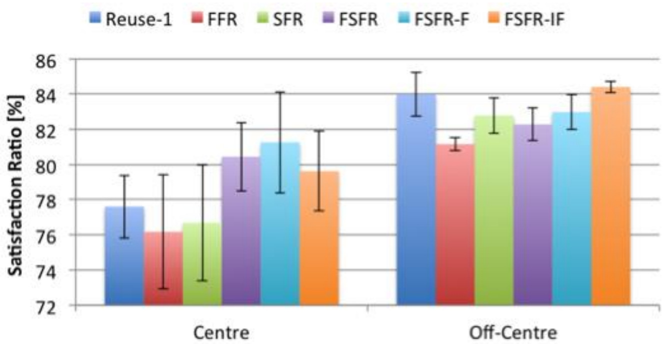


Figure 4.35 Average satisfaction ratio users for centre and off-centre zones, considering low load, 20 MHz bandwidth, in the 1800 MHz band.

4.4.2 Throughput

Regarding 2600 MHz band, the average user throughput without taking interference into account is shown in Figure 4.36, and in Figure 4.37 taking into account interference. From Figure 4.37, one can see that Reuse-1 scheme has the higher average user throughput, approximately 6.8 Mbit/s for centre zone and more than 7.2 Mbit/s for off-centre one. FSFR scheme has the second higher average, which for the centre zone is almost 6.4 Mbit/s and for the off-centre one is more than 6.4 Mbit/s, both have less 400 Kbit/s than Reuse-1 scheme. As expected, the average user throughput is higher when the network is in low load.

Considering the 2600 MHz band, in Figure 4.38 the degradation of the average user throughput after interference calculation is shown. One can see that the Reuse-1 scheme is the one where the average user throughput is more degraded, even so, as said before, it is the one with the higher average. SFR has the smaller degradation of average user throughput, although it has the worst average of all FRSs. FFR, FSFR, FSFR-F and FSFR-IF schemes have a similar degradation in average user throughput, FSFR being the one that has the closest average to the Reuse-1 scheme. Note that the degradation is less severe when the network is in low load, which is related to an increase in the average user SINR, as seen in Subsection 4.4.3.

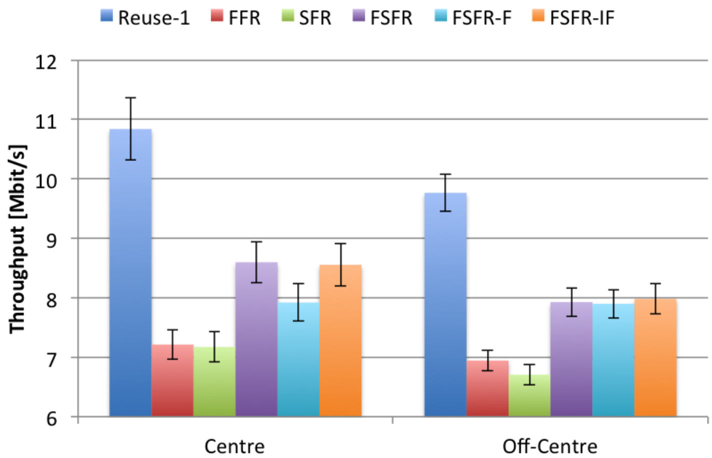


Figure 4.36 Average user throughput, not taking interference into account, considering low load, 20 MHz bandwidth, in the 2600 MHz band.

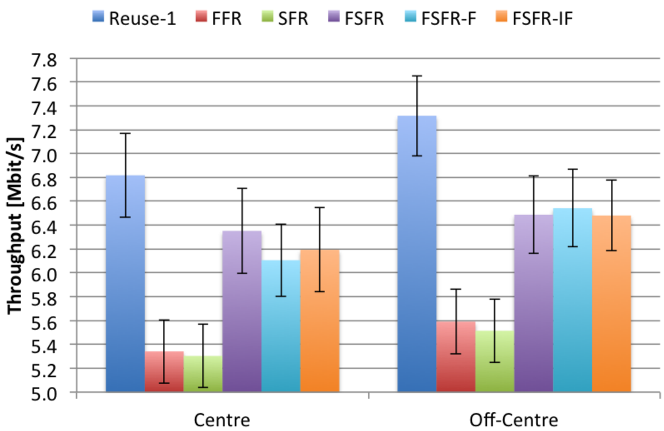
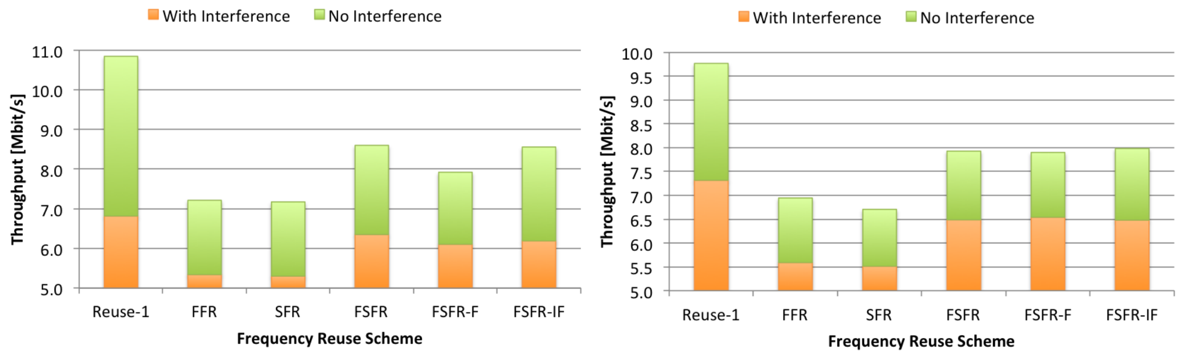


Figure 4.37 Average user throughput, taking interference into account, considering low load, 20 MHz bandwidth, in the 2600 MHz band.

In Figure 4.39 the average user throughput taking interference into account, for the 1800 MHz band, is presented. As expected, Reuse-1 scheme has the higher average user throughput for the centre and off-centre zones, approximately 7.25 Mbit/s and almost 7.5 Mbit/s, respectively. FSFR scheme has the second higher average user throughput, which for the centre zone is approximately 6.2 Mbit/s and for the off-centre zone is almost 6.5 Mbit/s. Note that the FSFR-F scheme presents an average user throughput very similar to FSFR scheme. As in 2600 MHz, FFR and SFR have the worst average user throughput, 5 Mbit/s for the centre zone and around 5.5 Mbit/s for the off-centre zone. When the network is in low load, the 1800 MHz band not only serves more satisfied users as also guarantees an higher average user throughput than 2600 MHz band, which is explained with the fact of interference being less severe that when a high load of the network is considered.



a) Centre b) Off-Centre

Figure 4.38 Degradation of average user throughput when taking into account interference, considering low load, 20 MHz bandwidth, in the 2600 MHz band.

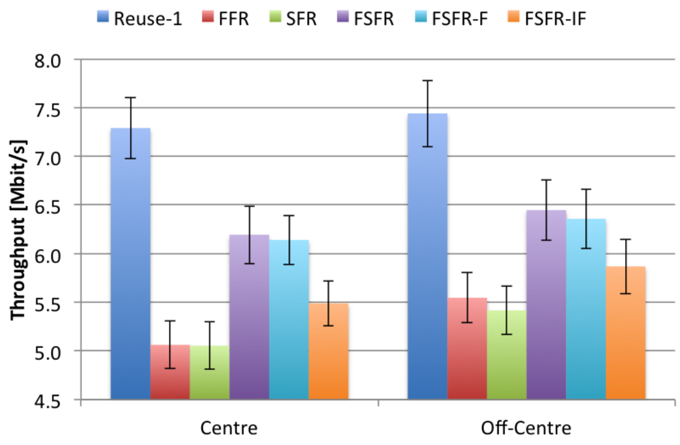


Figure 4.39 Average user throughput, taking interference into account, considering low load, 20 MHz bandwidth, in the 1800 MHz band.

4.4.3 Interference

Considering the 2600 MHz band, Figure 4.40 presents the average user SNR for satisfied users with a SINR higher than 5 dB, for the centre and off-centre zones, where Reuse-1 scheme has the worst SNR and FSFR-IF the best. For the centre zone, SFR and FFR have a worst SNR than the other four schemes, probably due to the limitation of RBs per sector. FSFR and FSFR-IF have the best SNR, followed by Reuse-1. For the off-centre zone, the SNR is very similar for the six FRS.

The average user SINR for satisfied users with SINR higher than 5 dB is shown in Figure 4.41, and the difference between average user SNR and average user SINR for the six FRS is presented in Figure 4.42. For the centre zone, FSFR presents the best SINR, almost 29 dB, and for the off-centre zone the SFR scheme presents the best average user SINR of almost 31 dB. The Reuse-1 scheme has the worst average user SINR, less than 21 dB for centre zone and less than 23 dB for the off-centre zone, and it has the bigger difference between average SNR and average SINR, which is more than 10 dB. As expected, in the overall the average user SINR improved in comparison with the network in high load conditions. One can see that when the network is in low load, the average user

SINR for FSFR, FSFR-F and FSFR-IF schemes has a significantly improvement, being for centre zone even better than FFR and SFR. The difference between average user SNR and SINR for these three schemes is much smaller than when a high load of the network is considered.

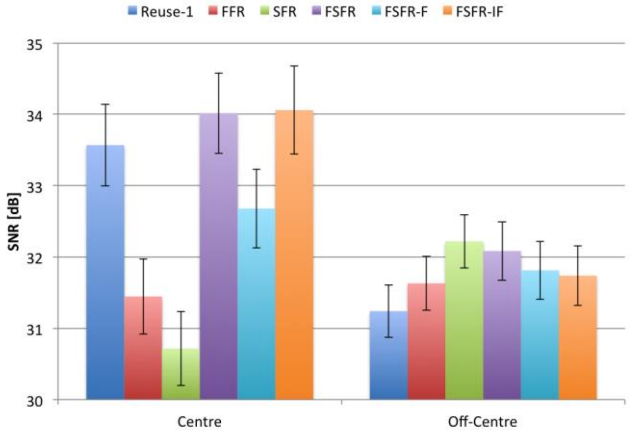


Figure 4.40 Average SNR for satisfied users with SINR higher than 5 dB, considering 20 MHz bandwidth, in the 2600 MHz band.

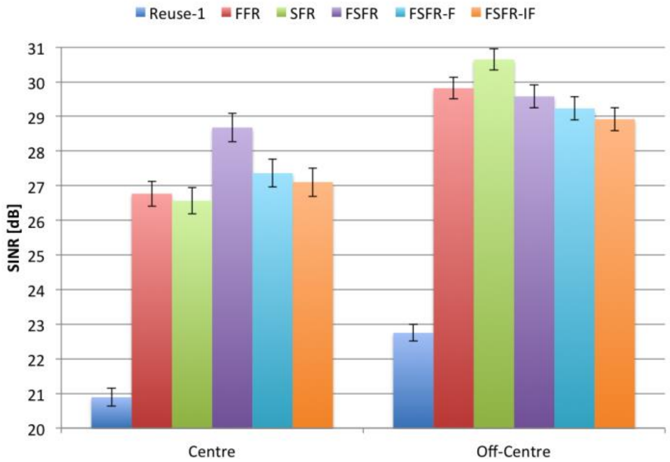
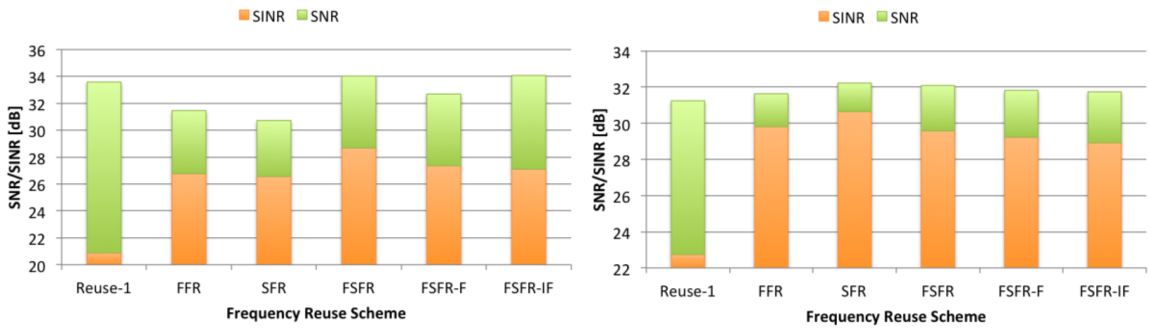


Figure 4.41 Average SINR for satisfied users with SINR higher than 5 dB, considering low load, 20 MHz bandwidth, in the 2600 MHz band.



a) Centre b) Off-Centre

Figure 4.42 Differences between SNR and SINR when taking into account interference, considering low load, 20 MHz bandwidth, in the 2600 MHz band.

Regarding the 1800 MHz band, the average user SINR for satisfied users with an SINR higher than 5 dB is presented in Figure 4.43. As expected, for this band the average user SINR is significantly smaller than for 2600 MHz band. Reuse-1 scheme has the worst average user SINR, with almost 19 dB for centre zone and 20 dB for off-centre zone. FSFR scheme has the best average user SINR, with more than 24 dB for the centre zone and more than 27 dB for the off-centre. FFR, SFR, FSFR-F and FSFR-IF schemes have an average user SINR very close to FSFR scheme, with a difference between 1 and 2 dB for the centre zone, and less than 1 dB for the off-centre region.

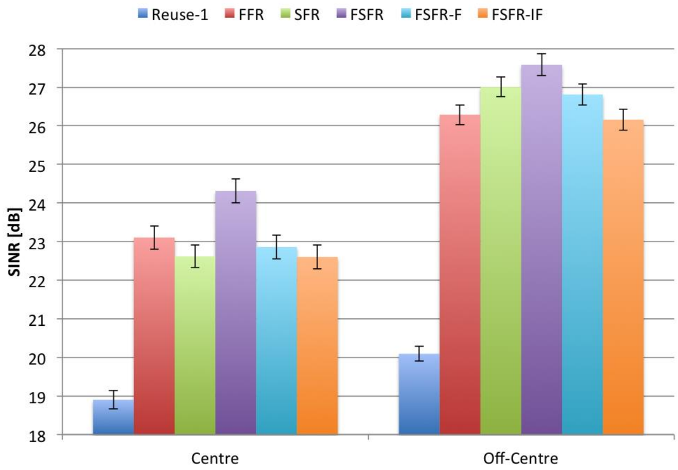


Figure 4.43 Average SINR for satisfied users with SINR superior to 5 dB, considering low load, 20 MHz bandwidth, in the 1800 MHz band.

4.5 Low Load Analysis for a Bandwidth of 10 MHz

This section presents the effects of the six FRSs in low load, considering a 10 MHz bandwidth and 2600 MHz and 800 MHz bands. Note that the 2600 MHz band is the reference band. This section is divided in three sub-sections: Users, Throughput and Interference. In each sub-section the FRSs are analysed and compared for the 2600 MHz and the 800 MHz bands.

4.5.1 Users

Regarding the 2600 MHz band, in Figure 4.44 the average number of satisfied users for the six FRSs is presented. For the centre zone, all FRS serve similar average number satisfied users, Reuse-1 being the best, serving about 150 satisfied users, and FSFR-F the worst, serving around 125 satisfied users. For the off-centre zone, Reuse-1 is the best scheme serving 275 satisfied users, followed by FFR and SFR, with 250 satisfied users, and FSFR and FSFR-F, with 225 satisfied users. The worst scheme is again FSFR-IF, with less than 200 satisfied users served. One can see that, as expected, for a 10 MHz bandwidth, the average number of satisfied users is significantly smaller.

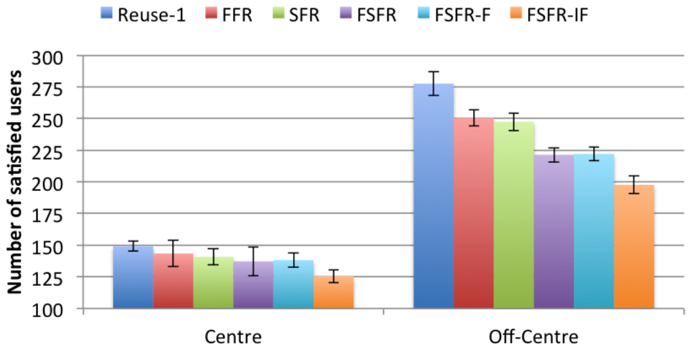


Figure 4.44 Average number of satisfied users for centre and off-centre zones, considering low load, 10 MHz bandwidth, in the 2600 MHz band.

Considering the 2600 MHz band, the average user satisfaction ratio for the six FRSs is presented in Figure 4.45. One can see that for the six FRSs the satisfaction ratio is significantly worse than for 20 MHz bandwidth. For the centre zone, FSFR has the best satisfaction ratio, more than 84%, followed by FSFR-F and FSFR-IF with around 82%. For the off-centre zone, FSFR and FSFR-F present the best average satisfaction ratio, around 83%, followed by Reuse-1 with almost 80%.

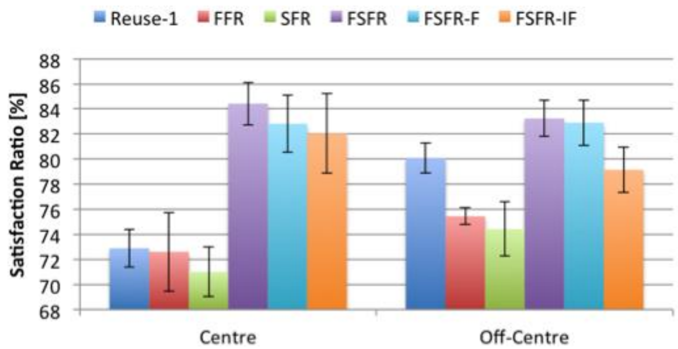


Figure 4.45 Average satisfaction ratio users for centre and off-centre zones, considering low load, 10 MHz bandwidth, in the 2600 MHz band.

Regarding 800 MHz frequency, the results presented in Figure 4.46 show that the average number of satisfied users for the six FRS is higher than for the 2600 MHz. For the centre zone, Reuse-1 serves almost 250 satisfied users, with the other five schemes serving almost the same. For the off-centre zone, Reuse-1 serves about 450 satisfied users, with SFR, FFR, FSFR and FSFR-F serving about 400 satisfied users.

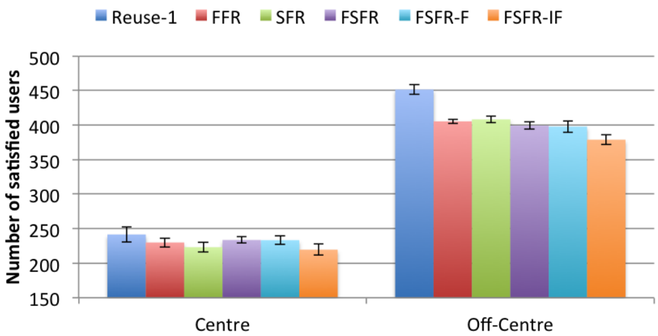


Figure 4.46 Average number of satisfied users for centre and off-centre zones, considering low load, 10 MHz bandwidth, in the 800 MHz band.

The average user satisfaction ratio for the 800 MHZ band is illustrated in Figure 4.47. Reuse-1 has the worst satisfaction ratio, 74% for the centre zone and 86% for the off-centre. The satisfaction ratio for the other five FRSs is similar, being between 84% and 86% for the centre zone, and between 90% and 92% for the off-centre one. The average satisfaction ratio is better than for the 2600 MHz band.

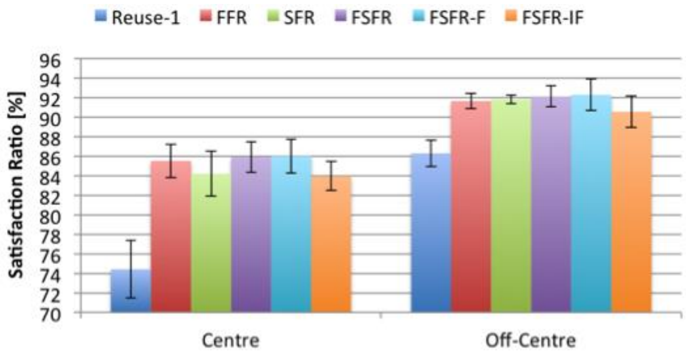


Figure 4.47 Average satisfaction ratio users for centre and off-centre zones, for 10 MHz bandwidth, in the 800 MHz band.

4.5.2 Throughput

Regarding the 2600 MHz band, the average user throughput after interference calculation is presented in Figure 4.48. As expected, for low load the average user throughput increases for all FRSs, mainly for the best schemes, Reuse-1 and FSFR, where the user throughput is increased almost 2 Mbit/s. Reuse-1 has the better average user throughput, with around 5.9 Mbit/s for the centre zone and around 6.4 Mbit/s for the off-centre one, followed by FSFR with 5.5 Mbit/s and almost 6.0 Mbit/s, respectively.

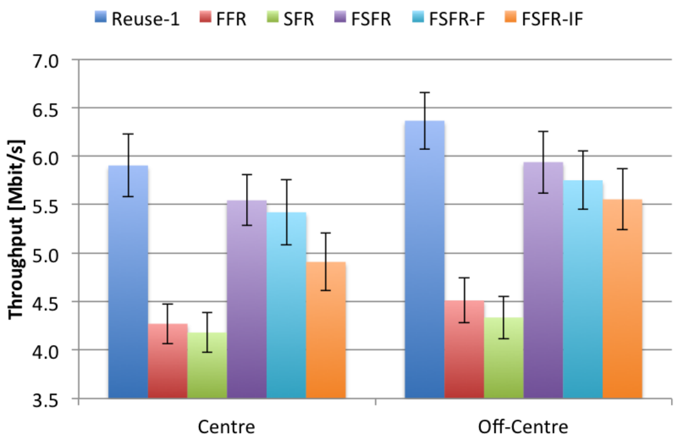


Figure 4.48 Average user throughput, taking interference into account, considering low load, 10 MHz bandwidth, in the 2600 MHz band.

Considering the 800 MHz band, the average user throughput after interference calculation is presented in Figure 4.49. As in the 2600 MHz band, for low load the average user throughput increases principally for Reuse-1 and FSFR schemes. One can see that in low load, the 800 MHz band guarantees a higher average user throughput than the 2600 MHz band. Reuse-1 has the better average user throughput, with almost 6 Mbit/s for the centre zone and around 6.8 Mbit/s for the off-centre one. The other schemes have at least a difference of 1 Mbit/s in the average user throughput comparing to Reuse-1. For the off-centre zone, FSFR and FSFR-F have a smaller average user throughput than for the 2600 MHz band in low load conditions.

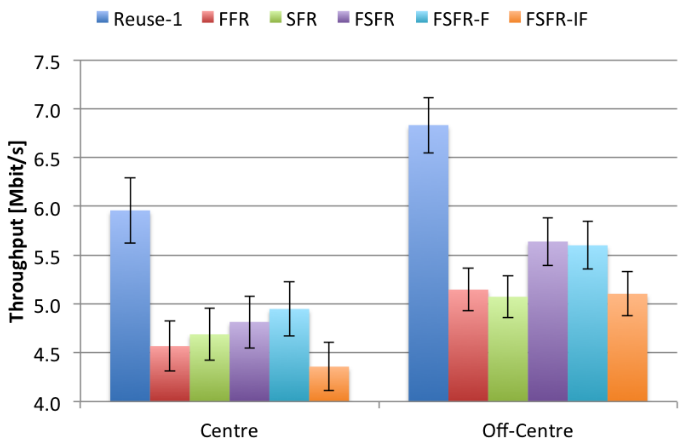


Figure 4.49 Average user throughput, taking interference into account, considering low load, 10 MHz bandwidth, in the 800 MHz band.

4.5.3 Interference

For the 2600 MHz band, the average user SINR for satisfied users with SINR higher than 5 dB is shown in Figure 4.50. As expected, the average user SINR for the six FRS increased in comparison with the network in high load conditions. As in 20 MHz bandwidth, Reuse-1 is the worst scheme, and FSFR, FSFR-F and FSFR-IF have a significant improvement in the average user SINR for low load conditions. For the centre zone, FSFR-F presents the best average user SINR, 27 dB, followed by FSFR-IF with 26 dB. For the off-centre zone, SFR, FSFR, FSFR-F and FSFR-IF have a similar average user SINR, around 28 and 29 dB.

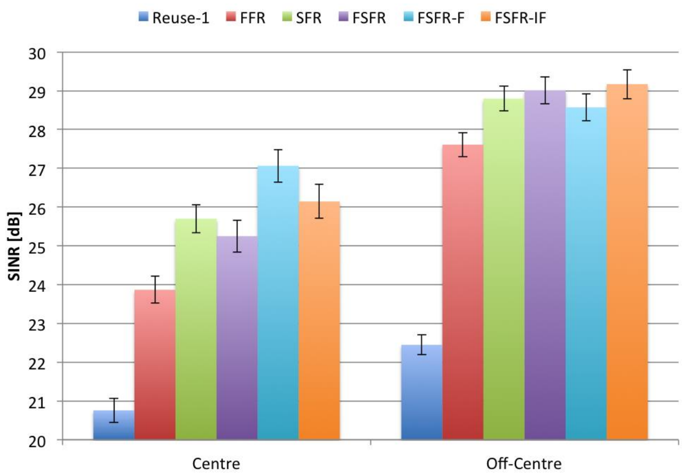


Figure 4.50 Average SINR for satisfied users with SINR higher than 5 dB, considering low load, 10 MHz bandwidth, in the 2600 MHz band.

Regarding 800 MHz band, the average user SINR for satisfied users with SINR higher than 5 dB is presented in Figure 4.51. The average user SINR increases when compared to high load conditions, although for this band the improvement noticed in FSFR, FSFR-F and FSFR-IF is much smaller than for 2600 MHz band. SFR is the scheme with the best averages user SINR, with more than 25 dB for the centre zone and more than 26 dB for the off-centre one. As expected, the 2600 MHz band grants a better average user SINR for the six FRSs than the 800 MHz band.

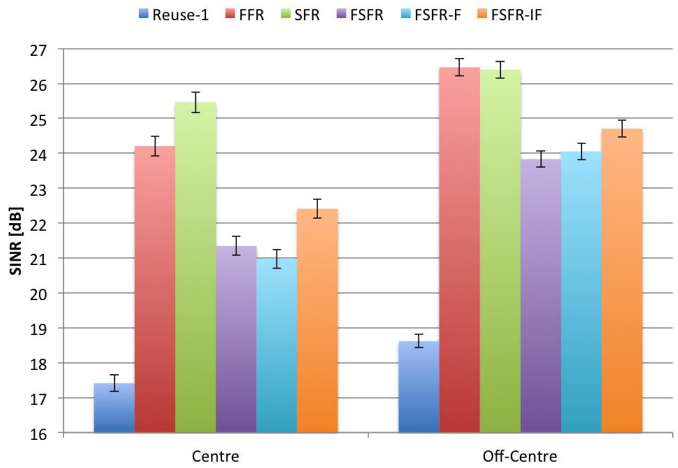


Figure 4.51 Average SINR for satisfied users with SINR higher than 5 dB, considering low load, 10 MHz bandwidth, in the 800 MHz band.

4.6 Global Results Analysis

From the high and low load analysis, one can see that FRSs really improve the average user SINR, normally increasing it from 5 dB to 10 dB for the three frequency bands considered. Regarding only the high load analysis, FFR and SFR are the schemes that most improve average user SINR, although the average number of satisfied users and the average user throughput in these schemes are always significantly lower than in Reuse-1. The schemes that consider inner region RBs reuse from the other neighbouring sectors of his serving cell, FSFR, FSFR-F and FSFR-IF, serve a similar number of users to Reuse-1. Although, for the lower frequency bands, especially for the 800 MHz band, Reuse-1 serves more satisfied users than the other FRS. Nevertheless, the most important parameter of comparison between FRS is the average user throughput, and in this parameter Reuse-1 always obtain the better results. This is even more noticeable for a low loaded network, where Reuse-1 even reach an average user throughput approximately 1 Mbit/s better than the second best FRS.

The average user throughput for the four analysis performed, only for the centre zone, is shown in Table 4.7. Note that the centre zone has average user throughputs lower than the off-centre one, this is due to the higher density of eNodeBs and users in the centre zone, and also due to the higher overlapping of sectors in this zone. As one can see, for a high loaded network, the lower the frequency band is, the lower is the average user throughput, but the same is not true for low load of the network.

As stated before, Reuse-1 is the scheme that always has the best average user throughput when comparing with the other FRSs, the difference being more severe for a low loaded network.

Table 4.7 Average user throughput in Mbit/s for the six FRSs considered in the four analysis (for the centre zone).

Analysis	Frequency Band [MHz]	Frequency Reuse Schemes					
		Reuse-1	FFR	SFR	FSFR	FSFR-F	FSFR-IF
High Load 20 MHz Bandwidth	2600	5.04	4.26	4.34	4.71	4.65	4.46
	1800	4.75	4.13	4.13	4.42	4.38	4.11
High Load 10 MHz Bandwidth	2600	4.08	3.64	3.67	3.94	3.85	3.64
	800	3.53	3.46	3.50	3.31	3.40	3.12
Low Load 20 MHz Bandwidth	2600	6.81	5.34	5.30	6.35	6.11	6.19
	1800	7.29	5.06	5.06	6.19	6.14	5.49
Low Load 10 MHz Bandwidth	2600	5.90	4.27	4.18	5.55	5.42	4.91
	800	5.96	4.57	4.69	4.82	4.95	4.36

In conclusion, Reuse-1 scheme offers the best average user throughput in all analyses, in spite of the average user SINR being much worse than in the other FRS. This means that in the overall, frequency reutilisation mechanisms improve the average user SINR but always with a penalty in average user throughput, meaning that they not bring improvements to LTE MIMO 2x2 urban networks as the operators wished.

Chapter 5

Conclusions

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

The main objective of this thesis was to analyse the impact of frequency reuse mechanisms in an LTE network, in terms of satisfied users, throughput and interference. In order to accomplish this goal, a model was developed and several simulations were done for high and low load conditions of the network, considering different bandwidths, in order to analyse the impact of FRSs for the 2600, 1800 and 800 MHz bands. One considered the Vodafone mobile network in the city of Lisbon. The simulations were done for a multi-user scenario, where users use different services, have different LoS and are randomly distributed around the network, with higher concentration in the areas of Lisbon where usually there are more users, and vice-versa.

Chapter 2 is focused on the LTE basic concepts, presenting the network architecture, radio interface, interference, coverage and capacity, services and applications, and state of the art. The first section addresses the network architecture describing the IP-packet system and the most import network elements, such as eNodeB, MME, among others. The second section addresses the radio interface, focusing on the multiple access techniques, modulation and coding, more specifically the AMC, bandwidth, physical channels, FDD and TDD, and frame structure for DL and UL. The third section introduces the problem of interference. It starts by explaining the different types of interference, intra-cell inference and ICI regarding macro-cells and also small cells, and then classifies and describes the most important interference mitigation mechanisms developed until now. In the fourth section, capacity and coverage are discussed, the theoretical equations for throughput, number of users and maximum radius calculation are presented, and the most important scheduling strategies are described, which are Maximum Rate, Round Robin and Proportional Fair. In the fifth section, services and applications are described and characterised as far as data rates, associated delay and error rates tolerance are concerned. Finally, the last section describes the state of the art, where other authors' work important for this thesis is presented, focusing different frequency reutilisation approaches, from traditional Reuse-1 to schemes with two or even three different regions in each sector, where different RBs are allocated.

Chapter 3 presents the model developed to study the impact of frequency reutilisation mechanisms in the network. In Section 3.1, the model description is presented, addressing the considered FRSs, and the calculations regarding path loss, interference, SNR, SINR and throughput. The FRSs considered for analysis are fully described: Reuse-1, which uses all available RBs in all sectors; FFR, which considers that the cell has two regions, inner and outer ones, and then defines which 1/3 of bandwidth is reserved for each sector and what RBs are used in each of the sectors' regions; SFR, which is very similar to FFR, but considers a higher transmission power for the RBs in the outer region and a lower transmission power for the RBs in the inner region; FSFR, that as SFR applies different transmission powers to outer and inner regions RBs, and also considers that each sector can reuse the RBs reserved for its neighbouring sectors of its serving eNodeB; FSFR-F, that is very similar to FSFR but considers a new type of users, the frontier region users, which are the users that receive a similar power at the same time from two different sectors of the same eNodeB, and this users are served with outer region resources; FSFR-IF, as FSFR-F considers frontier region users, but in this case each sector have RBs reserved only for the frontier region. In Section 3.2, the developed simulator is fully described. First the simulator overview is presented, presenting all modules of the simulator with special emphasis in the LTE DL Analysis Module, which is the one developed for this thesis, where the FRS are implemented. Then, a detailed description of this module is presented, focusing on the algorithms implemented in each of the four parts that constitute the model, the reading of input parameters, the user allocation in a snapshot basis, the calculation of interference and the generation of output. Section 3.3 addresses the simulator assessment in order to confirm the validity of the results.

In Chapter 4, the scenarios descriptions and the results obtained are addressed. Regarding scenarios descriptions, the considered network is presented, which is Vodafone's network in Lisbon. Then, the implemented propagation model and the parameters considered for it, the four different users' environments and the additional path loss, the number of RBs per region and transmission power per RB for each of the six FRSs considered, the default parameters for reference scenario and the services priority, minimum and maximum throughput are described. In the results, four analysis are performed, two for high load conditions of the network, one considering a 20 MHz bandwidth and other considering 10 MHz, and other two for low load conditions of the network, also considering 20 MHz and 10 MHz bandwidths. The objective is to analyse the six FRSs for 2600, 1800 and 800 MHz bands and for different load conditions, and then compare the obtained results. As all Portuguese operators have a 10 MHz bandwidth for the 800 MHz band, the reference band, 2600 MHz band, was also analysed for a 10 MHz bandwidth in order to compare it with the 800 MHz one.

Simulations regarding the 2600, 1800 and 800 MHz bands were done for high and low loads of the network, in order to analyse the impact of the six FRSs in the network for the three frequency bands. The city of Lisbon was divided into two zones, centre and off-centre ones, characterised as dense urban and urban, respectively, considering a higher concentration of users in the centre zone, in order to get more realistic results. In addition to the analysis of the number of satisfied users, user throughput and user SINR, for the reference band, the degradation of throughput and SINR when taking interference into account is also analysed. For the three frequency bands considered, the six FRSs area analysed and compared in terms of average number of satisfied users, average satisfaction ratio, average user throughput and average SINR. After the impact analysis of all implemented FRSs, the frequency bands are compared, meaning that the 1800 MHz band is compared with the 2600 MHz one for a 20 MHz bandwidth, and that the 800 MHz band is compared with the 2600 MHz one for a 10 MHz bandwidth.

Regarding the results for a high load, with about 8000 covered users in the two zones of the city, when considering a 20 MHz bandwidth and the 2600 MHz band, FFR and SFR serve much less satisfied users than Reuse-1, FSFR, FSFR-F and FSFR-IF. These four FRSs serve a similar number of satisfied users, about 600 satisfied users for the centre zone and around 1200 for the off-centre one. Reuse-1 has the worst average user SINR, with less than 17 dB for the centre zone and about 18 dB for the off-centre one. FSFR, FSFR-F and FSFR-IF have an average user SINR around 21 dB for the centre zone and around 24 dB for the off-centre one. FFR and SFR have the best average user SINR, with 26 dB for the centre zone and 29 dB for the off-centre one, although these two schemes have the worst average user throughput of the six schemes, with less 0.7 Mbit/s than Reuse-1. Reuse-1 has the best average user throughput, with more than 5.0 Mbit/s for the centre zone and about 5.15 Mbit/s for the off-centre one, followed by FSFR with about 4.7 Mbit/s for the centre zone and around 4.95 Mbit/s for the off-centre one. In conclusion, for the 2600 MHz band, FSFR presents the best average user SINR, but Reuse-1 presents the best average user throughput. FSFR has an approximately 5 dB better average user SINR and approximately a 0.3 Mbit/s worse average user throughput.

Considering the same high load conditions and the 1800 MHz band, as in the 2600 MHz band, FFR and SFR have the worst average number of satisfied users and user throughput and the best average user SINR of all six schemes. FSFR and FSFR-F serve slightly more users than Reuse-1 for the centre zone, a little less than 650 satisfied users, and they serve about the same number of satisfied users as Reuse-1 for the off-centre zone, a little less than 1300 satisfied users. Reuse-1 has again the best average user throughput and the worst average user SINR, with 4.7 Mbit/s and 16 dB for the centre zone, respectively, and 4.85 Mbit/s and 17 dB for the off-centre one. On the other hand, FSFR and FSFR-F have a lower average user SINR than FFR and SFR, but around 4 or 5 dB better than Reuse-1. Again, FSFR and FSFR-F have a lower average user throughput than Reuse-1, between 0.2 and 0.3 Mbit/s lower. The 1800 MHz band serves more satisfied users than the 2600 MHz band, around more 150 satisfied users, but have a worse average user throughput, 0.3 Mbit/s less, and also a worse average user SINR.

For a high load condition, but considering a 10 MHz bandwidth and the 800 MHz band, as in the 2600 MHz band, FFR and SFR have the worst average number of satisfied users and the best average user SINR of all six schemes, but for this band they have an average user throughput very close to Reuse-1. Overall, Reuse-1 serves the higher number of satisfied users of all six schemes. For the centre zone, Reuse-1, FSFR and FSFR-F serve the higher number of satisfied users, about 600 satisfied users, and for the off-centre one, Reuse-1 has the higher number of satisfied users, around 1400, and FSFR and FSFR-F serve less 200 satisfied users. Reuse-1 has again the best average user throughput and the worst average user SINR, with 3.5 Mbit/s and around 15 dB for the centre zone, respectively, and 3.9 Mbit/s and 16 dB for the off-centre one. On the other hand, FSFR and FSFR-F have a lower average user SINR than FFR and SFR, but around 5 dB better than Reuse-1. Again, FSFR and FSFR-F have a lower average user throughput than Reuse-1, between 0.05 and 0.1 Mbit/s lower. The 800 MHz band serves more satisfied users than the 2600 MHz band, around more 500 satisfied users considering a 10 MHz bandwidth, but have a worse average user throughput, 0.4 Mbit/s less, and also a worse average user SINR.

The three frequency bands were also analysed for low load conditions of the network, about 1000 covered users in the two zones of the city, considering 10 MHz and 20 MHz bandwidths. For the three frequency bands considered, the six FRSs serve a similar number of satisfied users, but Reuse-1 has much higher average user throughput than the other five FRSs, despite of having the worst average user SINR. For example, for the 2600 MHz band, the six FRS serve approximately 150 satisfied users for the centre region and between 250 and 275 satisfied users for the off-centre region. Reuse-1 has the worst average user SINR, however it has the best average user throughput. For the centre-zone, Reuse-1 has an average user throughput of 7.25 and of 7.4 Mbit/s for off-centre zone. FSFR has the second higher average user throughput, with less 0.6 Mbit/s than Reuse-1 for the centre zone and less 0.9 Mbit/s for the off-centre one. This is a much higher difference than when a high load of the network is considered. Contrary to what happens in high load conditions, not only the 1800 and the 800 MHz bands serve more satisfied users than the 2600 MHz band, as also guarantee a higher average user throughput.

The obtained results show that for an LTE MIMO 2x2 network in a urban environment the FRSs implemented effectively decrease the interference experienced by users and even sometimes serve more satisfied users than Reuse-1, but always with a penalty in the users' throughput, this penalty being much more severe when the network has a low load. The penalty in the average user throughput comes with the limitation of RBs for each sector imposed by the frequency reuse mechanisms, which indeed improves the users' channel conditions but in the overall give less RBs to each user, leading to an average user throughput below the average for Reuse-1. Due to the higher priority services that have a higher concentration of users and a higher maximum throughput, as is the case of Web, FFR and SFR schemes have the worst number of satisfied users and average user throughput. Note that when possible, the maximum throughput for all users' service is guaranteed, not limiting the maximum number of RBs per user. As for these FFR and SFR schemes there are less RBs reserved each region, the resources on each sector obviously starve faster than for the other FRS, which leads to worst results. For a high loaded network FSFR serve about the same satisfied users and have an average user throughput not much below Reuse-1. For a low loaded network, Reuse-1 is clearly the best scheme, guaranteeing a significantly higher average user throughput than the other FRSs. The results for high and low loads of the network lead to the conclusion that for today's LTE MIMO 2x2 networks frequency reutilisation mechanisms do not bring great improvements, therefore supporting that the limitation of the spectrum does not bring the expected advantages, and that for now, from the operators viewpoint, they are not a reliable alternative to mitigate interference in LTE.

The developed simulator proved to be a reasonable tool to make an approach to an Urban LTE network, although, in reality there are many characteristics to take into account that were not considered, as the tilt of the terrain, the sporadic high buildings that act as a shield of signal, and shapes coverage areas, avoiding overlapping areas; also the fact that some eNodeBs might not always be tri-sectorised and that the orientation of the sectors may be different from eNodeB to eNodeB as it was assumed. Obviously this simulator has inherent limitations as it is based on the allocation of resources on a snapshot basis, instead of having a temporal behaviour, which would bring a much more realistic approach to the scheduling of users when capacity is exceeded, possibly leading to different conclusions about the frequency reuse mechanisms.

Regarding future work, despite of the conclusions obtained in this thesis, which shows that frequency reuse mechanisms can really improve SINR but always with a penalty in the users throughput, there are many improvements that can be made that were not addressed in this thesis and can lead to better results and different conclusions. MIMO 4x4 and 8x8 could be implemented, for these antenna configurations the throughput per RB is much higher than for MIMO 2x2, and the limitation of RBs imposed by the frequency reuse mechanisms may not starve so much the resources for each sector leading to better results. It would also be interesting to study the impact of frequency reuse mechanisms for higher bandwidths, like 50 MHz or 100 MHz, as the number of RBs is much higher for these bandwidths, different distribution of the RBs for the sectors and regions could be tested. Moreover, if an allocation of resources with temporal behaviour was implemented, it would be possible to test the dynamic frequency reuse mechanisms, which are the most promising until now and have led to better results. In these dynamic FRSs, the RBs are distributed through the regions depending on the number of users and their distribution along the eNodeBs, better adapting the number of resources available in each region to users' needs, in theory leading to better results.

Annex A

Link Budget

This annex presents the link budget equations, used to calculate the simulation parameters related with propagation between transmitter and receiver, taking into account the losses along the link.

Link budget is a very important tool, being possible to calculate the power transmitted and received, the SNR and the SINR, which are one of the most important parameters. All the equations presented below were extracted from [Pire12].

The power available at the receiving antenna is given by (A.1):

$$P_{r[dBm]} = P_{t[dBm]} + G_{t[dBi]} + G_{r[dBi]} - L_{p[dB]} \tag{A.1}$$

where:

- P_t: Transmitted power;
- G_t: Gain from the transmitting antenna;
- G_r: Gain from the receiving antenna;
- L_p: Path loss.

The transmitted power in DL is obtained from (A.2):

$$P_{t[dBm]}{}^{DL} = P_{Tx[dBm]} - L_{c[dB]} \tag{A.2}$$

where:

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

The transmitted power in the UL is given by (A.3):

$$P_{t[\text{dBm}]}{}^{UL} = P_{Tx[\text{dBm}]} - L_{u[\text{dB}]} \tag{A.3}$$

where:

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

The power at the receiver in the DL is obtained from (A.4):

$$P_{Rx[\text{dBm}]}{}^{DL} = P_{r[\text{dBm}]} - L_{u[\text{dB}]} \tag{A.4}$$

The power at the receiver in the UL is given by (A.5):

$$P_{Rx[\text{dBm}]}{}^{UL} = P_{r[\text{dBm}]} - L_{c[\text{dB}]} \tag{A.5}$$

The path loss can be calculated as showed in (A.6):

$$L_{p\,[\text{dB}]} = L_{p,\ COST\,231\,WI\,[\text{dB}]} + L_{p,\ environment\,[\text{dB}]} + M_{SF\,[\text{dB}]} \tag{A.6}$$

where:

- $L_{p,COST\,231\,WI}$: Path loss from the COST 231 Walfisch-Ikegami Model;
- $L_{p,environment}$: Path loss from the user environment;
- M_{SF}: Slow fading margin.

SNR is calculated taking into account noise and the power at the receiver as shown in (A.7):

$$\rho_{N\,[\text{dB}]} = P_{r\,[\text{dBm}]} - N_{[\text{dBm}]} \tag{A.7}$$

where:

- P_r: Average signal power at the receiver;
- N: Average noise power at the receiver;

The noise power at the receiver can be obtained from (A.8).

$$N_{[\mathrm{dBm}]} = -174 + 10\log_{10}\Delta f_{[\mathrm{Hz}]} + F_{N\,[\mathrm{dB}]} \tag{A.8}$$

where:

- Δf: Bandwidth of the radio channel being used;
- F_N: Noise figure at the receiver.

SINR can be calculated by (A.9):

$$\rho_{IN\,[\mathrm{dB}]} = 10\log_{10}\left(\frac{P_{r\,[\mathrm{mW}]}}{N_{\,[\mathrm{mW}]}+I_{\,[\mathrm{mW}]}}\right) \tag{A.9}$$

where:

- I: Interference power at the receiver.

Annex B

COST 231 Walfisch-Ikegami

This annex provides an overview on the propagation model used to calculate the path loss in Lisbon (urban environment).

To calculate the path loss for urban scenarios, the COST 231 Walfisch-Ikegami propagation model was used. Figure B.1 shows a diagram with the parameters included. This annex is based on [Pire12].

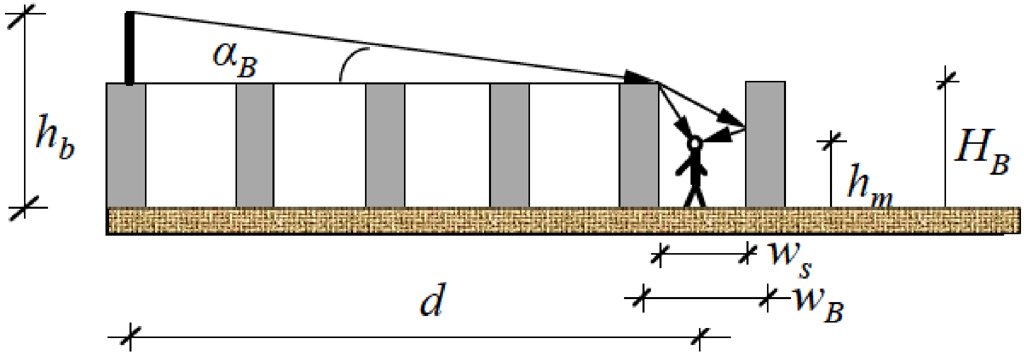


Figure B.1 COST 231 Walfisch-Ikegami Model diagram and parameters (extracted from [Corr13]).

The model standard deviation takes values from 4 dB to 7 dB and is valid for the following conditions:

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

For LoS propagation, the path loss is given by (B.1):

$$L_{p[\text{dB}]} = 42.6 + 26 \log d_{[\text{km}]} + 20 \log f_{[\text{MHz}]} \text{ , for } d > 0.02 \text{ km} \tag{B.1}$$

where:

- d: Horizontal distance between the eNodeB and the UE;
- f: Signal carrier frequency.

For NLoS propagation, the path loss is obtained from (B.2):

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

where:

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

The free space propagation path loss is given by (B.3):

$$L_{0[\text{dB}]} = 32.44 + 20 \log d_{[\text{km}]} + 20 \log f_{[\text{MHz}]} \tag{B.3}$$

The loss between the last rooftop and the MT is obtained from (B.4):

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

where:

- L_{bsh}: Loss due to the height difference between the rooftop and the antennas;

- k_a: Increase of path loss for the eNodeB antennas below the roof tops of the adjacent buildings;
- k_d: Controls the dependence of the multi-screen diffraction loss versus distance;
- k_f: Controls the dependence of the multi-screen diffraction loss versus frequency;
- w_B: Buildings separation distance.

The loss due to the height difference between the rooftop and the antennas is given by (B.5):

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

where:

- h_b: eNodeB height;
- H_B: Buildings height;

Other parameters are obtained from (B.6), (B.7) and (B.8):

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

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

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

The loss between the BS and the last rooftop is given by (B.9):

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

where:

- w_s: Width of the street;
- h_m: Height of the MT;
- L_{ori}: Street orientation loss.

The street orientation loss is obtained from (B.10):

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

where:

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

Annex C

SNR and Data Rate Models

This annex provides an overview of the SNR and data rate models.

This annex is based on [Pire12]. As shown in Table C.1, the channel models considered, Extended Pedestrian A (EPA), Extended Vehicular A (EVA) and Extended Typical Urban (ETU), are characterised in terms of the maximum Doppler frequency considered and maximum delay spread.

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

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

DL interpolations to derive the expressions for throughput in the physical layer and SNR are based on the results in [Duar08], [Jaci09], [Carr11] and trial measurements documented by the 3GPP. SIMO, MISO and MIMO configurations are considered for 10 MHz-bandwidth, using normal CP. For low delay spreads the EPA5Hz channel mode is considered. When results for the considered channel mode were not available, as was the case of MIMO 4×2 with QPSK, where an extrapolation was made, based on the results for the EVA5Hz channel, as shown in Table C.2. The extrapolation factors used to derive results for the EPA5Hz can also be easily used to obtain results for the EVA5Hz channel mode. Thus, the interpolations obtained present mean errors lower or approximately equal to 5%. Furthermore, saturation of the curves for higher values of SINR was done to assure coherence between different MIMO and modulation configurations.

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

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

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

Recent trial measures were done by 3GPP for LTE with MIMO 2x2, with more realistic curves relating the SNR with the throughput. In [Alme13], the extrapolation made to obtain the equations for QPSK, 16QAM and 64QAM is explained.

In the following expressions one considers the throughput for a single RB, in order to easily obtain results for different bandwidths. Channel throughput estimation is obtained by multiplying the average throughput per RB by the number of RBs used for the required channel bandwidth, according to Table C.3.

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

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

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

- EPA5Hz

$$\rho_{N_{[\mathrm{dB}]}} = \begin{cases} 2.55\times10^{7}{R_b}^{5} - 6.303\times10^{6}{R_b}^{4} + 5.803\times10^{5}{R_b}^{3} - 2.502\times10^{4}{R_b}^{2} + \\ +609.1\,R_b - 12.93, \quad 0.02037304 \le R_{b\,[\mathrm{Mbit/s}]} < 0.09338800 \\ 7.457\times10^{9}{R_b}^{3} - 2.126\times10^{9}{R_b}^{2} + 2.02\times10^{8}R_b - \\ -6.397\times10^{6}, \quad 0.09338800 \le R_{b\,[\mathrm{Mbit/s}]} \le 0.096261 \end{cases} \quad \text{(C.1)}$$

- ETU70Hz

$$\rho_{N_{[\mathrm{dB}]}} = \begin{cases} -61.62{R_b}^{2} + 104.2\,R_b - 8.231, \quad 0.04145 \le R_{b\,[\mathrm{Mbit/s}]} < 0.08313 \\ 4.465\times10^{4}{R_b}^{2} - 7476\,R_b + 313, \quad 0.08313 \le R_{b\,[\mathrm{Mbit/s}]} \le 0.0916893 \end{cases} \quad \text{(C.2)}$$

For SIMO 1×2, coding rate of 1/2 and using 16QAM, SNR in DL is obtained, according to the results in [Duar08], by (C.3) and (C.4):

- EPA5Hz

$$\rho_{N_{[\mathrm{dB}]}} = \begin{cases} -70.91{R_b}^{2} + 61.37R_b - 5.045, \quad 0.09042 \le R_{b\,[\mathrm{Mbit/s}]} < 0.2200675 \\ \left(820.7{R_b}^{5} + 1151{R_b}^{4} - 644.9{R_b}^{3} + 180.6{R_b}^{2} - 25.26R_b + 1.412\right)\times10^{8}, \\ 0.2200675 \le R_{b\,[\mathrm{Mbit/s}]} \le 0.29382 \end{cases} \quad \text{(C.3)}$$

- ETU70Hz

$$\rho_{N_{[\mathrm{dB}]}} = \begin{cases} 2968{R_b}^4 - 1233{R_b}^3 - 12.73{R_b}^2 + \\ +93.33R_b - 6.971, \quad 0.08175 \le R_{b\,[\mathrm{Mbit/s}]} < 0.27310179 \\ (1664{R_b}^4 - 1824{R_b}^3 + 749.5{R_b}^2 - \\ -136.9R_b + 9.374) \times 10^9, \quad 0.27310179 \le R_{b\,[\mathrm{Mbit/s}]} \le 0.27500964 \end{cases} \tag{C.4}$$

In SIMO 1×2, coding rate of 3/4 and 64QAM modulation, one gets for DL the expressions (C.5) and (C.6), [Duar08]:

- EPA5Hz

$$\rho_{N_{[\mathrm{dB}]}} = \begin{cases} -3.891 \times 10^4{R_b}^4 + 1.418 \times 10^4{R_b}^3 - \\ -1756{R_b}^2 + 110R_b - 0.1967, \quad 0.003036 \le R_{b\,[\mathrm{Mbit/s}]} < 0.152616 \\ -7931{R_b}^3 + 4946{R_b}^2 - 946.6R_b + 62.48, \quad 0.152616 \le R_{b\,[\mathrm{Mbit/s}]} < 0.25014 \\ 455.2{R_b}^4 - 599.4{R_b}^3 + 246.2{R_b}^2 - \\ -11.18R_b + 6.022, \quad 0.25014 \le R_{b\,[\mathrm{Mbit/s}]} < 0.637095 \\ 1.547 \times 10^4{R_b}^2 - 1.972 \times 10^4R_b + 6300, \quad 0.637095 \le R_{b\,[\mathrm{Mbit/s}]} < 0.648575 \end{cases} \tag{C.5}$$

- ETU70Hz

$$\rho_{N_{[\mathrm{dB}]}} = \begin{cases} \left(-9.862{R_b}^4 + 3.195{R_b}^3\right) \times 10^4 - \\ -3458{R_b}^2 + 165.5R_b + 0.8493, \quad 0 \le R_{b\,[\mathrm{Mbit/s}]} < 0.1428556 \\ 7838{R_b}^3 - 3441{R_b}^2 + 527R_b - 21.91, \quad 0.1428556 \le R_{b\,[\mathrm{Mbit/s}]} < 0.220953 \\ 198.2{R_b}^3 - 267.3{R_b}^2 + 135.4R_b - 7.904, \quad 0.220953 \le R_{b\,[\mathrm{Mbit/s}]} < 0.5656632 \\ 2290{R_b}^2 - 2617R_b + 766.5, \quad 0.5656632 \le R_{b\,[\mathrm{Mbit/s}]} < 0.6068352 \\ (3.684{R_b}^2 - 4.472R_b + 1.375) \times 10^4, \quad 0.6068352 \le R_{b\,[\mathrm{Mbit/s}]} \le 0.6076992 \end{cases} \tag{C.6}$$

For MIMO 2×2, coding rate of 1/2 and 16QAM, for DL, SNR is obtained by (C.7) and (C.8), and this expressions are based on [3GPP08a], [3GPP08b], [3GPP08c] and [3GPP08d]:

- EPA5Hz

$$\rho_{N_{[\mathrm{dB}]}} = \begin{cases} 683.8{R_b}^3 - 399.4{R_b}^2 + 115.8R_b - 7.195, \quad 0.081909 \le R_{b\,[\mathrm{Mbit/s}]} < 0.2619 \\ 5.149 \times 10^4{R_b}^5 - 1.056 \times 10^5{R_b}^4 + 8.561 \times 10^4{R_b}^3 - \\ -3.43 \times 10^4{R_b}^2 + 6812R_b - 528, \quad 0.2619 \le R_{b\,[\mathrm{Mbit/s}]} < 0.52724 \\ 2740{R_b}^2 - 2868R_b + 766.7, \quad 0.52724 \le R_{b\,[\mathrm{Mbit/s}]} < 0.5507425 \\ 2.851 \times 10^4{R_b}^2 - 3.105 \times 10^4R_b + 8472, \quad 0.5507425 \le R_{b\,[\mathrm{Mbit/s}]} \le 0.5531 \end{cases} \tag{C.7}$$

- ETU70Hz

$$\rho_{N_{[\mathrm{dB}]}} = \begin{cases} 23.21{R_b}^2 + 27.73R_b - 0.7635, \quad 0.02782 \le R_{b\,[\mathrm{Mbit/s}]} < 0.23376343 \\ 1.765 \times 10^4{R_b}^3 - 1.391 \times 10^4{R_b}^2 + \\ +3675R_b - 317.4, \quad 0.23376343 \le R_{b\,[\mathrm{Mbit/s}]} < 0.3024 \\ 1.019 \times 10^4{R_b}^4 - 1.595 \times 10^4{R_b}^3 + \\ +9329{R_b}^2 - 2396R_b + 237.4, \quad 0.3024 \le R_{b\,[\mathrm{Mbit/s}]} < 0.5155584 \\ 197.8R_b - 85.95, \quad 0.5155584 \le R_{b\,[\mathrm{Mbit/s}]} < 0.5206152 \\ (3.909{R_b}^2 - 4.0689R_b + 1.059) \times 10^5, \quad 0.5206152 \le R_{b\,[\mathrm{Mbit/s}]} < 0.5232 \end{cases} \tag{C.8}$$

For MIMO 2×2, with a coding rate of 1/3 and a QPSK modulation, SNR is given by (C.9), and the expressions are based on [Alme13]:

$$\rho_{N_{[\mathrm{dB}]}} = \frac{\ln\left(\frac{1.027*2280441.2727217874*3*0.588}{R_{b\,[bps]}} - 14.005140037510571\right)}{-0.5778969006043214} \tag{C.9}$$

For MIMO 2×2, with a coding rate of 1/2 and a 16QAM modulation, SNR is given by (C.10), and the expressions are based on [Alme13]:

$$\rho_{N_{[\mathrm{dB}]}} = \frac{\ln\left(\frac{47613.05094787189*2*0.602}{R_{b\,[bps]}} - 0.0926274904521111\right)}{-0.295838412098985} \tag{C.10}$$

For MIMO 2×2, with a coding rate of 3/4 and a 64QAM modulation, SNR is given by (C.11), and the expressions are based on [Alme13]:

$$\rho_{N_{[\mathrm{dB}]}} = \frac{\ln\left(\frac{0.0326023}{R_{b\,[bps]}} - 0.022018582206702525\right)}{-0.2449102441508849} \tag{C.11}$$

The interpolated expressions considering throughput in the physical layer as a function of the SNR in LTE, are presented below.

For SIMO 1×2, coding rate of 1/3 and using QPSK, DL throughput is given by (C.12) and (C.13), [Duar08] and [3GPP08a]:

- EPA5Hz

$$R_{b\,[\mathrm{bit/s}]} = \begin{cases} (0.0190\rho_N{}^3 - 0.1455\rho_N{}^2 + 0.3516\rho_N + 9.3388) \times 10^{-2}, & -2 \le \rho_{N_{[\mathrm{dB}]}} < 2 \\ (0.0063\rho_N + 9.6009) \times 10^4, & 2 \le \rho_{N_{[\mathrm{dB}]}} < 4 \\ 96261, & 4 < \rho_{N_{[\mathrm{dB}]}} \le 6 \end{cases} \tag{C.12}$$

- ETU70Hz

$$R_{b\,[\mathrm{bit/s}]} = \begin{cases} (0.01035\rho_N + 0.08285) \times 10^6, & -4 \le \rho_{N_{[\mathrm{dB}]}} < 0 \\ (0.0001279\rho_N{}^3 - 0.001638\rho_N{}^2 + 0.006616\rho_N + 0.08313) \times 10^6, & 0 \le \rho_{N_{[\mathrm{dB}]}} \le 6 \\ 91484.4, & \rho_{N_{[\mathrm{dB}]}} > 6 \end{cases} \tag{C.13}$$

For SIMO 1×2, coding rate of 1/2 and 16QAM, DL throughput is given by (C.14) and (C.15), [Duar08] and [3GPP07]:

- EPA5Hz

$$R_{b\ [\mathrm{bit/s}]} = \begin{cases} -263.5{\rho_N}^3 + 303{\rho_N}^2 + 26360\rho_N + 90420,\ -4 \leq \rho_{N_{[\mathrm{dB}]}} < 2 \\ (-0.000945{\rho_N}^4 + 0.0103{\rho_N}^3 - 0.0141{\rho_N}^2 + 0.1696\rho_N + 1.0083) \times 10^5, \\ 2 \leq \rho_{N_{[\mathrm{dB}]}} < 6 \\ (0.0048{\rho_N}^3 - 0.1503{\rho_N}^2 + 1.5644\rho_N - 2.4858) \times 10^5,\ 6 \leq \rho_{N_{[\mathrm{dB}]}} < 12 \\ 293820,\ 12 \leq \rho_{N_{[\mathrm{dB}]}} \leq 14 \end{cases} \tag{C.14}$$

- ETU70Hz

$$R_{b\ [\mathrm{bit/s}]} = \begin{cases} (0.002862{\rho_N}^2 + 0.03113\rho_N + 0.07953) \times 10^6, -4 \leq \rho_{N_{[\mathrm{dB}]}} \leq 0 \\ (1.204{\rho_N}^2 + 12.02\rho_N + 81.75) \times 10^3,\ 0 < \rho_{N_{[\mathrm{dB}]}} \leq 8 \\ 66,41{\rho_N}^2 + 1909\rho_N + 261300,\ 8 < \rho_{N_{[\mathrm{dB}]}} \leq 14 \\ 275009.64,\ \rho_{N_{[\mathrm{dB}]}} > 14 \end{cases} \tag{C.15}$$

For SIMO 1×2, coding rate of 3/4 and 64QAM, DL throughput is obtained by (C.16) and (C.17), [Duar08]:

- EPA5Hz

$$R_{b\ [\mathrm{bit/s}]} = \begin{cases} (-0.1292{\rho_N}^3 + 1.3299{\rho_N}^2 - 0.4279\rho_N + 0.3036) \times 10^4,\ 0 \leq \rho_{N_{[\mathrm{dB}]}} < 6 \\ (-0.1018{\rho_N}^2 + 2.92\rho_N + 3.8494) \times 10^4,\ 6 \leq \rho_{N_{[\mathrm{dB}]}} < 10 \\ (0.0585{\rho_N}^2 - 1.0032\rho_N + 6.4581) \times 10^5,\ 10 \leq \rho_{N_{[\mathrm{dB}]}} < 16 \\ (0.4354\rho_N - 1.6098) \times 10^5,\ 16 \leq \rho_{N_{[\mathrm{dB}]}} < 18 \\ (-0.0241{\rho_N}^2 + 1.0214\rho_N - 4.33555) \times 10^5,\ 18 \leq \rho_{N_{[\mathrm{dB}]}} < 22 \\ 647085,\ 22 \leq \rho_{N_{[\mathrm{dB}]}} \leq 26 \end{cases} \tag{C.16}$$

- ETU70Hz

$$R_{b\ [\mathrm{bit/s}]} = \begin{cases} 727.4\rho_N,\ 0 \leq \rho_{N_{[\mathrm{dB}]}} < 2 \\ 127.6{\rho_N}^4 - 3709{\rho_N}^3 + 34850{\rho_N}^2 - 91410\rho_N + 72490,\ 2 \leq \rho_{N_{[\mathrm{dB}]}} < 10 \\ 3933{\rho_N}^2 - 71940\rho_N + 5.364 \times 10^5,\ 10 \leq \rho_{N_{[\mathrm{dB}]}} < 18 \\ -100.8{\rho_N}^4 + 9480{\rho_N}^3 - 334300{\rho_N}^2 + 5.239 \times 10^6\rho_N - \\ -30.18 \times 10^6, 18 \leq \rho_{N_{[\mathrm{dB}]}} \leq 26 \\ 604499.2,\ ,\ \rho_{N_{[\mathrm{dB}]}} > 26 \end{cases} \tag{C.17}$$

For MIMO 2×2, with a coding rate of 0.588 and a QPSK modulation, DL throughput is given by (C.18), and the expressions are based on [Alme13]:

$$R_{b\ [bps]} = \frac{1.027*2280441.2727217874*3*0.588}{14.005140037510571 + e^{-0.5778969006043214*\rho_{N_{[\mathrm{dB}]}}}} \tag{C.18}$$

For MIMO 2×2, with a coding rate of 0.602 and a 16-QAM modulation, DL throughput is given by (C.19), and the expressions are based on [Alme13]:

$$R_{b\ [bps]} = \frac{47613.05094787189*2*0.602}{0.0926274904521111 + e^{-0.295838412098985*\rho_{N_{[\mathrm{dB}]}}}} \tag{C.19}$$

For MIMO 2×2, with a coding rate of 0.926 and a 64-QAM modulation, DL throughput is given by

(C.20), and the expressions are based on [Alme13]:

$$R_{b\ [bps]} = \frac{17603.857570084674*2*0.926}{0.022018582206702525+e^{-0.2449102441508849*\rho_{N_{[\mathrm{dB}]}}}} \qquad \text{(C.20)}$$

Annex D

eNodeBs and Users Distribution Along the Network

This annex describes the heterogeneity of the network in terms of location and density of eNodeBs and users along the city of Lisbon.

To get more realistic results, the simulations performed in this thesis consider a real network with differences in location and density of the eNodeBs. However, only tri-sectorised cells are considered and the sectors of all eNodeBs have the same orientations. Users distribution along the network is done according to the density of population assigned by district.

From Figure D.1, one can see the distribution of eNodeBs along the districts of Lisbon, with eNodeBs marked blue and green. Blue eNodeBs belong to the centre zone of Lisbon, marked as blue in the map, and the green eNodeBs to the off-centre zone, marked as yellow in map. One can see in Figure D.1 that the centre zone as a higher concentration of eNodeBs, and also that the off-centre zone has a more heterogeneous distribution of eNodeBs, the higher concentration zone being the Northwest of Parque das Nações, which is a recent business zone, and the lower concentration zones the Airport of Portela and the Forest Park of Monsanto at West.

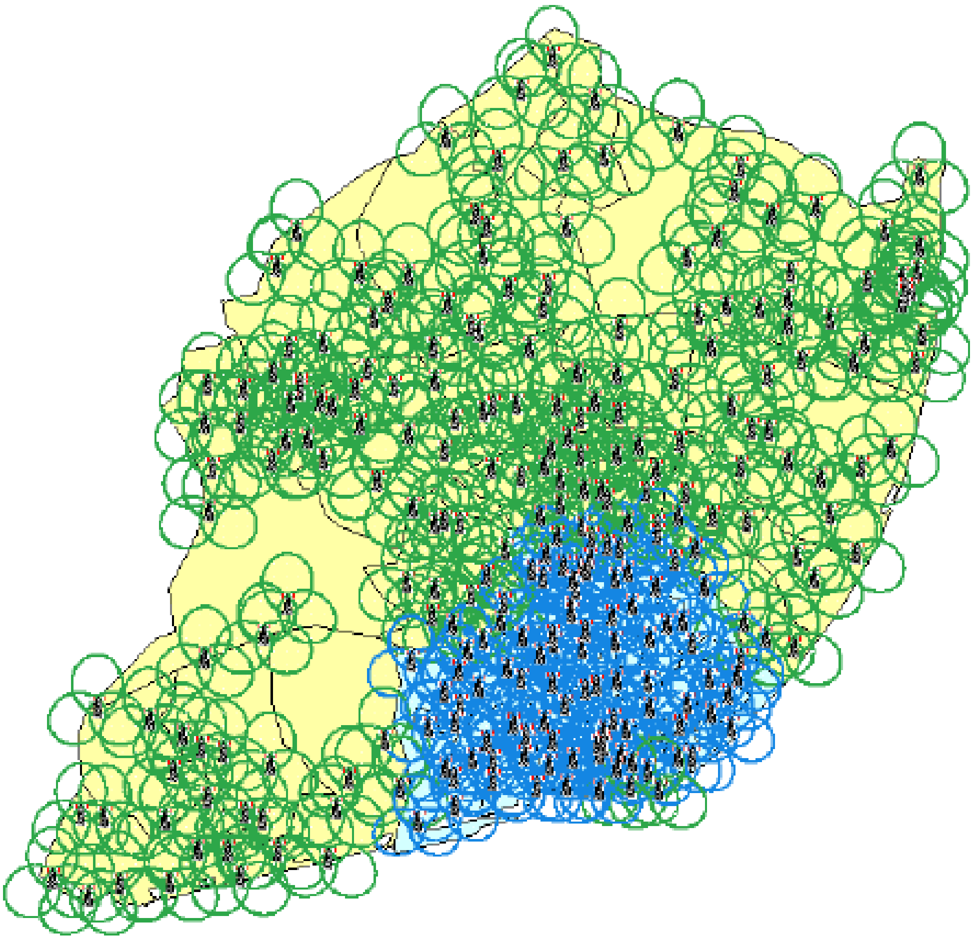


Figure D.1 Network of eNodeBs in the city of Lisbon.

Figure D.2 shows the distribution of users through the districts of Lisbon, which are represented by a coloured flag, where the colour defines the service of the user. As one could expect, the zones that have a higher concentration of eNodeBs are also the ones with the higher density of users. Airport of Portela and the Forest Park of Monsanto at West have the lower density of users, with much less users than the other zones of Lisbon. The centre zone of Lisbon has the higher concentration of users, and the off-centre zone has a more heterogeneous distribution.

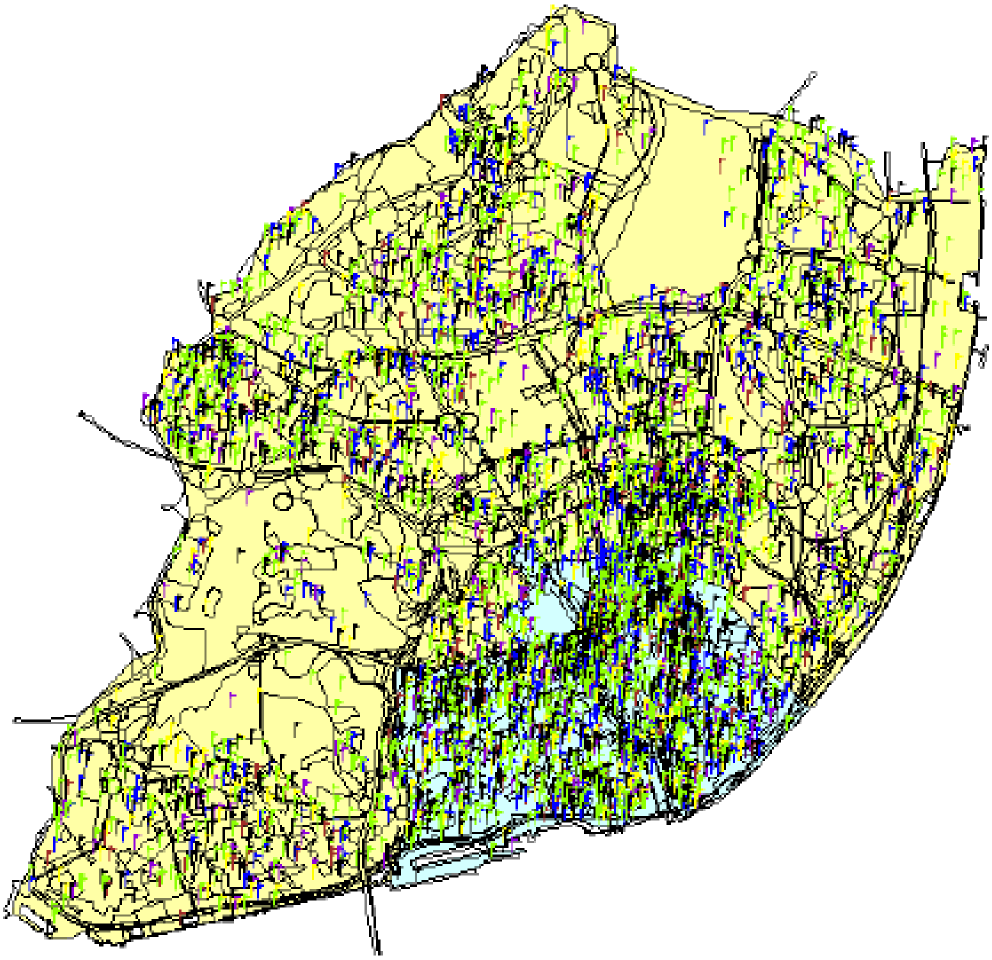


Figure D.2 Distribution of users through the districts of Lisbon.

Annex E

User's Manual

This annex explains how to configure and run the simulator.

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

- “Ant65deg.TAB”, with the eNodeBs antennas gain structure;
- “DADOS.TAB”, with the information regarding the city of Lisbon and its districts;
- “ZONAS.TAB”, with area characterisation regarding the districts.

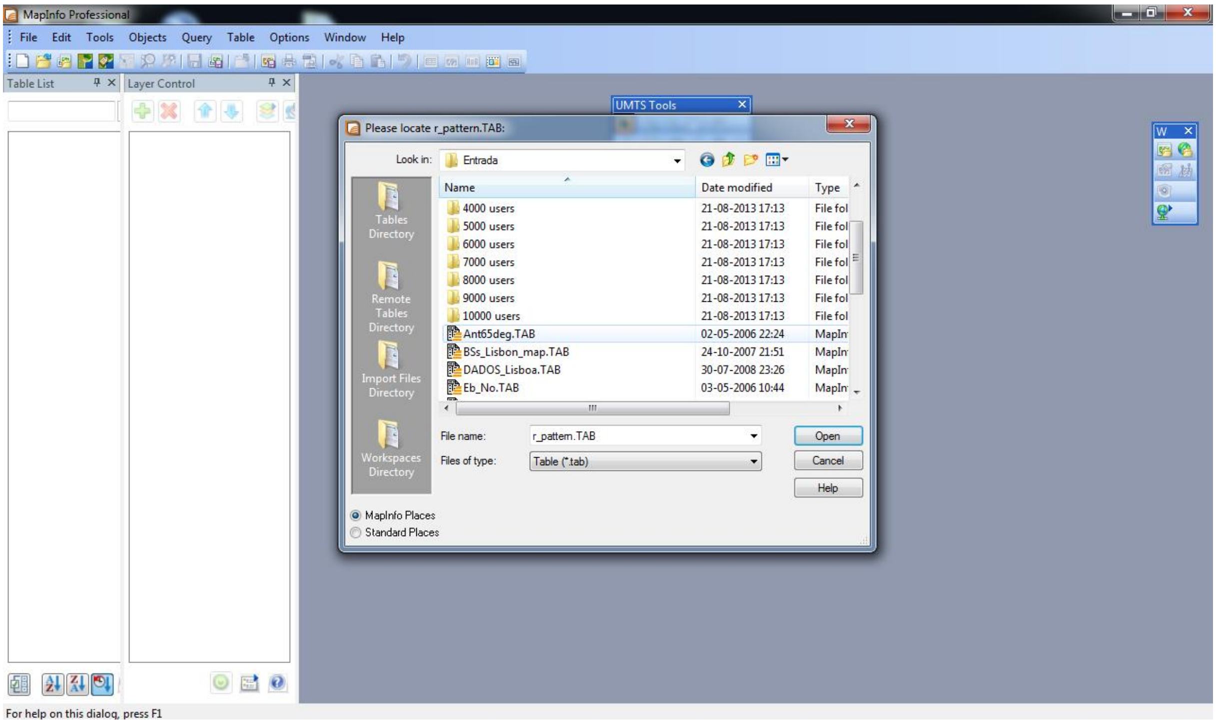


Figure E.1 Window for the selection of the radiation pattern file.

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

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

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

After the associated services throughputs are set up, the tab “Insert users” is available and must select this tab and insert the files with the users that will be placed in the city of Lisbon, as in Figure E.6. The users files are created by the Users Generator (SIM) program developed whose functioning is detailed at [LaCo06]. After the users are loaded, users are represented in the map by flags, each one of a colour that represents the required service. Then one must load the BSs network, by selecting the "Deploy Network" tab and choose the desired network table, which contains in each row the identification and coordinates of each BS, as illustrates Figure E.7. When the network is loaded, it is represented with the users along the map and one can finally select "Run Simulation" in order to run the simulation, as shown in Figure E.8.

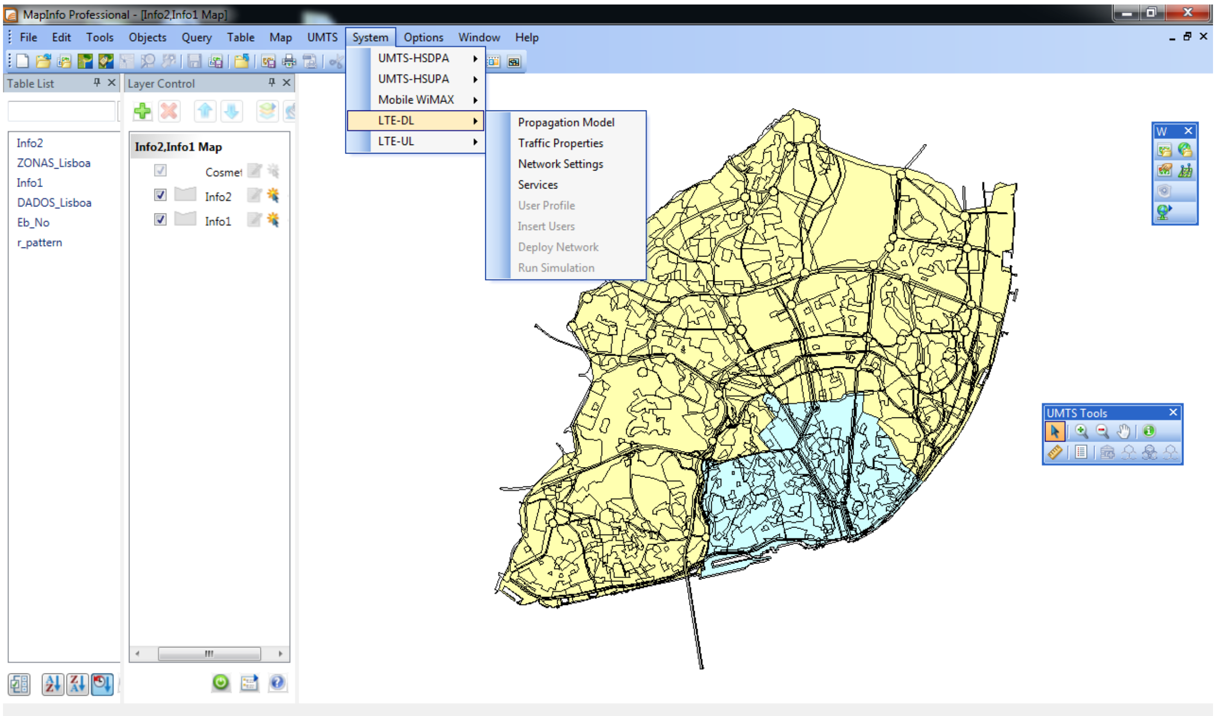


Figure E.2 System tab with the LTE-DL.

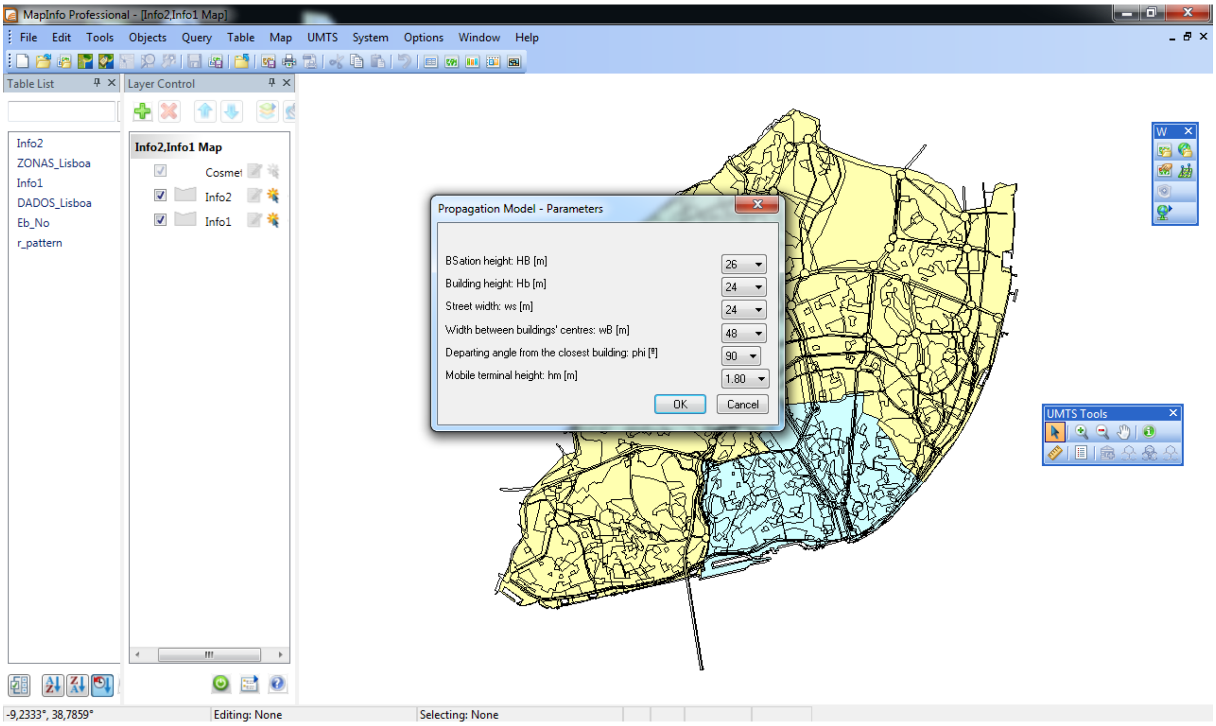


Figure E.3 Propagation model parameters.

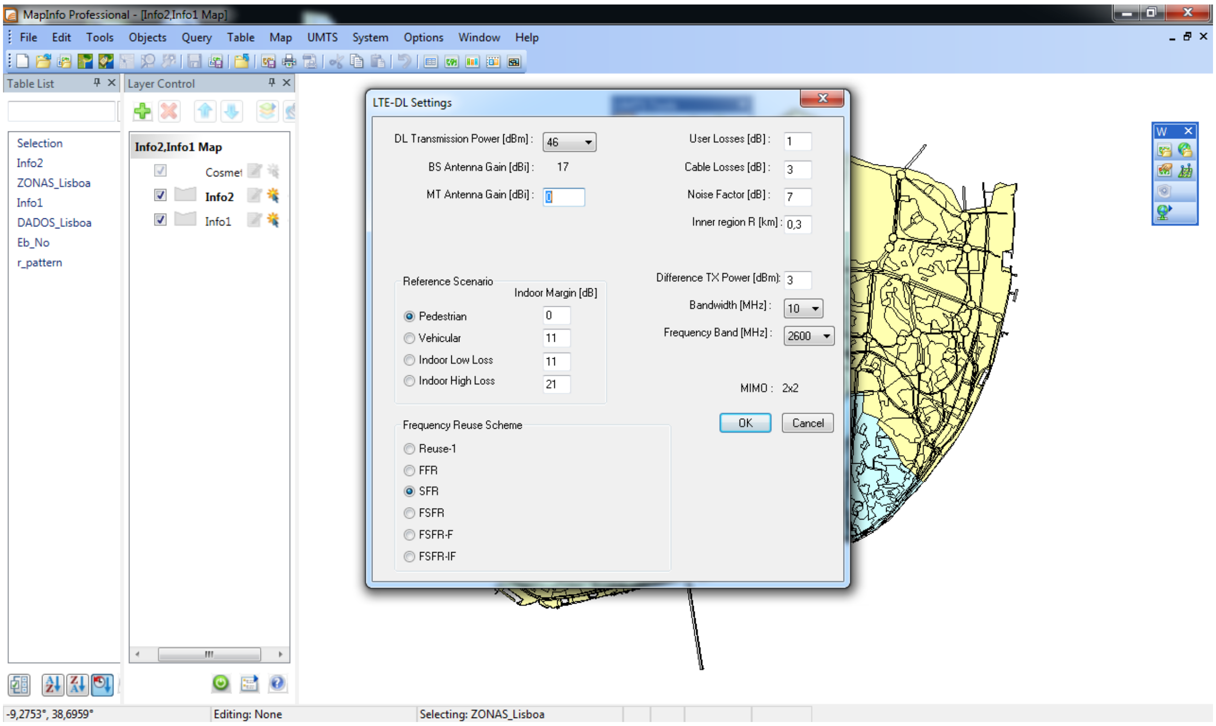


Figure E.4 Radio Interface parameters

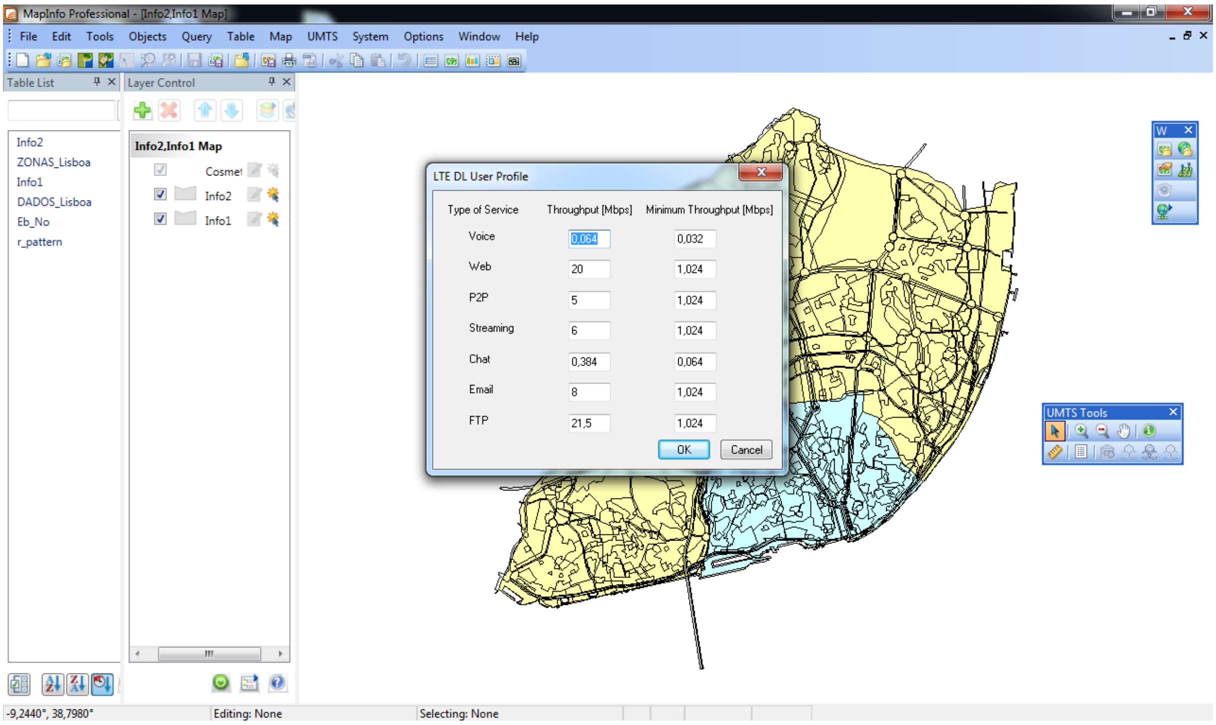


Figure E.5 User Profile parameters.

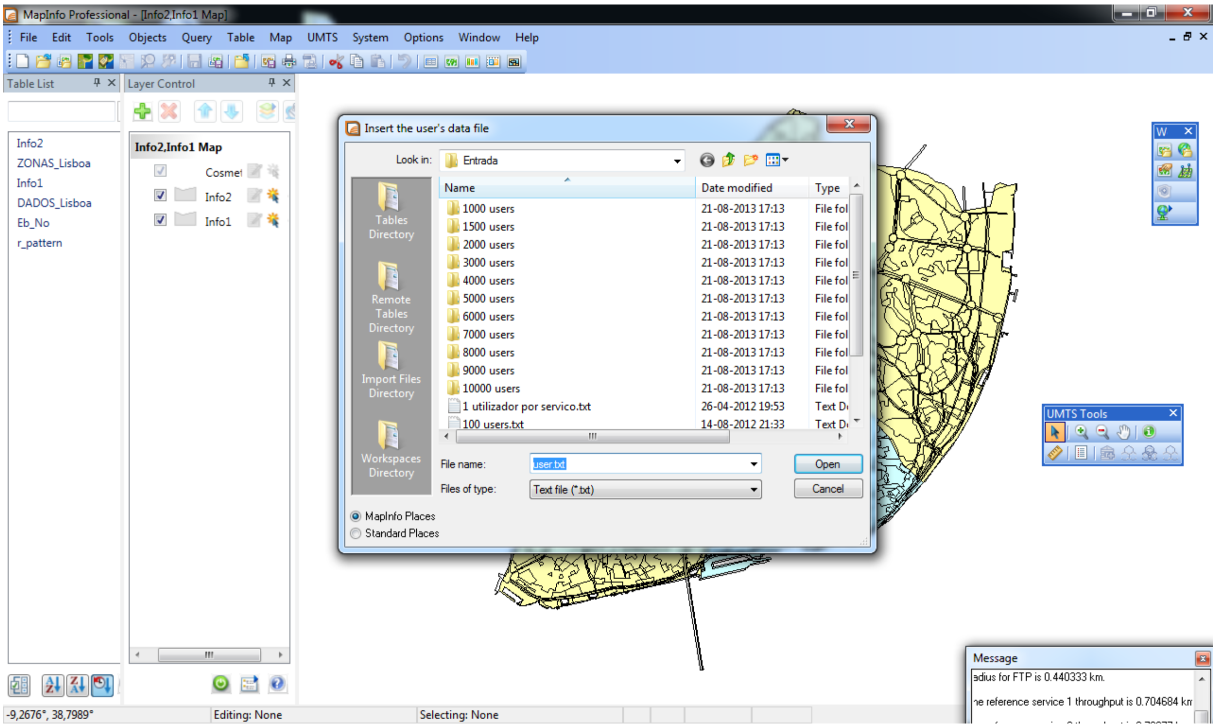


Figure E.6 Users data file.

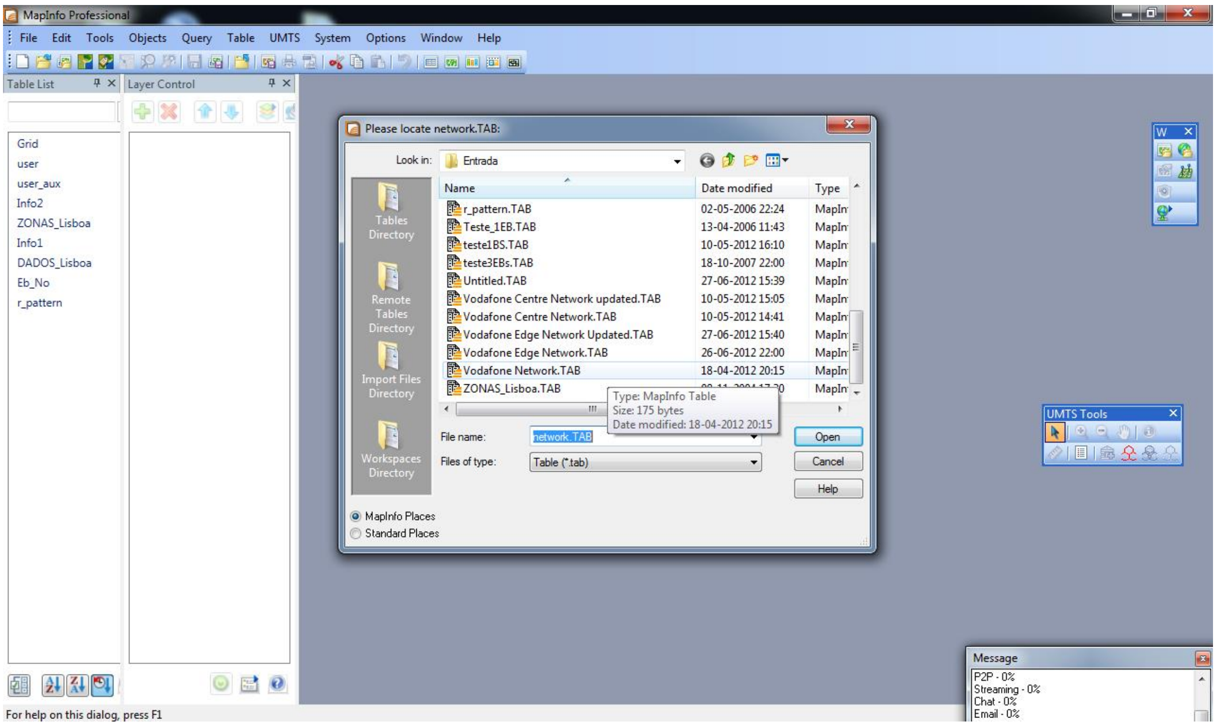


Figure E.7 Deploy Network window.

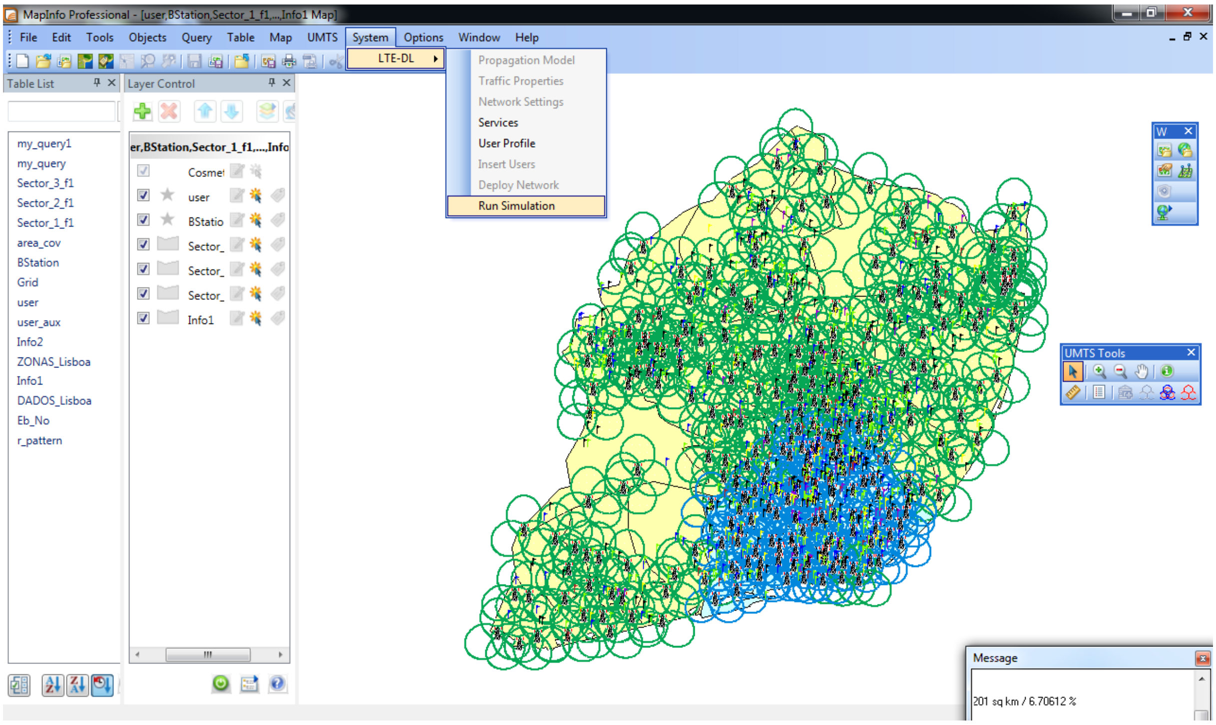


Figure E.8 Run Simulation command.

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