Coverage Planning of Mobile Networks Using a Software Tool

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Thesis to obtain the Master of Science Degree in

Electrical and Computer Engineering

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Declaration

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

In a moment as special as this one, I would like to thank my parents and my sister. I can not describe how thankful I feel for the support, effort, help and encouragement they gave me, not only through this last few years as a university student, but throughout all my life. Without them, their parenting and all their love, nothing would be possible.

I want to thank the rest of my family for being there throughout my life and, in a direct or indirect way, having influenced me to be the person I am today.

I would also like to thank my supervisors Professor António Rodrigues, Professor Paula Queluz and Professor Pedro Vieira who were my biggest supporters during the thesis development, answering to my questions, helping me through the obstacles and making me see the bigger picture by thinking above and beyond, in order to produce a valuable work.

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Resumo

O contínuo crescimento do tráfego e aumento da complexidade das redes móveis, leva à constante necessidade do avanço tecnológico dos mesmos, no sentido de se criarem soluções mais eficientes para a sua gestão e planeamento, de modo a obter a Qualidade de Serviço (QoS) desejada. A Quinta Geração (5G) de Comunicações Móveis tem vindo a ser projetada para fazer face a estes desafios. No entanto, o seu desenvolvimento ainda se encontra numa fase inicial, pelo que também a Quarta Geração (4G) terá de continuar a evoluir para ajudar a resolver esta conjuntura.

Neste sentido, este trabalho surge com o objetivo de apresentar uma plataforma capaz de fazer o planeamento da rede ao nível da distribuição de Estações Base (BSs) através da projeção da sua área de cobertura. Para obter resultados mais realistas, é usado um módulo de calibração baseado em medidas de campo, designadas por Drive Tests (DTs).

Primeiramente, foram feitas todas as validações e otimizações necessárias à plataforma, principalmente em relação ao modelo de propagação e à sua calibração. Em seguida, foi implementado um modelo de propagação de rádio-frequências para valores entre 0,5 e 100 GHz, permitindo à plataforma ser utilizada para as tecnologias de comunicações móveis atuais e em desenvolvimento.

A plataforma foi testada através de BSs de duas Redes de Acesso Rádio (RAN), de forma a avaliar o seu desempenho em diferentes ambientes de propagação. A primeira engloba toda a área do centro de Lisboa, de forma a abranger um teste em ambiente urbano, e a segunda, em Vila Franca de Xira, num teste em ambiente suburbano. Foram efetuadas comparações quanto ao nível de potência recebida, entre os resultados da aplicação e os valores medidos em DTs não usado na calibração. Para o centro de Lisboa, foram obtidos erros absolutos médios (MAE) de 4.63 dB, 5.09 dB e 3.78 dB para as frequências de 800 MHz, 1800 MHz e 2600 MHz, respetivamente. Para Vila Franca de Xira, foram obtidos MAE de 6.26 dB e 6.67 dB para as frequências de 800 MHz e 2100 MHz, respetivamente.

Depois da devida validação da plataforma, foi feita a previsão de cobertura das redes consideradas, utilizando frequências de 800 MHz e 3.5 GHz. Em ambas as redes, obteve-se uma percentagem de cobertura de praticamente 100% para ambas as frequências, permitindo concluir que o número de BSs implementadas garante os requisitos mínimos de QoS, sobretudo ao nível de cobertura.

Palavras-chave: Tráfego, QoS, Comunicações Móveis, Planeamento, Cobertura, DT.
Abstract

With the increase in traffic and in the complexity of mobile networks, there is a need for their technological advancement, by creating more efficient solutions for their management and planning, in order to provide the desired Quality of Service (QoS) to the network users. The Fifth Generation (5G) of Mobile Communications is being designed to address these challenges. However, the development of this technology is still in its early stages, and operators must continue working with the Forth Generation (4G) in order to handle the current demand.

In this sense, this work aims to propose a tool capable of planning the network Base Stations (BSs) distribution, through the projection of their coverage area. For more realistic results, the tool features a calibration module based on field measurements, called Drive Tests (DTs).

Firstly, all the necessary validations and optimizations for the tool development were done, mainly related to the propagation model and its calibration. Then, a propagation model was implemented for frequencies between 0.5 and 100 GHz, so that it can be used for current and future mobile communications technologies.

The tool was tested using the BSs of two Radio Access Networks (RAN), in order to evaluate its performance in different propagation environments. The first encompasses the whole area of Lisbon center, to cover a test in urban environment, and the second, in Vila Franca de Xira, to cover a test in a suburban environment. Comparisons were made regarding the level of received power between the results of the algorithm and a set of DTs not used in the calibration. For Lisbon center, values for the Mean Absolute Errors (MAEs) of 4.63 dB, 5.09 dB and 3.78 dB for the frequencies 800 MHz, 1800 MHz and 2600 MHz respectively, were obtained. In Vila Franca de Xira, values of 6.26 dB and 6.67 dB were obtained for the MAEs, in the 800 MHz and 2100 MHz frequencies, respectively.

After the platform validation, the coverage prediction for the same networks was performed, using the frequency bands of 800 MHz and 3.5 GHz. In both networks, a coverage percentage of almost 100% for both frequencies were acquired, allowing to conclude that these networks have enough BSs, in order to ensure the minimum requirements of QoS, mainly in terms of coverage.

Keywords: Traffic, QoS, Mobile Communications, Planning, Coverage, DT.
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<th>Symbol</th>
<th>Description</th>
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</thead>
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<tr>
<td>$\Delta_{LAT}$</td>
<td>Delta Latitude.</td>
</tr>
<tr>
<td>$\Delta_{LON}$</td>
<td>Delta Longitude.</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Impulse.</td>
</tr>
<tr>
<td>$\gamma_{[DL]}$</td>
<td>Signal-to-Interference-plus-Noise Ratio for downlink.</td>
</tr>
<tr>
<td>$\gamma_{[UL]}$</td>
<td>Signal-to-Interference-plus-Noise Ratio for uplink.</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength.</td>
</tr>
<tr>
<td>$\phi_{3dB}$</td>
<td>3 dB beamwidth.</td>
</tr>
<tr>
<td>$\phi_h$</td>
<td>Horizontal angle between antenna and user.</td>
</tr>
<tr>
<td>$\phi_v$</td>
<td>Vertical angle between antenna and user.</td>
</tr>
<tr>
<td>$\tau_n$</td>
<td>Time delay from the first signal component in the multipath $n$.</td>
</tr>
<tr>
<td>$\varphi_n$</td>
<td>Phase in the multipath $n$.</td>
</tr>
<tr>
<td>$a(h_{re})$</td>
<td>Correction factor for the effective height of the receiving antenna.</td>
</tr>
<tr>
<td>$A_{[m]}$</td>
<td>Maximum horizontal attenuation.</td>
</tr>
<tr>
<td>$A_h$</td>
<td>Horizontal attenuation.</td>
</tr>
<tr>
<td>$A_n$</td>
<td>Amplitude in the multipath $n$.</td>
</tr>
<tr>
<td>$A_v$</td>
<td>Vertical attenuation.</td>
</tr>
<tr>
<td>$B_{IDL}$</td>
<td>Downlink interference margin.</td>
</tr>
<tr>
<td>$B_{IUL}$</td>
<td>Uplink interference margin.</td>
</tr>
<tr>
<td>$B_{LNF}$</td>
<td>Log-normal fading margin.</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of Light.</td>
</tr>
<tr>
<td>$d$</td>
<td>Distance.</td>
</tr>
<tr>
<td>$d_{2D}$</td>
<td>2D distance.</td>
</tr>
</tbody>
</table>
\(d_{3D}\)  
3D distance.

\(d_{BP}\)  
Breakpoint distance.

\(F\)  
Average ratio of path gains for interfering cells to those of the serving cell.

\(f\)  
Carrier Frequency.

\(F_c\)  
Average ratio between the received power from other cells to that of own cell at cell edge locations.

\(f_{doppler}\)  
Doppler Frequency.

\(G_{\text{max}}\)  
Maximum antenna gain.

\(G_r\)  
Receiver Gain.

\(G_t\)  
Transmission Gain.

\(h\)  
Height

\(h(t)\)  
Radio channel output.

\(h_{BS}\)  
Base Station height.

\(h_{ef}\)  
Effective height.

\(h_{\text{Roof}}\)  
Building height of the base station antenna

\(h_{UE}\)  
User equipment height.

\(k\)  
Independent factor.

\(L_0\)  
Free space propagation loss.

\(L_{BL}\)  
Body loss.

\(L_{BPL}\)  
Building penetration loss.

\(L_{\text{bsb}}\)  
Increase of path loss due to a reduced base station antenna height.

\(L_{CPL}\)  
Car penetration loss.

\(L_{\text{dif}}\)  
Diffraction losses.

\(L_{j}\)  
Tower mounted amplifier insertion loss.

\(L_{\text{msd}}\)  
Multi-screen diffraction loss.

\(L_{\text{ori}}\)  
Orientation loss.

\(L_{p_{\text{max}}}\)  
Maximum allowed path loss.

\(L_p\)  
Path loss attenuation.
\( L_{rts} \)  
Roof-top-to-street diffraction and scattering loss.

\( L_{sa,cell\text{range}} \)  
Signal attenuation at cell range.

\( N \)  
Number of paths with time delayed signals.

\( n'_{RB} \)  
Number of resource blocks that can be allocated to obtain a certain bit rate.

\( N_I \)  
Noise figure.

\( N_{RB} \)  
Thermal noise per resource block.

\( n_{RB} \)  
Number of resource blocks.

\( N_t \)  
Thermal noise.

\( P_{BS,RB} \)  
Output power of the base station per resource block.

\( P_{BS} \)  
Output power of the base station.

\( P_r \)  
Received power.

\( P_t \)  
Transmitted power.

\( P_{UE,RB} \)  
Output power of the user equipment per resource block.

\( P_{UE} \)  
Output power of the user equipment.

\( Q_{DL} \)  
Average downlink system load.

\( Q_{UL} \)  
Average uplink system load.

\( R \)  
Bit rate.

\( r_e \)  
Effective Earth radius.

\( R_{RB} \)  
Bit rate per resource block.

\( S_{DL} \)  
Downlink sensitivity.

\( S_{UL} \)  
Uplink sensitivity.

\( SLA[v] \)  
Maximum vertical attenuation.

\( \tan^{-1}() \)  
Inverse tangent.

\( v \)  
Speed.

\( w_b \)  
Distance between buildings along the signal path.

\( W_{RB} \)  
Bandwidth per resource block.

\( w_s \)  
Street width.
### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>2G</td>
<td>Second Generation</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>3G</td>
<td>Third Generation</td>
</tr>
<tr>
<td>3GPP</td>
<td>Third Generation Partnership Project</td>
</tr>
<tr>
<td>4G</td>
<td>Fourth Generation</td>
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<tr>
<td>5G</td>
<td>Fifth Generation</td>
</tr>
<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>BSIC</td>
<td>Base Station Identity Code</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
</tr>
<tr>
<td>CM</td>
<td>Configuration Management</td>
</tr>
<tr>
<td>CN</td>
<td>Core Network</td>
</tr>
<tr>
<td>CP</td>
<td>Cyclic Prefix</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
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<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>DT</td>
<td>Drive Test</td>
</tr>
<tr>
<td>E-UTRAN</td>
<td>Evolved UMTS Terrestrial Radio Network</td>
</tr>
<tr>
<td>EDGE</td>
<td>Enhanced Data rates for GSM Evolution</td>
</tr>
<tr>
<td>EDT</td>
<td>Electrical Downtilt</td>
</tr>
<tr>
<td>EM</td>
<td>Element Manager</td>
</tr>
<tr>
<td>eNodeB</td>
<td>Evolved Node Base Station</td>
</tr>
<tr>
<td>EPA</td>
<td>Extended Pedestrian A model</td>
</tr>
<tr>
<td>EPC</td>
<td>Evolved Packet Core</td>
</tr>
<tr>
<td>EPS</td>
<td>Evolved Packet System</td>
</tr>
<tr>
<td>ETU</td>
<td>Extended Typical Urban model</td>
</tr>
<tr>
<td>EVA</td>
<td>Extended Vehicular A model</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>--------------</td>
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<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>FM</td>
<td>Fault Management</td>
</tr>
<tr>
<td>FTP</td>
<td>File Transfer Protocol</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>HSPA</td>
<td>High-Speed Packet Access</td>
</tr>
<tr>
<td>HSS</td>
<td>Home Subscriber Server</td>
</tr>
<tr>
<td>ID</td>
<td>Identity</td>
</tr>
<tr>
<td>IDFT</td>
<td>Inverse Discrete Fourier Transform</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>ISI</td>
<td>Inter-Symbol Interference</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>KPI</td>
<td>Key Performance Indicator</td>
</tr>
<tr>
<td>LoS</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
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<tr>
<td>MAE</td>
<td>Mean Absolute Error</td>
</tr>
<tr>
<td>MDT</td>
<td>Mechanical Downtilt</td>
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<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>MME</td>
<td>Mobility Management Entity</td>
</tr>
<tr>
<td>NE</td>
<td>Network Element</td>
</tr>
<tr>
<td>NLoS</td>
<td>Non Line of Sight</td>
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<tr>
<td>NM</td>
<td>Network Manager</td>
</tr>
<tr>
<td>NR</td>
<td>Network Resource</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
</tr>
<tr>
<td>OLSM</td>
<td>Open Loop Spatial Multiplexing</td>
</tr>
<tr>
<td>OS</td>
<td>Operations System</td>
</tr>
<tr>
<td>P-GW</td>
<td>PDN Gateway</td>
</tr>
<tr>
<td>PAPR</td>
<td>Peak-to-Average Power Ratio</td>
</tr>
<tr>
<td>PAR</td>
<td>Peak-to-Average Ratio</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>PCEF</td>
<td>Policy Control Enforcement Function</td>
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<tr>
<td>PCI</td>
<td>Physical Cell ID</td>
</tr>
<tr>
<td>PCRF</td>
<td>Policy and Charging Rules Function</td>
</tr>
<tr>
<td>PDCCH</td>
<td>Physical Downlink Control Channel</td>
</tr>
<tr>
<td>PDN</td>
<td>Packet Data Network</td>
</tr>
<tr>
<td>PM</td>
<td>Performance Management</td>
</tr>
<tr>
<td>PRB</td>
<td>Physical Resource Block</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RB</td>
<td>Resource Block</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
</tr>
<tr>
<td>RRM</td>
<td>Radio Resource Management</td>
</tr>
<tr>
<td>S-GW</td>
<td>Serving Gateway</td>
</tr>
<tr>
<td>SC</td>
<td>Scrambling Code</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single Carrier Frequency Division Multiple Access</td>
</tr>
<tr>
<td>SIMO</td>
<td>Single-Input Multiple-Output</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-Interference-plus-Noise Ratio</td>
</tr>
<tr>
<td>SNMP</td>
<td>Simple Network Management Protocol</td>
</tr>
<tr>
<td>SON</td>
<td>Self-organized Network</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TMA</td>
<td>Tower Mounted Amplifier</td>
</tr>
<tr>
<td>TMN</td>
<td>Telecommunication Management Network</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>VoIP</td>
<td>Voice over IP</td>
</tr>
<tr>
<td>WGS 84</td>
<td>World Geodetic System 1984</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

In this chapter, the scope of this thesis is described. The motivation for the development of this work is presented, as well as its main objectives. The document structure and the presented publication under its scope are also presented.

1.1 Motivation

A study made in 2018 by Ericsson, shows that the mobile data traffic is expected to increase significantly until 2023 [1]. This expected growth is presented in Figure 1.1, for the different regions of the world. It is possible to see that in 2017 the mobile data traffic per month, varied between 1 and 2.5 Exabytes, and the predictions for 2023, show a huge growth in these values, with the overall mobile data traffic being 6 to 11 times more than in 2017, reaching up to 25 Exabytes per month in the North East Asia. The main reasons for this are the increasing number of users, the increasing number of services and their higher bit rates, leading to much more complex mobile networks.

![Regional mobile data traffic (exabytes per month)](image)

Figure 1.1: Mobile data growth study from Ericsson [1].
With such complex mobile networks, its management is becoming much more difficult for the operators. Therefore, the technological improvement of these networks is necessary, and also its good planning and optimization.

In order to face this problem, the Fifth Generation (5G) of mobile communications is being designed and developed, and its initial deployment is expected by 2020. This technology promises to have characteristics such as higher transmission rates for download and upload, low latency, higher capacity, and more granularity in the management of the network. All of this, without significantly augmenting the end users costs. However, the development of this technology is still in its early stages, and the operators will also have to work with the Fourth Generation (4G) in order to handle the current traffic growth, and the requirements for the services associated with it.

1.2 Objectives

This work aims to fulfill two main objectives:

- The first is to propose, validate and optimize a C# tool, capable of showing the coverage planning of the mobile network, using Radio Frequency (RF) propagation models, and Drive Tests (DTs) for the models calibration.

- The second is to implement a propagation model for frequencies between 0.5 and 100 GHz (where all mobile technologies are included, such as Second Generation (2G) / Third Generation (3G) / 4G / 5G), allowing the coverage prediction of the mobile network in an urban and suburban/rural area, for the frequencies which will be part of the future network deployments.

Applications like this, represent a step towards the concept of Self-organized Network (SON), i.e., networks capable of autonomously change the network configuration, in order to improve its performance.

1.3 Thesis Outline

The following sections of this work, are structured as follows:

Chapter 2 presents a literature review. It starts with an overview of the Long Term Evolution (LTE) network, the methods for data collection of network performance, and also the propagation models. In Chapter 3, the RF Footprint Simulator is described. The required input data is presented, together with the algorithm description and also, the main modules of the simulator. Chapter 4 focus on the tool validation, along with the implemented optimizations, and on the implementation of the propagation model for the frequencies between 0.5 to 100 GHz. In Chapter 5, the optimizations results are presented, together with the results of coverage planning prediction for an urban and suburban/rural area. Finally, in chapter 6, the main conclusions of this work are highlighted, along with possible future work.
1.4 Publications

During the execution of this thesis, one article was submitted and presented in the URSI 2018 conference:

Chapter 2

State of the Art

2.1 Introduction

In this chapter, the state of the art and all the necessary theoretical knowledge for this work are presented. It starts with an LTE network overview, focusing on its architecture and the multiple access technologies. Then, the methods for data collection of the network performance are enumerated, highlighting the performance management, configuration management and DTs. Finally, the propagation models are also presented, with the description of the environment characteristics, multipath propagation, fading losses and path loss models.

2.2 Long Term Evolution

This section is based on [2–4].

The LTE is a standard for high-speed 4G wireless communication for mobile devices and data terminals, based on the Global System for Mobile Communications (GSM) Enhanced Data rates for GSM Evolution (EDGE) and Universal Mobile Telecommunications System (UMTS) High-Speed Packet Access (HSPA) technologies, which was developed by the Third Generation Partnership Project (3GPP).

The LTE refers to the access part of the Evolved Packet System (EPS) and its main goal is to provide high spectral efficiency, high peak data rates, short round trip time as well as flexibility in frequency and bandwidth [5].

2.2.1 LTE Architecture

The architecture of an LTE network consists of three main components, the User Equipment (UE), the Evolved Packet Core (EPC) and the Evolved UMTS Terrestrial Radio Network (E-UTRAN) [6], as shown in Figure 2.1. Both EPC and E-UTRAN architectures, are presented with more detail, in Figures 2.2 and 2.3, respectively.
As presented in Figure 2.1, the EPC communicates with the Packet Data Networks (PDNs), through the "SGi" interface. The "S1" interface interconnects the EPC and the E-UTRAN, while the "Uu" interface assures the communication between the E-UTRAN and UEs.

The EPC is responsible for the overall control of the UE and the establishment of the bearers, and its main logical nodes are the PDN Gateway (P-GW), Serving Gateway (S-GW) and Mobility Management Entity (MME). The EPC also has other logical nodes and functions such as the Home Subscriber Server (HSS) and the Policy and Charging Rules Function (PCRF):

- The HSS is a central database that contains information about all the networks operator’s subscribers.
- The PCRF is the component that is responsible for policy control decision-making, as well as for controlling the flow-based charging functionalities in the Policy Control Enforcement Function.
(PCEF), which resides in the P-GW.

- The P-GW allocates the Internet Protocol (IP) address for the UE, as well as Quality of Service (QoS) enforcement and flow-based charging, filtering the downlink user IP packets into the different QoS-based bearers.

- The S-GW behaves as a router and transfers all user IP packets, working as the local mobility anchor for the data bearers when the UE moves between the Evolved Node Base Stations (eNodeBs).

- The MME is the main control element in the EPC and it processes the signaling between the UE and the Core Network (CN).

---

The E-UTRAN is the radio component of the LTE and consists in a network of multiple eNodeBs, as illustrated in Figure 2.3. For normal traffic there is no centralized controller so this architecture is said to be flat. These evolved Base Stations (BSSs) are interconnected with each other through the “X2” interface, forming a mesh network. They can cover one or more cells and handle all the radio related protocols (e.g., handover). The E-UTRAN main functions are:

- Radio Resource Management (RRM) - This module covers all the functions related with the radio bearers, such as radio bearer control, radio admission control, radio mobility control, scheduling and dynamic allocation of resources to UEs, in both uplink and downlink.
- Header Compression – It helps to ensure efficient use of the radio interface by compressing the IP packet headers that could, otherwise, represent a significant overhead, especially for small packets such as Voice over IP (VoIP).
- Security – All data sent over the radio interface is encrypted.
- Connectivity to the EPC – It encompasses the signaling towards the MME and the bearer path through the S-GW.

### 2.2.2 LTE Multiple Access Technologies

The LTE uses two different access technologies, the Single Carrier Frequency Division Multiple Access (SC-FDMA) for uplink, and the Orthogonal Frequency Division Multiple Access (OFDMA) for downlink, as shown in Figure 2.4.

![Figure 2.4: OFDMA and SC-FDMA technologies](5).

In a Single Carrier transmission, as presented in more detail in Figure 2.5, the information is modulated only to one carrier, adjusting the phase and/or amplitude of the carrier, as well as the frequency. In a digital system, the higher the data rate, the higher the symbol rate, which increases the available bandwidth. The number of bits per symbol of the signal can be adjusted using Quadrature Amplitude Modulation (QAM).

![Figure 2.5: Single Carrier transmitter](2).

In the Frequency Division Multiple Access (FDMA), different users use different carriers or sub-carriers to access the system simultaneously with their data modulation, around a different center fre-
quency. The waveform must be created in a way that there is no excessive interference between the carriers without using extensive guard bands between users. Figure 2.6 presents the FDMA principle.

![FDMA principle](image)

Figure 2.6: FDMA principle [2].

In the Multi-Carrier principle, the data is divided in different sub-carriers for only one transmitter - see Figure 2.7.

![Multi-carrier principle](image)

Figure 2.7: Multi-carrier principle [2].

**SC-FDMA**

In the uplink, LTE uses SC-FDMA instead of OFDMA, since the latter presents a major drawback in the uplink. The transmitted signal power suffers large variations, resulting in a high Peak-to-Average Power Ratio (PAPR), causing problems for the transmitters power amplifier. In the downlink this is solved through the use of large and expensive devices in the BS transmitters, that can use expensive power amplifiers. This can not happen in the uplink, since the mobile transmitter needs to be as cheap as possible.

The basic form of the SC-FDMA technology is similar to the QAM modulation, where each symbol is sent one at a time, similarly to the Time Division Multiple Access (TDMA) systems. For the generation of the signal in the frequency domain, presented in Figure 2.8, the property of good spectral waveform of the OFDMA is added, which eliminates the need for guard bands between different users, as in the OFDMA downlink.
Also similarly to OFDMA, a cyclic extension is added periodically to the signal, but with the exception of not being added to the end of each symbol, due to the symbol rate being faster in SC-FDMA. This extension prevents the Inter-Symbol Interference (ISI) between blocks of symbols and also simplifies the receiver design. The remaining inter-symbol interference is handled by running the receiver equalizer at the receiver for a block of symbols, until reaching a guard period, called Cyclic Prefix (CP).

Figure 2.8: SC-FDMA transmitter and receiver with frequency domain signal generation [2].

With SC-FDMA, the transmission occupies the continuous part of the spectrum allocated to the user, and for LTE, the system facilitates a 1 ms resolution allocation rate. When the resource allocation in the frequency is doubled, so is the data rate, assuming that the level of overhead is the same. The individual transmission gets shorter in the time domain but wider in the frequency domain. The allocations do not need to have continuity in the frequency domain, but can take any set of continuous allocations of frequency domain resources. The allowed amount of 180 kHz resource blocks that can be allocated are defined by the practical signaling constraints. The maximum allocated bandwidth, which depends on the system bandwidth used, can be up to 20 MHz, but tends to be smaller as it is required to have a guard band towards the neighboring operator.

It is only in the time domain that the transmission is done, so the system keeps its good envelope properties and the waveform characteristics are highly dependent of the applied modulation method, which allows for SC-FDMA to reach a very low signal Peak-to-Average Ratio (PAR), and also makes the power amplifiers in the terminal devices more efficient.

Regarding the BS receiver for SC-FDMA, it is slightly more complex than the corresponding OFDMA receiver, especially if it needs equalizers able to perform as well as OFDMA receivers. These disadvantages are far less important then the advantages of using SC-FDMA for the uplink, such as range and device battery life time. However, by having a dynamic resource usage of 1 ms resolution, there is no base-band receiver per UE on standby but, for those who do have data to transmit, the BS is used dynamically. In any case, the part that consumes more resources, in both uplink and downlink receiver chains, is the channel decoding with increased data rates.
**OFDMA**

In order to avoid possible large guard bands, which can lead to the miss use of the available bandwidth, the system parameters are chosen in such a way that orthogonality between the different transmissions is achieved, as well as the creation of sub-carriers, in a way that they do not interfere with each other, but their spectrum can still overlap in the frequency domain. This is what OFDMA achieves, where the selection of the center frequency of the sub-carriers is made in order to the neighboring sub-carriers have zero value at the sampling instant of the desired sub-carrier, as shown in Figure 2.9.

![Figure 2.9: Maintaining the sub-carriers orthogonality](image)

The main reasons for the use of OFDMA in LTE are [2]:

- Good performance in frequency selective fading channels;
- Low complexity of base-band receiver;
- Good spectral properties and handling of multiple bandwidths;
- Link adaptation and frequency domain scheduling;
- Compatibility with advanced receiver and antenna technologies.

The challenges of OFDMA are [2]:

- Tolerance to frequency offset. This was solved in LTE design by choosing a sub-carrier spacing of 15 kHz, which gives a large enough tolerance for Doppler shift due to velocity and implementation imperfections.
- The high PAPR of the transmitted signal, which requires high linearity in the transmitter. The linear amplifiers have a low power conversion efficiency and therefore, they are not ideal for mobile uplinks. As stated in the previous section, this problem was solved by using the SC-FDMA, which enables better power amplifier efficiency.
The OFDMA is based on the use of Discrete Fourier Transform (DFT) and the Inverse Discrete Fourier Transform (IDFT) to move from time domain representation to a frequency domain one, and the other way around. In the case of LTE, the sub-carriers are spaced with 15 kHz from each other, and a CP is inserted between each symbol, shown in Figure 2.10, which is used to overcome the ISI that results from multipath delays.

![Figure 2.10: OFDMA transmitter and receiver [2].](image)

The CP is inserted by copying part of the symbol at the end of it, and attached to the beginning of the next symbol. It is preferable to use the CP than a break in transmission (guard interval), because using the CP will make it look like a periodic symbol, which causes an impact into the channel that seems like a multiplication by a scalar (if CP is long enough), allowing for a discrete Fourier spectrum, and enabling the use of the DFT and IDFT.

An advantage of using OFDMA in a BS transmitter is that it can allocate the users in any of its sub-carriers in the frequency domain, so that the scheduler benefit from frequency diversity. However, the resulting signalling resolution caused by the overhead, prevents this from happening, forcing the use of a Physical Resource Block (PRB) consisting of 12 sub-carriers, with a minimum of 180 kHz of bandwidth that can be allocated. In the time domain, this allocation corresponds to 1 ms and it is also denoted by one Transmission Time Interval (TTI), although each PRB lasts only 0.5 ms. In LTE, each PRB can be modulated independently, either through Quadrature Phase Shift Keying (QPSK) or QAM, more specifically 16-QAM and 64-QAM.
2.3 Data collection of network performance

With the evolution of the telecommunication networks complexity, new methods to collect data from the network to handle the needed monitoring and managing operations, started being applied. With these new methods, we can understand if the network is providing the required and established quality to the users, and they also grant a better network planning and optimization.

2.3.1 Performance Management

This subsection is based on [7, 8].

The Performance Management (PM) consists in the evaluation and reporting of both the behavior and effectiveness of network elements, by gathering statistical information, maintaining and examining historical logs, determining system performance and modifying the system modes of operation. The PM was one of the concepts added to the Telecommunication Management Network (TMN) standard, defined by the International Telecommunication Union (ITU), with the intention of managing the telecommunication networks and services as a measure to face the growing complexity of the networks. The other added concepts of TMN standard are security, fault, accounting and configuration.

The PM involves the configuration of data-collection methods and network testing, collection of performance data, optimization of the network service response time, proactive management and report, and management of the consistency and quality of the network services.

The PM also encompasses the measurement of network and application traffic in order to deliver a consistent and predictable level of service at a given instance, and across a defined period of time. To meet the performance requirements, this concept involves monitoring the network, application, and service activity and adjusting designs and configurations.

In order to solve potential threats in advance and prevent faults, the PM can help the operator by [8]:

- Informing the operator of impending performance deterioration.
- Managing and prioritizing traffic.
- Informing the operator of network availability and Key Performance Indicator (KPI) breaches.
- Network performance reporting in real time.
- Monitoring bandwidth and categorizing network application traffic.
- Providing the tools to pinpoint causes of performance deterioration or failure.

The PM system architecture consists in four layers:

- **Data Collection and Parsing Layer** - the data is collected using network specific protocols (e.g. File Transfer Protocol (FTP) and Simple Network Management Protocol (SNMP)), stored in files and sent to the parser.
• **Data Storage and Management Layer** - consists on a warehouse for the data from the parser, which is validated, normalized and where the process of KPIs calculation is initialized.

• **Application Layer** - processes all the collected and stored data.

• **Presentation Layer** - works as web-based user interface, presenting the PM results in the form of dashboards and real-time reports.

### 2.3.2 Configuration Management

This subsection is based on [9–11].

With the Configuration Management (CM), the operator has the ability to assure correct and effective operation of the network as it evolves. The CM takes care of both control and monitoring the active configuration of Network Elements (NEs) and Network Resources (NRs), which can be started by the operator or by functions in the Operations Systems (OSs) or NEs. These actions can be taken as part of an implementation or optimization program, and to maintain the general QoS. They may target only a single or several NEs as part of a complex procedure.

#### CM service components

Whenever a network is first installed and activated, the operators will enhance it, adapt it to fulfill short and long term requirements, and also optimize it to satisfy customer needs. To cover these requirements, the CM has to provide the operator a set of capabilities, such as initial system installation, system operation to adapt it to short and long term requirements, system update whenever is necessary, to overcome software bugs or equipment faults and system upgrade, to enhance or extend the network. All of these capabilities are provided by the management system, through the system modification service and monitoring service components.

The **system modification service component** is used whenever a new or modified data needs to be introduced into the system, due to optimization or new configurations. This concept includes the following aspects:

• When data modifications are performed due to subscriber traffic impacting, the NEs and NRs concerned are first cleared from traffic in a controlled way;

• The necessary modification is performed by the Element Manager (EM) or NE;

• The concerned NEs and NRs are only put back into traffic, once all needed data is given to the system;

• Safeguards are available within the NEs to prevent changes in the configuration from affecting service(s) in use. In emergencies, it is possible to override these safeguards.

The **system monitoring service component** allows the operator to receive reports on the configuration of the entire network or parts of it, from NEs. When an autonomous change of the states or
other values happens due to Fault Management (FM) actions, the NE sends spontaneous reports. Any inconsistencies found by the Network Manager (NM), need to be reported to the operator so that he can take further actions.

**CM functions**

The CM requirements took to the need of system modification functions, such as creation, deletion and conditioning of the NEs and NRs. For all of these functions, the following requirements are applied:

- Minimum disturbance of the network, if needed, by taking the affected resources out of service;
- Physical modifications and related logical modifications should be independent;
- Before the resources are brought into service, all required actions should be finished;
- Data consistency checks should be taken.

### 2.3.3 Drive Tests

This subsection is based on [12].

The DTs are another method to collect network data, that consists in a test performed in a cellular network, by collecting data while in a moving vehicle. The DTs provide real-world capture of the RF environment under a particular set of network and environmental conditions. The collected data can be relative to voice or other types of communications, and relative to coverage analysis and RF metrics.

In order to proceed with a DT, the required hardware is a notebook with specific installed software, at least one mobile phone and a Global Positioning System (GPS) device. The environment must be chosen accordingly to the DT type. Its factors are the area type, which can be urban, suburban or rural, the route and the day time. Concerning the day time, at daylight the DT shows the actual condition of the network, especially in relation to the loading aspect of it, while at night it is more adequate, for example, to test changes on the site parameters or to test transmitters, as the number of affected users will be minimized at this moment.

The duration of the phone calls also depends on the DT type, which can be of long or short duration. The long calls are for tests related with mobility and retainability of KPI categories, and they should be used to verify handovers. On the other hand, the short calls are for tests related with accessibility of KPI and they should be used to check the establishment and completion of a phone call.

The main types of DTs are:

- **Network Performance Analysis** - made into clusters or group of cells, and it is done in an area with sites of interest or in specific situations.

- **Integration of new sites** - where two types of tests can be performed: avoiding handover in order to check the site coverage level, and with handover to evaluate the site global performance once this is its final state.
• **Changes on Sites parameters** - where it is performed a DT similar to the integration of a new site.

• **Marketing** - which the company marketing area normally requests, for example showing the coverage in certain situations.

• **Benchmarking** - used to compare network performance within competitive operators.

The main disadvantage of DTs are the huge costs for mobile operators, which leads to the appearance and increasing use of new forms of acquiring network data [13].

### 2.4 Propagation Models

All subsections of Propagation Models are mainly based on [14–17].

The growth of wireless mobile communications brought the need for engineers, to understand and predict the radio-propagation characteristics in various urban and suburban areas, and even inside buildings, so that the capability to determine the optimum BSs location become possible. As site measurements are costly, propagation models have been developed as a low-cost and suitable alternative in order to provide guidelines for mobile systems.

These propagation models represent the mathematical formulation for the characteristics of the radio wave propagation, and they are based on factors as frequency, distance, terrain undulation or environment. They are used to evaluate specific cases of network performance and they produce results, mainly, relative to the received power signal, making use of data related with the environment characteristics and accounting for its influence on channel characteristics, like path loss, fading or time-delay spread.

The propagation models can be classified as empirical or deterministic models:

• **Empirical Models** are based on extensive measurement data. In these models all environment factors are implicitly considered, which makes them only valid for scenarios similar to the specific circumstances in which the data was gathered. They are easier to implement and require less computational effort, and they are also less affected by the environment geometry.

• **Deterministic Models** are based on the theory of electromagnetic wave propagation. These models rely on the knowledge of the propagation conditions instead of extensive measurements, providing accurate predictions of the received signal, making possible to extend the original test conditions. They require more computational effort and are more accurate, but require a lot of data regarding geometry, terrain profile or buildings locations.

Usually, in cellular planning, deterministic models are used for specific locations and set of circumstances, or in connections over irregular terrain, while empirical models are used for an average cellular-type mobile network in regular terrains.

For the study of propagation models, we must consider two main radio channel characteristics: fading and path loss.
2.4.1 Environment Characteristics

The propagation of a signal can be indoor or outdoor so, for each of these cases there are different models.

For the indoor scenario, the covered distance is much smaller and variability of the environment is much greater, since there are many different types of materials in buildings, and the format in which the rooms are displayed change a lot. For these reasons, the propagation for indoor cases has a much more complex multipath.

For the outdoor scenario, the type of area must be taken into account, being mostly divided into urban, suburban or rural. The terrain profile must also be considered, as it can be open area, flat ground surface, curved but smooth, hilly terrain or highly mountainous region. Lastly, the presence of obstacles such as trees, buildings and moving cars needs to be considered. The main types are defined as follows:

- **Urban areas** - city or large town with large buildings and houses with two or more floors, or large villages with close houses and tall, thickly grown trees;
- **Suburban areas** - village or highway scattered with trees and houses, some obstacles near the receiving antenna but not very congested;
- **Rural areas** - open space, no tall trees or buildings in propagation path, plot of land cleared for 300-400 m ahead.

Lastly, it is important to talk about the frequency Doppler effect on the channel characterization. This consist on a shift of the frequency due to the movement of the mobile wireless receiver [18].

The Doppler effect for radio, $f_{doppler}$, is given by:

$$f_{doppler}[Hz] = \frac{2v[m/s]f[Hz]}{c[m/s]}$$  \( (2.1) \)

where $v$ is the speed of the moving UE, $f$ is the carrier frequency and $c$ is the speed of light.

For example, if a wireless mobile phone is operating at 900 MHz and is traveling by car at 120 km/h, then the Doppler shift would be given by:

$$f_{doppler} = \frac{2 \times 120000 \times 900 \times 10^6}{3600 \times 3 \times 10^8} = 200Hz$$  \( (2.2) \)

This result means that, if the car is moving towards the BS, the real frequency is actually 200 Hz higher than 900 MHz, while if the car is moving away from the BS, it is 200 Hz lower. Even with such a small value for the Doppler Shift, this will have an impact in the processing of the modulated signal.

2.4.2 Multipath Propagation

In wireless communications, multipath propagation is the phenomenon of radio signals reaching the receiving antenna by more than one path. The receiving antenna receives the transmitted waves via multiple paths mainly due to atmospheric ducting, ionospheric reflection and refraction, and reflecting in water and objects, like mountains, buildings and trees.
The reflected signal has a longer distance to travel than the direct Line of Sight (LoS) one, reaching the receiver from different directions, amplitudes, phases and time delays, which can cause a constructive or destructive interference.

This phenomenon leads to lower values of the received power of the mobile antenna.

The radio channel output, $h(t)$, is the resulting sum of all of the paths contributions. As an example, if the input signal is a unit impulse, $\delta(t)$, the output will be the channel impulse response, which can be written as:

$$h(t) = \sum_{n=1}^{N} A_n \delta(t - \tau_n) \exp^{-j\varphi_n} \quad (2.3)$$

where $N$ is the number of paths with time delayed signals, $A_n$ is the amplitude, $\tau_n$ is the time delay from the first signal component, and $\varphi_n$ is the phase, in the multipath $n$.

Even though this interference degrades massively the performance of the communication systems, little can be done to eliminate it [16]. However, a better understanding of the medium and the propagation mechanisms, can lead to a better design of the system, achieving a better quality of service. Within the possible techniques to solve the interference problem, those that present better perspectives are related to diversity and spatial multiplexing, more specifically Multiple-Input Multiple-Output (MIMO) [19].

In the propagation of a signal, the direct path reflections, diffraction and scattering are the main contributions that impact the multipath propagation, hence, the power of a signal at a receiver. They are briefly explained below.

- **Reflection** occurs when the propagating wave hits an object of large dimension compared to the wavelength. The reflection contribution is mainly done by the surface of the ground and from walls of buildings. As reflection occurs, it may happen that the wave is also refracted. The coefficients of both reflection and refraction are related to the material properties of the medium in which the wave hits, and can depend on the polarization, the angle of incidence and the frequency of the propagation wave.

- **Diffraction** involves a change on the direction of the propagation waves, occurs when there is a surface with sharp edges obstructing the path between the transmitter and receiver, bending the electromagnetic waves and making it travel around. For high frequencies, diffraction depends on the geometry of the object, and amplitude, phase and polarization of the incident wave.

- **Scattering** occurs when the propagation wave hits a small object compared to the wavelength size, and goes through it. In mobile communications systems, the main inducers of scattering are the foliage, street signs, lampposts and stairs within buildings.

### 2.4.3 Fading

In free-space, a signal follows one path and arrives at the receiver without encountering any obstacles, leading to a small attenuation of the signal. Although these are the ideal characteristics of the path, this
is normally not the case, as all the buildings, hills, forests and other obstacles, in the path, will cause fading. This fading is characterized by changes in the intensity of the transmitted signal while travelling through the propagation path, from the transmitter to the receiver.

The fading effect has many types and it depends on the nature of the transmitted signal, and the characteristics of the channel. Figure 2.11 describes the different types of fading and the different relationships that exist among them [20]. It can be classified into two main groups, large-scale fading and small-scale fading. The large-scale fading is a result of signals that have encountered obstacles and travelled a long distance until the receiver, while the small-scale fading results from signals that travelled short distances, after encountering obstacles near the receiver.

In the small-scale fading group, if there is time spreading of the signal and the delay spread is greater than the symbol period, it is called frequency-selective fading, while if the delay spread is less than the symbol period it is called flat fading.

If there is time variance of the channel, due to Doppler effect, the channel can be considered as a fast-fading or slow-fading channel. If the channel impulse response changes at a rate much faster than the transmitted signal, it is assumed as a fast-fading channel [21]. Otherwise, the channel is assumed to be slow-fading.

### 2.4.4 Path Loss

The Path Loss, $L_p$, is the average RF attenuation that a transmitted signal suffers through the path between the transmitter and the receiver. It is defined as:

$$L_p[\text{dB}] = P_t[\text{dBm}] + G_t[\text{dBi}] + G_r[\text{dBi}] - P_r[\text{dBm}]$$ \hspace{1cm} (2.4)

where $P_t$ and $P_r$ are the transmitted and received power, respectively, and $G_t$ and $G_r$ are the gain
of the transmitting and the receiving antenna, respectively.

If the signal is traveling in free space, the Friis formula shows that the path loss is given by:

\[
L_p[dB] = 20 \log\left(\frac{4\pi d}{\lambda}\right)
\]

(2.5)

where \( \lambda \) is the wavelength and \( d \) is the distance between the transmitting antenna and the receiving antenna.

However, in an urban or rural environment, the free space condition is rarely verified, and it is necessary to apply different propagation models according to the propagation environment.

The most commonly used path loss models for outdoor environment are:

- Okumura-Hata model;
- COST-231 Walfisch-Ikegami model;
- Lee model;
- Dual-Slope model.

**Okumura-Hata Model**

The Okumura-Hata model defines the median value of the propagation path loss, for urban areas, as [22]:

\[
L_p[dB](urban) = 69.55 + 26.16 \log(f[MHz]) - 13.82 \log(h_{be}[m])
+ [44.90 - 6.55 \log(h_{be}[m])] \log(d[km]) - a(h_{re}[m])[dB]
\]

(2.6)

where \( f \) is the carrier frequency, \( h_{be} \) is the effective height of the BS antenna, \( h_{re} \) is the effective height of the receiver antenna, \( d \) is the distance of the propagation path and \( a(h_{re}) \) is the correction factor for the effective height of the receiving antenna.

For small and medium sized cities, the correction factor is given by:

\[
a(h_{re})[dB] = (1.11 \log(f[MHz]) - 0.7)h_{re}[m] - (1.56 \log(f[MHz]) - 0.8)
\]

(2.7)

while for a large city, it is given by:

\[
a(h_{re})[dB] = \begin{cases} 
8.29(\log^2(1.54 h_{re}[m])) - 1.1 & \text{for } f_{[MHz]} \leq 300 \\
3.2(\log^2(11.75 h_{re}[m])) - 4.97 & \text{for } f_{[MHz]} > 300
\end{cases}
\]

(2.8)

In order to obtain the path loss for a suburban area, it is necessary to had a correction factor to the urban formula:

\[
L_p[dB](suburban) = L_p[dB](urban) - 2[\log^2\left(\frac{f_{[MHz]}}{28}\right)] - 5.4
\]

(2.9)

For rural and open areas, the resulting formula with its correction factor is:
\[
L_{p[\text{dB}]}(\text{rural}) = L_{p[\text{dB}]}(\text{urban}) - 4.78 \log^2(f_{\text{MHz}}) + 18.33 \log(f_{\text{MHz}}) - 40.98 \tag{2.10}
\]

The Okumura-Hata model is restricted to:

- \( f \in [150, 2000] \text{MHz} \);
- \( d \in [1, 100] \text{km} \);
- \( h_{\text{be}} \in [30, 1000] \text{m} \);
- \( h_{\text{re}} \in [1, 10] \text{m} \).

**COST-231 Walfisch-Ikegami Model**

The COST-231 Walfisch-Ikegami model utilizes the theoretical Walfisch-Bertoni model \cite{23}, and it is composed of three terms, defining the median value of the propagation path loss as \cite{24}:

\[
L_{p[\text{dB}]} = \begin{cases} 
L_0[\text{dB}] & \text{for } L_{\text{rts}[\text{dB}]} + L_{\text{msd}[\text{dB}]} \leq 0 \\
L_0[\text{dB}] + L_{\text{rts}[\text{dB}]} + L_{\text{msd}[\text{dB}]} & \text{for } L_{\text{rts}[\text{dB}]} + L_{\text{msd}[\text{dB}]} > 0 
\end{cases} \tag{2.11}
\]

where \( L_0 \) represents the free space propagation loss, \( L_{\text{rts}} \) is the roof-top-to-street diffraction and scattering loss and \( L_{\text{msd}} \) is the multi-screen diffraction loss.

The free space propagation loss, \( L_0 \), is given by:

\[
L_0[\text{dB}] = 32.4 + 20 \log(d_{\text{km}}) + 20 \log(f_{\text{MHz}}) \tag{2.12}
\]

where \( d \) is the distance between the BS and UE antennas, and \( f \) is the carrier frequency.

The roof-top-to-street diffraction and scattering loss, \( L_{\text{rts}} \), is given by:

\[
L_{\text{rts}[\text{dB}]} = -16.9 - 10 \log(w_{\text{s}[\text{m}]}) + 10 \log(f_{\text{MHz}}) + 20 \log(h_{\text{Roof}[\text{m}]} - h_{\text{m}[\text{m}]}) + L_{\text{ori}[\text{dB}]} \tag{2.13}
\]

where \( w_{\text{s}} \) is the street width, \( h_{\text{Roof}} \) is the height of the building in which the BS antenna is, and \( h_{\text{m}} \) is the height of the mobile antenna, and \( L_{\text{ori}} \) is the orientation loss.

The orientation loss, \( L_{\text{ori}} \), is given by:

\[
L_{\text{ori}[\text{dB}]} = \begin{cases} 
-10 + 0.354\phi & \text{for } 0^\circ \leq \phi < 35^\circ \\
2.5 + 0.075(\phi - 35) & \text{for } 35^\circ \leq \phi < 55^\circ \\
4.0 - 0.114(\phi - 55) & \text{for } 55^\circ \leq \phi \leq 90^\circ 
\end{cases} \tag{2.14}
\]

where \( \phi \) is the angle of incidence relative to the direction of the street.

The multi-screen diffraction loss, \( L_{\text{msd}} \), is given by:

\[
L_{\text{msd}[\text{dB}]} = L_{\text{hsh}[\text{dB}]} + k_a + k_d \log(d_{\text{km}}) + k_f \log(f_{\text{MHz}}) - 9 \log(w_{\text{b}[\text{m}]}) \tag{2.15}
\]
where \( w_b \) is the distance between buildings along the signal path, \( L_{bsh} \) and \( k_a \) represent the increase of path loss due to a reduced BS antenna height, \( k_d \) and \( k_f \) are terms that control the dependence of the multi-screen diffraction loss as a function of distance, and the radio frequency of operation, respectively.

The loss due to a reduced BS antenna height, \( L_{bsh} \), is given by:

\[
L_{bsh}[dB] = \begin{cases} 
0 & \text{for } h_{BS}[m] \leq h_{Roof}[m] \\
-18 \log((h_{BS}[m] - h_{Roof}[m]) + 1) & \text{for } h_{BS}[m] > h_{Roof}[m]
\end{cases}
\]

where \( h_{BS} \) is the BS antenna height.

The terms \( k_a \) and \( k_d \), are given by:

\[
k_a = \begin{cases} 
54 & \text{for } h_{BS}[m] > h_{Roof}[m] \\
54 - 0.8(h_{BS}[m] - h_{Roof}[m]) & \text{for } d[km] \geq 0.5 \text{ and } h_{BS}[m] \leq h_{Roof}[m] \\
54 - 1.6(h_{BS}[m] - h_{Roof}[m])d[km] & \text{for } d[km] < 0.5 \text{ and } h_{BS}[m] \leq h_{Roof}[m]
\end{cases}
\]

\[
k_d = \begin{cases} 
18 & \text{for } h_{BS}[m] > h_{Roof}[m] \\
18 - 15 \frac{h_{BS}[m] - h_{Roof}[m]}{h_{Roof}[m]} & \text{for } h_{BS}[m] \leq h_{Roof}[m]
\end{cases}
\]

Lastly, the term \( k_f \), is given by:

\[
k_f = \begin{cases} 
-4 + 0.7\left(\frac{f[MHz]}{925}\right) - 1 & \text{for urban and suburban areas} \\
-4 + 1.5\left(\frac{f[MHz]}{925}\right) - 1 & \text{for dense urban areas}
\end{cases}
\]

The COST-231 Wallisch-Ikegami model is restricted to:

- \( f \in [800, 2000] MHz \);
- \( d \in [0.02, 5] km \);
- \( h_{BS} \in [4, 50] m \);
- \( h_m \in [1, 3] m \).

And in the absence of specific values, the following are recommended:

- \( w_b \in [20, 50] m \);
- \( w_s[m] = \frac{w_{b[m]}}{2} \);
- \( h_{Roof}[m] = 3 \ast (\# \text{floors}) + 3 \) for pitched roofs;
- \( h_{Roof}[m] = 3 \ast (\# \text{floors}) \) for flat roofs.

**Lee Model**

The Lee model is a point-to-point model that forecasts the received power mean along a radial in a mobile communications environment. This model allows measurement integration [15], being able to
approximate the model to a specific environment, through the use of DTs, in order to minimize the error between the prediction and the real network measurements.

This model defines the received power as:

\[
Pr[dBm] = Pr_0[dBm] - \gamma[dB/\text{decade}] \log\left(\frac{d[km]}{d_0[km]}\right) + Af[dB] + G_{Effh}[dB](h_{be}[m], h_{BS}[m]) + L[dB] + \alpha[dB] \tag{2.20}
\]

where \(Pr_0\) is the received power at the intercept point, \(\gamma\) is the propagation attenuation decay, \(d\) is the distance between antennas, \(d_0\) is the distance between the BS and the intercept point, \(G_{Effh}\) is the gain associated to the effective height of the antenna, \(h_{be}\) is the effective height of the BS antenna, \(h_{BS}\) is the real height of the BS antenna, \(L\) is the diffraction losses of the terrain, Shadow Loss, \(Af\) is the adjustment factor of the carrier frequency, and \(\alpha\) is the adjustment factor of the signal.

In order to get the values for \(Pr_0\) and \(\gamma\), data collection is needed, through the execution of network measurements, namely DTs, for each specific city. If this data can not be collected, it is possible to use the values presented in Table 2.1 \[15\].

Table 2.1: Received power at the intercept point and propagation attenuation decay for different environments.

<table>
<thead>
<tr>
<th>Environment</th>
<th>(Pr_0[dBm])</th>
<th>(\gamma[dB/\text{dec}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Space</td>
<td>-45.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Open Area</td>
<td>-49.0</td>
<td>43.5</td>
</tr>
<tr>
<td>Suburban</td>
<td>-61.7</td>
<td>38.4</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>-70.0</td>
<td>36.8</td>
</tr>
<tr>
<td>Newark</td>
<td>-64.0</td>
<td>43.1</td>
</tr>
<tr>
<td>Tokyo</td>
<td>-84.0</td>
<td>30.5</td>
</tr>
<tr>
<td>New York</td>
<td>-77.0</td>
<td>48.9</td>
</tr>
</tbody>
</table>

For urban environments, the adjustment factor of the carrier frequency, \(Af\), is given by:

\[
Af[dB] = \begin{cases} 
-30\log\left(\frac{f[MHz]}{850}\right) - 20\log\left(\frac{f[MHz]}{850}\right) & \text{for } 150 \leq f[MHz] < 450 \\
-30\log\left(\frac{f[MHz]}{850}\right) & \text{for } 450 \leq f[MHz] \leq 2400
\end{cases} \tag{2.21}
\]

while for other environments, the following formula applies:

\[
Af[dB] = \begin{cases} 
-20\log\left(\frac{f[MHz]}{850}\right) & \text{for } 150 \leq f[MHz] < 850 \\
-30\log\left(\frac{f[MHz]}{850}\right) & \text{for } 850 \leq f[MHz] \leq 2400
\end{cases} \tag{2.22}
\]

The gain associated to the effective height of the antenna, \(G_{Effh}\), is given by:
$$G_{Eff}[dB] = \begin{cases} 
20\log\left(\frac{h_{be}[m]}{h_{BS}[m]}\right) \text{ for a rising terrain or flat terrain with } h_{be}[m] > h_{BS}[m] \\
6\log\left(\frac{h_{be}[m]}{h_{BS}[m]}\right) \text{ for a descending terrain or flat terrain with } h_{be}[m] < h_{BS}[m] 
\end{cases}$$
(2.23)

The diffraction losses of the terrain, $L$ is given by:

$$L_{[dB]} = \begin{cases} 
0 \text{ for } 1 \leq v \\
20\log(0.5 + 0.62v) \text{ for } 0 \leq v < 1 \\
20\log(0.5e^{0.95v}) \text{ for } -1 \leq v < 0 \\
20\log(-\frac{0.255}{v}) \text{ for } v < -2.4 
\end{cases}$$
(2.24)

where $v$ is an dimensionless parameter given by:

$$v = -h_p[m] \sqrt{\frac{2}{\lambda[m]} \left(\frac{1}{r_1[m]} + \frac{1}{r_2[m]}\right)}$$
(2.25)

where $h_p$ is the height of obstruction above or below the direct LoS, $\lambda$ is the wavelength, $r_1$ is the distance between the BS and the obstacle and $r_2$ is the distance between the obstacle and the mobile antenna.

Lastly, the adjustment factor of the signal, $\alpha$, is given by:

$$\alpha_{[dB]} = 10\log\left(\frac{P_{t1}[W]}{P_{t2}[W]}\right) + 20\log\left(\frac{h_1'[m]}{h_1[m]}\right) + 10\log\left(\frac{h_2'[m]}{h_2[m]}\right) + (g_{t2}[dBd] - g_{t2}[dBd]) + (g_{m}[dBd] - g_{m}[dBd])$$
(2.26)

where $P_{t1}$ is the actual transmitted power by the BS, $P_t$ is the standard transmitted power by the BS, 10 W, $h_1'$ is the BS height, $h_1$ is the standard BS height, 30 m, $h_2'$ is the mobile antenna height, $h_2$ is the standard mobile antenna height, 3 m, $g_{t2}$ is the BS antenna gain, $g_{t2}$ is the standard BS antenna gain, 6 dBd, $g_{m}'$ is the mobile antenna gain and $g_m$ is the standard mobile antenna gain, 0 dBd.

**Dual-Slope Model**

The Dual-Slope model is based on a two-ray model [25, 26]. This model is suitable for LoS propagation regions [16], and defines the median value of the propagation path loss as a function of the distance between the BS and the receiver, $d$, given by [27]:

$$L_{b}[dB] + 10n_1\log(d[m]) + L(d_0) \text{ for } 1 < d[m] < d_{BP}[m]$$

$$L_{b}[dB] + 10(n_1 - n_2)\log(d_{BP}[m]) + L(d_0) \text{ for } d[m] \geq d_{BP}[m]$$
(2.27)

where $d_{BP}$ is the breakpoint distance, $L_b$ is a basic transmission-loss parameter that depends on
the carrier frequency and antenna heights, $n_1$ and $n_2$ represent the slopes of the best-fit line before and after the breakpoint, and $L(d_0)$ is the path loss at the reference point.
Chapter 3

Radio Frequency Footprint Simulator

3.1 Introduction

This chapter introduces the RF Footprint Module tool, used during this thesis development. It allows to simulate and design the telecommunications networks cells footprints based on several input parameters, which can be based on real network data or entirely theoretical. This tool, together with its map representation, was developed by Celfinet, and its enhancement is also within the scope of this work.

In telecommunications, a footprint represents the cell coverage area, as well as the respective signal level in each position. Usually, this type of simulation uses Propagation Models calculation, selected according to the environment where the cell is inserted, and with the typical parameters of each environment. In this work, the simulations are going to be performed using real and specific data from the environment under test. This data encompasses, terrain elevation, buildings and network parameters, as well as BSs position and cells height. Additionally, drive-tests data is going to be used for validation purposes. Thus, the performed simulations are expected to be much closer from what happens in a real network, allowing to produce footprints which reflects how is the network behaviour in terms of coverage, providing a powerful tool for both network planning and optimization.

This chapter presents a brief explanation of the main algorithm modules, and some processes used to produce the cells footprint. The necessary input data is detailed and configuration parameters are explained, depending on whether it is a pure or real network simulation.

3.2 Introducing Input Data

Since this thesis work is based on real network data regarding its simulations and results, the RF needs some input network parameters to operate in this scenario. Those inputs are the network topology, terrain elevation data, DTs if calibration is desirable and, a configuration module. A brief description of them is provided in the following subsections.
3.2.1 Network Topology

In order to calculate the received power, it is required to know the characteristics and some parameters of the cells under test (target cell). Moreover, the algorithm also needs certain characteristics from the target cell neighbours (surrounding cells) since, in some situations, there are not enough DTs for calibration in the chosen cell and thus, depending on certain evaluation factors, DTs from the surrounding cells may be used.

The required parameters are:

- Carrier frequency;
- Height of the BS;
- Cell Identity (ID), which as to be unique in the network;
- Latitude and Longitude;
- Electrical Downtilt (EDT) and Mechanical Downtilt (MDT);
- Technology, 3G, 4G or 5G;
- Type, Macro, Micro or Indoor.

There are other parameters that have default values, thus, they are not mandatory but can be given:

- Antenna Gain, default value of 17 dBi;
- Beam Width 3 dB, default value of 10°;
- Power Transmitted, default value of 33.2 dBm.

3.2.2 Terrain Elevation

The terrain elevation is obtained from Eurostat [28]. This raster contains a Digital Elevation Model (DEM) and it gives the representation of the terrain elevation. The Rasters are converted to the geographic coordinate system, World Geodetic System 1984 (WGS 84), before being used by the algorithm.

The resolution of each bin used for the raster is presented in Table 3.1. For each bin, the value of height is given by the mean of all values inside the bin area of the raster, taking the buildings into account.

<table>
<thead>
<tr>
<th>Coordinate</th>
<th>Resolution [°]</th>
<th>Bin Size [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta_{LAT} )</td>
<td>0.000272</td>
<td>30.3</td>
</tr>
<tr>
<td>( \Delta_{LON} )</td>
<td>0.000224</td>
<td>24.9</td>
</tr>
</tbody>
</table>
3.2.3 Drive Tests

The RF Footprint module has the functionality of calibrating the radio propagation model in order to obtain the best possible results and in such scenario, DTs data is needed.

The DTs are defined as a collection of “Drive Test Samples” in the algorithm, where the following parameters are collected from real DTs data:

- Cell ID(s) and respective received signal values, for all the cells scanned in each of the DT samples location;
- A unique code for each Cell ID, which can be the Base Station Identity Code (BSIC), Scrambling Code (SC) or Physical Cell ID (PCI), depending on the cell technology;
- Location: latitude and longitude of the sample;
- Power(s) Received, one for each Cell ID.

As explained previously, if there are few or no DTs at all, there are two options; either the “default” values of the propagation model are used, or use surrounding cells, in order to obtain more DTs.

3.2.4 Configuration Module

The configuration module consists in the parameters given by the user that define some aspects of the simulation. These parameters are:

- The Cell ID of the target cell;
- The Radius, in kilometers, for which the footprint will be calculated;
- The Surrounding Cells Number, which are the number of cells that the calibration will take into account;
- The Surrounding Cells Percentage, which is the percentage of the surrounding cells number to be ranked and selected.

The Footprint module will be executed for each target cell, which is chosen by the user, and only for this cell a footprint will be generated. As for the surrounding cells, only cells with the same frequency of the target cell will be loaded by the algorithm.

3.3 Algorithm Description

This section presents a brief explanation of the main algorithm modules, and some processes used to produce the cells footprint.

The algorithm calculates all the necessary specifications in order to estimate the expected received power of a mobile user, through radio frequency propagation models, served by a certain cell of a BS,
The final result is a matrix where each entry is a bin, that represents a rectangular area of the terrain. Each of those entries (bins) is assigned with an expected received power value in dBm, and it is colored according to the interval in which the value is, forming a footprint.

The algorithm was programmed using Visual Studio 2017, which uses C# code, which is an object-oriented programming language used on the .NET platform. Therefore, not only to understand how the algorithm works was necessary, but also, to study and learn about the C# programming language.

This algorithm is divided in three main parts. The **Executor** starts the program and runs both the **Data Loader** and the **Processor**. The **Data Loader**, loads all necessary inputs from a data base and the **Processor** uses all this loaded data to calculate the necessary values to generate the footprint.

The main operations of the **Data Loader** and the **Processor** are presented in Figure 3.1. A brief explanation of the interaction between the Data Loader and the Processor is described below.

![Figure 3.1: Data Loader and Processor main operations.](image)

⇒ **Data Loader**

- The Data Loader receives the configuration of the network, with values for the size of the resulting footprint, surrounding cells number, surrounding cells percentage and the ID of the selected cell (target cell) to estimate the footprint.

- It starts by creating the terrain matrix for a specific area from a .tiff file. Then it creates the raster matrix, where each element of this matrix corresponds to a pixel of the image, with the average height of the terrain plus buildings in that bin.
After creating the terrain matrix, it makes a list of the target cell neighbours (surrounding cells), by frequency. Afterwards, it orders this list by proximity to the target cell, and only keeps as many cells as the value of surrounding cells number, which is specific for each algorithm running instance.

Once the surrounding cells are determined, for each one of them, the corresponding DTs are obtained, by technology. To achieve this, a bounding box is created, around all the selected cells (target plus surrounding), and the DTs within this area are collected.

**Processor**

The Processor works with the outputs of the Data Loader, i.e., the terrain matrix, target and surrounding cells, DTs by cell and the configuration of the network.

For the target cell, a piece of the terrain matrix is selected, depending on the size of the footprint that is aimed to estimate. This piece of terrain, is centered in the target cell, and its radius is also, a specific parameter of each instance of the algorithm. For simplicity, this new smaller matrix around the target cell, is called cropped matrix and it is presented in Figure 3.2. This process is repeated for each of the surrounding cells.

![General Matrix](image1.png)  ![Cropped Matrix](image2.png)  ![Footprint Radius](image3.png)

**Figure 3.2:** Cropped matrix and footprint radius representation.

Once the cropped matrices are created, the parameters needed for the path loss model, the azimuth, the distance to the cell, the effective height between the cell and the UE, the vertical angle, gain of the antenna, diffraction losses of the path, terrain dispersion and cell density, are calculated for each entry.
• After the estimation of the parameters, the cells are filtered according to the value of the surrounding cells percentage. These cells are chosen through similarity with the target cell, which has two indexes, terrain dispersion and cell density.

• Once the cells are filtered, a path loss sample list is created, where each element has the location and received power value for each DT.

• The calibration is then performed, running for the target cell. It starts by checking if the cell is in line of sight with each path loss sample, to assure if there are diffraction losses. After that, the values for the model factors are calculated, using the Constrained Least Squares method.

• The path loss matrix is then calculated for the target cell, using the chosen propagation model, and finally, the received power matrix is estimated in order to draw the target cell footprint.

• The final algorithm output, should be the resulting footprint of the target cell. Figure 3.3 presents the footprint of a target cell located in Intendente, Lisbon.

![Figure 3.3: Resulting footprint of a cell from Intendente Lisbon.](image)

3.4 Main Modules Operation

3.4.1 Surrounding Cells Selection

As stated before, a certain number of surrounding cells is usually needed due to the lack of DTs, what would lead to an unreliable calibration, nevertheless, ideally, only the target cell as well as the corresponding DTs should be used. When the surrounding cells are needed, they are chosen by frequency
and proximity to the target cell. The number of required Surrounding Cells varies with the target cell location and with the number of DTs available on that area.

The percentage of surrounding cells used, is chosen by similarity with the target cell. If the surrounding cells number is 100 and the percentage given by the user for the surrounding cells is 80%, only the 80 most similar cells to the target cell will be used. This similarity is given by the indexes of terrain dispersion and cell density, which are estimated for each cell, and those with the closest indexes are the most similar.

In order to get the estimation of the terrain dispersion index, the elevation of every bin within a radius, which is defined by a tier finder algorithm (a Celfinet algorithm), is stored. Then, the 10th quantile is subtracted to the 90th quantile of that distribution of elevations, resulting in the dispersion of the terrain in that region of interest.

The cell density is calculated by dividing the number of surrounding cells chosen, by the area that contains those cells, where the result is given in cells per squared kilometer ($\text{cells/km}^2$).

Some limitations of these metrics are:

- It is possible that some far away cells have a more similar terrain than those close to the target cell. These far away cells can belong to a different clutter, which is a problem since this can be worse than using cells with different terrain but same clutter.
- When deploying sites of a given frequency, cell density might be highly misleading;
- Cell density is dependent of the “Surrounding Cells Number” input parameter.

### 3.4.2 Estimation of the Cell Parameters

As mentioned before, the terrain elevation data is represented by a matrix, and for each cell, it is selected part of this terrain matrix, creating a smaller one, that corresponds to the surrounding area of each cell. To estimate the received power, in order to get the resulting footprint, it is necessary to calculate some parameters for each entry of the respective cell matrix. Those parameters and their dependencies are listed in Table 3.2.

**Azimuth**

In order to calculate the azimuths, it is necessary to estimate the angle between the position of the cell and the position of each entry of the matrix, and then, it is subtracted the azimuth of the cell. If the result is lower then 0 degrees it is added 360 degrees to the result.

**Distance**

The distances matrix is built by calculating the Euclidean distance between the cell location to every bin (entry) in the matrix. The Euclidean distance for two dimensions is given by:

$$d(p, q)[m] = \sqrt{(q_1[m] - p_1[m])^2 + (q_2[m] - p_2[m])^2} \quad (3.1)$$
Table 3.2: Cell parameters and their dependencies.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Dependencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain Elevation</td>
<td>[m]</td>
<td>Explained in Section 3.2.2</td>
</tr>
<tr>
<td>Azimuth</td>
<td>[°]</td>
<td>Terrain Elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cells location and azimuth</td>
</tr>
<tr>
<td>Distance</td>
<td>[m]</td>
<td>Terrain Elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cells location and height</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UE height</td>
</tr>
<tr>
<td>Effective Height</td>
<td>[m]</td>
<td>Terrain Elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cells location and height</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UE height</td>
</tr>
<tr>
<td>Vertical Angle</td>
<td>[°]</td>
<td>Terrain Elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cells location and height</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UE height</td>
</tr>
<tr>
<td>Transmission Gain</td>
<td>[dBi]</td>
<td>Azimuth</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vertical Angle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Antennas radiation pattern</td>
</tr>
<tr>
<td>Diffraction Losses</td>
<td>[dB]</td>
<td>Terrain Elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cells location and height</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UE height</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deygout Model</td>
</tr>
</tbody>
</table>

Effective Height

The effective height, \( h_{ef} \), is equal to the module of the difference between the BS height, \( h_{BS} \), and the height of the UE, \( h_{UE} \). The BS height is the terrain elevation at the BS position plus the antenna height, and the height of the UE is the terrain elevation at that position plus 1.5 meters (by default the height of mobile antenna from the terrain is 1.5 meters).

The formula for the effective height is given by:

\[
h_{ef[m]} = |h_{BS[m]} - h_{UE[m]}| \tag{3.2}
\]

Vertical Angle

The vertical angle is equal to the inverse tangent of the effective height, dividing by the distance from the BS and the bin. As it is used in degrees, it is necessary to multiply by 180 degrees and divide by pi.

The formula of the vertical angle is given by:

\[
VerticalAngle_{[\circ]} = \tan^{-1}(\frac{h_{BS[m]} - h_{UE[m]}}{d[m]}) \times \frac{180^\circ}{\pi} \tag{3.3}
\]

Transmission Gain

In order to estimate the transmission gain in every bin, it can be used the real or the theoretical radiation patterns. In this algorithm the theoretical radiation pattern is used, since the previously mentioned
Figure 3.4: Theoretical radiation pattern, on the left the horizontal lobe and on the right the vertical lobe.

parameters are sometimes inaccurate, either due to database errors, or due to measures of the terrain elevation.

Even if the theoretical pattern is not a perfect approximation of a real scenario, it still presents better results, since the real radiation pattern is much more sensible for miscalculated angles.

For the estimation of the theoretical radiation pattern, presented in Figure 3.4, it is necessary to calculate the vertical and horizontal attenuation \([29, 30]\).

The horizontal attenuation is given by:

\[
A_{h[dB]}(\phi) = -\min[12 \times (\frac{\phi_{h[\degree]}}{\phi_{3dB[\degree]}})^2, A_{m[dB]}]
\]

(3.4)

where:

- \(\phi_{3dB[\degree]}\), has a typical value of 65\(^\circ\);
- \(A_{m[dB]}\), has typical value of 25 dB as recommended by 3GPP;
- \(-180 \leq \phi_{h[\degree]} \leq 180\).

While the vertical attenuation is given by:

\[
A_{h[dB]}(\phi) = -\min[12 \times (\frac{\phi_{v[\degree]}}{\phi_{3dB[\degree]}})^2, SLA_{v[dB]}]
\]

(3.5)

where:

- \(\phi_{3dB[\degree]}\), has a typical value of 10\(^\circ\);
- \(SLA_{v[dB]}\), has typical value of 20 dB as recommended by 3GPP;
- \(-180 \leq \phi_{v[\degree]} \leq 180\).

Finally, the transmission gain can be calculated, as a result of the sum of the maximum gain of the antenna, which is usually around 17 dBi, and both antennas attenuation values:
Figure 3.5: Deygout geometry for a single edge obstacle [31].

\[ G_{t[dB]} = G_{max[dB]} + A_h[dB] + A_v[dB] \]  

(3.6)

**Diffraction Losses**

For the estimation of the diffraction losses in every bin, the modified Deygout method presented on the recommendation ITU-R P.526 [31], is used.

The geometry respective calculations for this method are shown in Figure 3.5.

Given this geometry, the necessary formulas to estimate the diffraction losses are:

\[ J_{[dB]}(v) = 6.9 + 20 \log_{10}(\sqrt{(v - 0.1)^2 + 1} + v - 0.1) \]  

(3.7)

\[ v_n = \bar{h} \sqrt{\frac{2d_{ab}}{\lambda d_{an}d_{nb}}} \]  

(3.8)

\[ \bar{h} = h_n + \frac{d_{an}d_{nb}}{2r_c} - h_a d_{ab} + h_b d_{an} \]  

(3.9)

where:

- \( v \) is a dimensionless parameter that is a combination of the profile geometric characteristics;
- \( J(v) \) is the diffraction losses from a single step of the profile;
- \( \bar{h} \) is the difference between the obstacle height and the height of direct line of sight between both antennas;
• $h_a$, $h_b$ and $h_n$ are the vertical heights shown in Figure 3.5;
• $d_{ab}$, $d_{an}$ and $d_{nb}$ are the horizontal distances shown in Figure 3.5;
• all variables are in self consistent units (for example all in meters).

Since the diffraction losses are estimated for a given profile, for every step of that profile, the value of the dimensionless parameter $v$, needs to be calculated. Then, if the highest value of $v$, which is where the main obstacle is located, nominated $v_p$, is higher than -0.78, the value of $J(v_p)$ is calculated. After this, the link is divided on that point in two links, one that comes from the transmitter to the obstacle and other from the obstacle to the receiver. The highest values of $v$ in these links, are nominated $v_t$ and $v_r$, respectively. Then, if $v_t$ is higher than -0.78, the value of $J(v_t)$ is calculated, and the same process is applied for $v_r$.

Finally, the total value of the diffraction losses is given by the following equations:

$$
\begin{cases}
  v_p > -0.78 \rightarrow L_{df}[dB] = J_{[dB]}(v_p) + T(J_{[dB]}(v_t) + J_{[dB]}(v_r) + C) \\
  v_p \leq -0.78 \rightarrow L_{df}[dB] = 0
\end{cases}
$$

(3.10)

where:

$$
C = 10 + 0.04D_{[km]}
$$

(3.11)

$$
T = 1 - e^{-\frac{J_{[dB]}(v_p)}{6}}
$$

(3.12)

• $T$ and $C$ are empirical corrections;
• $D$ is the total links distance.

In this algorithm, the Deygout method is applied up to the three main obstacles of the path, meaning that for each bin all these equations might occur a maximum of three times.

### 3.4.3 Path Loss Model

To estimate the received power matrix, in order to draw the footprint of the cell, it is necessary to calculate the received power from the cell on a given bin, which can be calculated through the formula below:

$$
P_{r[dBm]} = P_{t[dBm]} + G_{t[dBi]} + G_{r[dBi]} - L_{p[dB]}
$$

(3.13)

Since the receiving antennas are isotropic, which means a 0 dBi gain, and based of the calculations aforementioned, the only missing the only missing value is the path loss.

In this algorithm the model used to estimate the path loss attenuation is a combination of the COST-231 Hata and Lee model, resulting in the formula:

$$
L_{p[dB]} = k_1 + k_2\log_{10}(h_{ef}[m]) + k_3\log_{10}(d_{[km]}) + k_4L_{df}[dB]
$$

(3.14)
where:

- $k_1$, $k_2$, $k_3$ and $k_4$ are independent factors associated with frequency, effective height, distance and diffraction losses respectively.

Finally, the footprint can be calculated using the equations 3.13 and 3.14.

### 3.4.4 Calibration

The calibration of the path loss model should be used, since the propagation models are a general approach for a certain environments (urban, in this case), but they do not take into account specific aspects of each city so, depending on the available network metrics, worse results would be acquired when calibration is not used. The DTs allow this model calibration to a certain city, as they represent realistic values of the received power by a user, in a specific place.

The independent factors of the path loss model are calculated through the calibration of the model. This calibration is done with the DTs loaded from the data base. For each DT sample, the necessary parameters to be loaded are its location and the received power value. With these parameters, the path loss can be calculated for each DT using the equation 3.13. Then, using the linear least squares regression, the values for the independent factors can be estimated through the equation 3.14. The combination of each independent factor will result in a path loss model.
Chapter 4

Validation and Enhancements
Towards 5G

4.1 Introduction

In this chapter, the implementations made in order to validate the algorithm results, are presented, with different parameters and approaches tested. The enhancing modules and changes produced, will also be highlighted, with the calibration module improvement, and the algorithm processes optimization.

In order to see if the algorithm is viable, tests must be performed to check if the program is running as expected. For this reason, tests were made regarding the error between the resulting footprint of the received power at a given position, and the DTs from the same position. The calibration process was also analyzed. The correct dependency of the received power with the distance, the frequency and the effective height, was checked, individually, in order to see if its behaviour is as expected in a RF propagation environment. Lastly, the same was achieved for the diffraction losses.

This chapter also presents the implementation of a path loss model capable of working for frequencies between 0.5 and 100 GHz, in order for the RF Footprint Simulator to work for higher frequencies and future mobile communication technologies.

4.2 Footprint Errors Validation

The simulation for these tests was applied in Lisbon center, covering a total area of 26,1 \( km^2 \). In this region, there are a total of 470 cells from the 4G technology, presented in Figure 4.1, with three different frequencies between them. More specifically, there are 236 cells at 800 MHz, 79 cells at 1800 MHz, and 155 cells at 2600 MHz frequency, and they have around 150000, 100000 and 70000 DT samples, respectively. The simulation was done considering 50 surrounding cells as the default value.

In order to validate the algorithm, a comparison with real network DTs was performed, to check the footprint errors, since the projected footprint should not have too different received power values from
the DTs, when in the exact same locations (bins, in this scenario).

From all the available DTs, 80% were used for calibration of the propagation model and the remaining 20% worked as validation set, being applied in the mean error estimation.

To estimate the footprint errors, the validation set of DTs is compared to the received power matrix. For each entry of the matrix, if there is a DT in that location, the subtraction between the received power values is done, and the mean value for all entries of the matrix is the final result of the mean error of a cell. In case there is more than one DT in an entry, the median of the various DTs received power values is calculated.

The error metrics used for comparison of the resulting footprint and the DTs were the median of the absolute errors, Mean Absolute Error (MAE) and Root Mean Square Error (RMSE).

The MAE and RMSE are given by:

\[
MAE = \frac{1}{n} \sum_{1}^{n} |y_n| \tag{4.1}
\]

\[
RMSE = \sqrt{\frac{1}{n} \sum_{1}^{n} (y_n^2)} \tag{4.2}
\]

where:

- \( n \) is the number of tested cells;
• $y_n$ is the mean error value for the cell $n$.

The obtained results from these tests are presented in Table 4.1. The obtained value for MAE was 4.924 dB, which is considered an acceptable error, since a good value for errors associated with the propagation models is around 6 dB [32]. Thus, it was concluded that the algorithm has good results for the projected footprints.

Table 4.1: Median Absolute Error, MAE and RMSE for 470 cells.

<table>
<thead>
<tr>
<th>Median Error $[\text{dB}]$</th>
<th>MAE $[\text{dB}]$</th>
<th>RMSE $[\text{dB}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.088</td>
<td>4.924</td>
<td>6.273</td>
</tr>
</tbody>
</table>

4.3 Algorithm Dependencies

In order to validate the RF module, it is necessary to evaluate the dependencies of the received power and the diffraction losses, with the distance, frequency and antennas height. The dependencies of the received power and the diffraction losses will be evaluated separately.

According to the path loss model it is easy to understand that the received power should decrease when the distance to the BS increases. This factor is also influenced by the frequency, since for higher frequencies, due to a bigger sensitivity of the signal to obstacles, it will result in smaller covering areas. On the opposite, the received power is expected to grow with the effective height between the BS and UE antennas, because the factor that multiplies with the logarithmic function of the effective height ($k_2$ in the Equation 3.14), is negative. The fact that the increasing of the effective antennas height, does not change the distance between the BS and UE antenna, should be noted, since it is the Two Dimensional (2D) distance that is applied in the path loss model.

As for the diffraction losses, it is possible to conclude by the Deygout method, already discussed in Section 3.4.2, that they are supposed to decrease with the distance, to increase for higher values of frequency, and also be bigger for higher values of the difference between the obstacle height and the height of direct line of sight between BS and UE antennas, shown in Figure 3.5, and nominated as $\overline{t}$.

4.3.1 Received Power Analysis

Received Power with Distance

Due to processing limitations, not all cells can be tested from the Lisbon center area. For this reason, in the tests for the evolution of the received power with the distance the BS, only ten tri-sector BSs from different places of the area, were tested. For all tested cells, thirty cells for each of the three different frequencies, the values of each entry of the received power and distance matrices, of each cell, were collected. The resulting graph is presented in Figure 4.2.

Through the analysis of the evolution of the received power with distance, it is possible to conclude that the algorithm is working as expected, since the trend line of the received power is decreasing as the distance increases.
Received Power with Frequency

For the evolution of the received power with the frequency, the same ten tri-sector BSs from Lisbon center were tested, using three different frequencies in each sector: 800 MHz, 1800 MHz and 2600 MHz.

The same tests with the distance were performed, but separated by frequency, resulting in a graph with three different set of samples and respective trend lines.

Through the analysis of the evolution of the received power with the distance for the three different frequencies, presented in Figure 4.3, it is possible to conclude that the expected result is not being achieved in the vicinity of the BSs. It is expected that, at the same distance from the BS, the received power should be smaller for higher frequencies.

In order to solve this problem, some changes were performed in the way, that the path loss model was implemented into the algorithm. An independent factor, \(k_0\), used for corrections of the model, was added, and also the independent factor associated with the frequency, \(k_1\), was multiplied by the logarithmic function of the carrier frequency.

With these changes, the model used for the estimation of the path loss attenuation is still a combination of the COST-231 Hata and Lee model, with the resulting formula:

\[
L_p[\text{dB}] = k_0 + k_1 \log_{10}(f[\text{MHz}]) + k_2 \log_{10}(h_{e,f}[\text{m}]) + k_3 \log_{10}(d[\text{km}]) + k_4 L_{dif}[\text{dB}] 
\]  

(4.3)

where:

- \(k_0\) is an independent factor, used for corrections of the model;
- \(k_1\), \(k_2\), \(k_3\) and \(k_4\) are independent factors associated with the frequency, effective height, distance and diffraction losses respectively.
Figure 4.3: Evolution of the received power with the distance for three different frequencies.

After adding the new independent factor, the same test was performed, with results from Figure 4.4. Its analysis show that the algorithm is now working as expected, since for the same distance, higher values for the frequency always leads to a bigger received power.

**Received Power with Effective Height**

For the evolution of the received power with the effective height between the BS and UE antennas, it was tested the same ten tri-sector BSs from Lisbon center.

For all tested cells, the values of each entry of the received power and effective height matrices were collected, at a distance between 1450 meters and 1500 meters from the respective cell and for each frequency individually. This way, only the effective height is changing in every location, because the frequency is always the same and the distance is set into a small interval.

These tests were performed twice, once for the real cell height, and once with the cell height increased by twenty meters, which leads to an increase of twenty meters for the effective height between BS and UE antennas.

Figure 4.5, presents the evolution of the received power with the effective height of the BS and UE antennas for two different cell heights, using the cells in the 800 MHz. It is possible to conclude that the algorithm is working properly, since the received power is higher for the trend line with the increased cell height, which leads to a bigger effective height of the antennas.

**4.3.2 Diffraction Losses Analysis**

**Diffraction Losses with Distance**

For the evolution of the diffraction losses with the distance to the BS, one cell was tested, at the east side of the hill of the forest park of Monsanto, Lisbon. Only values from the tested area section were
Figure 4.4: Evolution of the received power with the distance for three different frequencies for the new model.

Figure 4.5: Evolution of the received power with the effective height using the 800 MHz cells, for a distance between 1450 and 1500 meters.
taken, presented in Figure 4.6, to assure that the main obstacle for the location being tested was the hill.

As expected, through the analysis of the evolution of the diffraction losses with distance, presented in Figure 4.7, it can be concluded that the algorithm is working as expected, since the trend line of the diffraction losses is decreasing with the increase of the distance to the cell.

**Diffraction Losses with Frequency**

For the evolution of the diffraction losses with the frequency, the same ten tri-sector BSs from Lisbon center were selected, using three different frequencies for each sector.

The selected cells were gathered by frequency, and for each group, it was done a Cumulative Distribution Function (CDF) of the diffraction losses values. The resulting CDFs are presented in Figure 4.8. Its analysis shows that the algorithm is working as expected, higher frequencies lead to the increase of the diffraction losses.

**Diffraction Losses with $\overline{h}$**

For this analysis, the same ten BSs from Lisbon center were selected. The cells from different frequencies were tested separately because the frequency influences this result.

For the diffraction losses, it is possible to understand from the Deygout method, that the diffraction losses are dependent of the difference between the obstacle height and the height of the direct line of sight between BS and UE antennas, $\overline{h}$. Higher values of $\overline{h}$, results in the increase of the diffraction losses. For this reason, the evolution of the diffraction losses with $\overline{h}$ was tested, presented in Figure 4.9. The analysis of this graph shows that the algorithm is working as expected since the trend line is increasing with the $\overline{h}$ value.
Figure 4.7: Evolution of the diffraction losses with the distance.

Figure 4.8: CDFs for the three frequencies.
4.4 Calibration Model Optimization

As stated before, the DTs are used in the calibration, to calculate the independent factors of the path loss model, in order to get a more realistic footprint of the received power values.

At first, to implement the calibration model, a NMath library was used, from CenterSpace Software [33]. In order to calibrate the path loss model, this library tries to resolve the constrained least squares problem, by reformulating it as a quadratic programming problem.

The formula for the quadratic programming problem is [34]:

\[
\min [q(x)] = \frac{1}{2} x^T H x + x^T c
\]

subject to:

\[
x \in \mathbb{R}^n
\]

\[
a_i^T x = b_i, \ i \in E
\]

\[
a_i^T x \geq b_i, \ i \in I
\]

where \( H \) is the Hessian matrix of the objective function \( q(x) \), \( E \) and \( I \) are finite sets of indices, and \( c, x, a_i \) and \( b_i \) are vectors in \( \mathbb{R}^n \).

The use of this library requires bounds for the solution of the independent factors, and also default values, which are used in case of the solver can not converge to a solution for the problem inside those bounds.

The chosen values for these bounds and default solution for the initial path loss model are presented in Table 4.2. As for the optimized path loss model, discussed in Section 4.3, these values are presented in Table 4.3.

Although this first attempt for the calibration model had good results, for some cells, the solution for the calibration problem could not be found. Meaning these cells will have a model with the default values.
Table 4.2: Independent factors lower and upper bounds, and default values, for the initial path loss model.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_1$</td>
<td>110</td>
<td>160</td>
<td>156</td>
</tr>
<tr>
<td>$k_2$</td>
<td>20</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>$k_3$</td>
<td>-20</td>
<td>10</td>
<td>-13.82</td>
</tr>
<tr>
<td>$k_4$</td>
<td>0</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 4.3: Independent factors lower and upper bounds, and default values, for the optimized path loss model.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_0$</td>
<td>50</td>
<td>90</td>
<td>69.55</td>
</tr>
<tr>
<td>$k_1$</td>
<td>16</td>
<td>36</td>
<td>26.16</td>
</tr>
<tr>
<td>$k_2$</td>
<td>20</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>$k_3$</td>
<td>-20</td>
<td>10</td>
<td>-13.82</td>
</tr>
<tr>
<td>$k_4$</td>
<td>0</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

This can result in footprints that are not much realistic, leading to high values for the errors between the projected footprint and the DTs.

In order to solve this problem and optimize the calibration, a second calibration model was implemented, the theoretical model of the linear least squares. To solve a linear least squares problem, $Ax = b$, it is necessary to minimize the error of $||Ax - b||^2$.

The solution for this minimization is given by:

$$x = (A^TA)^{-1}A^Tb$$

(4.5)

where $A$ is the matrix representation of the path loss model, with dimension $n \times m$, where $n$ is equal to the number of DTs used for calibration, and $m$ is the number of factors to be calculated. $A^T$ is the transposed matrix of $A$, $b$ and $x$ are vectors of size $n$, with the path loss values of each DT and with the solution for each factor, respectively.

The advantage of this calibration model is that it always has a solution, the disadvantage is that there are no bounds, leading to possible excessively high or low values, of the independent factors.

In order to prevent this, both models of calibration were used, where the first is always tested, and only in case of failure the second is used.

4.5 Propagation Model for 0.5 to 100 GHz

In order to keep up with the evolution of the technology, a new propagation model was implemented for frequencies between 0.5 and 100 GHz (where all mobile communications technologies are inserted, 2G, 3G, 4G and 5G). This model is an adaptation of the path loss model from 3GPP [35, 36], which is defined for frequencies between 0.5 and 100 GHz.

It is divided into urban or dense urban environments, and into rural or suburban environments, and for both types, there is a LoS and a Non Line of Sight (NLoS) case.
The Three Dimensional (3D) distance, \(d_{3D}\), is used, presented in Figure 4.10, and it is given by:

\[
d_{3D[m]} = \sqrt{d_{2D[m]}^2 + (h_{BS[m]} - h_{UT[m]})^2} = \sqrt{d_{2D[m]}^2 + h_{ef[m]}^2}
\]

where \(d_{2D}\) is the 2D distance, \(h_{BS}\) is the BS antenna height, \(h_{UT}\) is the mobile antenna height and \(h_{ef}\) is the effective height between those antennas.

**4.5.1 Urban and Dense Urban**

**Line of Sight**

For the LoS case in an urban environment, the propagation model is a dual slope model, meaning there are two different path loss functions used to characterize the propagation. The first function, \(L_{p1}\), is used for values of 2D distance, \(d_{2D}\), lower than the breakpoint distance, \(d_{BP}\). The other function, \(L_{p2}\), is used for higher values than \(d_{BP}\), and both of them are restricted to a maximum of 5000 meters for \(d_{2D}\):

\[
L_{p\text{LoS}[dB]} = \begin{cases} 
L_{p1[dB]} & \text{if } d_{2D[m]} \leq d_{BP[m]} \\
L_{p2[dB]} & \text{if } d_{BP[m]} \leq d_{2D[m]} \leq 5000 
\end{cases}
\]

\[
L_{p1[dB]} = k_0 + k_1 \log(f_{[GHz]}) + k_2 \log(d_{3D[m]})
\]

\[
L_{p2[dB]} = k_a + k_b \log(f_{[GHz]}) + k_c \log(d_{3D[m]}) + k_d \log(d_{BP[m]} + h_{ef[m]})
\]

\[
d_{BP[m]} = 4(h_{BS[m]})(h_{UT[m]})(\frac{f_{[GHz]}}{c[m/s]})
\]

where \(f\) is the carrier frequency, \(d_{3D}\) is the 3D distance, \(h_{ef}\) is the effective height between the
BS antenna and UE antenna, $h_{UT}$ is the UE antenna height, $h_{bs}$ is the BS antenna height, $c$ is the light speed, and all $k'$s are independent factors which can be calibrated, and the chosen values for the bounds and default solution are presented in Table 4.4.

Table 4.4: Independent factors lower and upper bounds, and default values for Urban and Dense Urban LoS model.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_0$</td>
<td>14</td>
<td>42</td>
<td>28</td>
</tr>
<tr>
<td>$k_1$</td>
<td>10</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>$k_2$</td>
<td>11</td>
<td>33</td>
<td>22</td>
</tr>
<tr>
<td>$k_a$</td>
<td>14</td>
<td>42</td>
<td>28</td>
</tr>
<tr>
<td>$k_b$</td>
<td>10</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>$k_c$</td>
<td>20</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>$k_d$</td>
<td>-13.5</td>
<td>-4.5</td>
<td>-9</td>
</tr>
</tbody>
</table>

Non Line of Sight

The propagation model for the NLoS case in an urban environment, is the maximum between the LoS model and the equation $L_{p3}$, and can be used for a maximum of 5000 meters for $d_{2D}$:

$$L_{pNLoS}[dB] = \max(L_{pLoS}[dB]; L_{p3}[dB]) \quad \text{for } d_{2D}[m] \leq 5000 \quad (4.11)$$

$$L_{p3}[dB] = k_0 + k_1 \log(f[GHz]) + k_2 \log(d_{3D}[m]) \quad (4.12)$$

where $f$ is the carrier frequency, $d_{3D}$ is the 3D distance, and all $k'$s are independent factors which can be calibrated and the chosen values for the bounds and default solution are presented in Table 4.5.

Table 4.5: Independent factors lower and upper bounds, and default values for Urban and Dense Urban NLoS model.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_0$</td>
<td>6.7</td>
<td>20.3</td>
<td>13.54</td>
</tr>
<tr>
<td>$k_1$</td>
<td>10</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>$k_2$</td>
<td>20</td>
<td>60</td>
<td>39.08</td>
</tr>
</tbody>
</table>

4.5.2 Rural and Suburban

Line of Sight

Once again, for the LoS case in a rural environment, the propagation model is a dual slope model, with two different path loss functions used to characterize the propagation. The first function, $L_{p1}$, is used for
values of 2D distance, $d_{2D}$, lower than the breakpoint distance, $d_{BP}$. The second function, $L_{p2}$, is used for higher values than $d_{BP}$. Both functions are restricted to a maximum of 10000 meters for $d_{2D}$:

$$L_{p\text{LoS}[dB]} = \begin{cases} 
L_{p1}[dB] & \text{if } d_{2D[m]} \leq d_{BP[m]} \\
L_{p2}[dB] & \text{if } d_{BP[m]} \leq d_{2D[m]} \leq 10000 
\end{cases} \quad (4.13)$$

$$L_{p1}[dB] = k_0 + k_1 \log(40\pi d_{3D[m]} \frac{f_{[GHz]}}{3}) + k_2 \log(d_{3D[m]}) + k_3 d_{3D[m]} \quad (4.14)$$

$$L_{p2}[dB] = k_0 + k_1 \log(40\pi d_{3D[m]} \frac{f_{[GHz]}}{3}) + k_2 \log(d_{3D[m]}) + k_3 d_{3D[m]} + k_4 \log(\frac{d_{3D[m]}}{d_{BP[m]}}) \quad (4.15)$$

where $f$ is the carrier frequency, $d_{3D}$ is the 3D distance, $h_{UT}$ is the UE antenna height, $h_{bs}$ is the BS antenna height, $c$ is the light speed, and all $k'$s are independent factors which can be calibrated and the chosen values for the bounds and default solution are presented in Table 4.6, considering that the average building height is ten meters.

Table 4.6: Independent factors lower and upper bounds, and default values for Rural and Suburban LoS model.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_0$</td>
<td>1.16</td>
<td>3.46</td>
<td>2.31</td>
</tr>
<tr>
<td>$k_1$</td>
<td>10</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>$k_2$</td>
<td>0.79</td>
<td>2.36</td>
<td>1.57</td>
</tr>
<tr>
<td>$k_3$</td>
<td>0.003</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>$k_4$</td>
<td>20</td>
<td>60</td>
<td>40</td>
</tr>
</tbody>
</table>

**Non Line of Sight**

The model for NLoS case in a rural environment, is the maximum between the LoS model and the equation $L_{p3}$, and can be used for a maximum of 5000 meters for $d_{2D}$:

$$L_{p\text{NLoS}[dB]} = \max(L_{p\text{LoS}[dB]}, L_{p3}[dB]) \text{ for } d_{2D[m]} \leq 5000 \quad (4.17)$$

$$L_{p3}[dB] = k_0 + k_1 \log(f_{[GHz]}) + k_2 \log(d_{3D[m]}) + k_3 \log(h_{BS}) + k_4 \log(\frac{h_{BS}}{h_{BS}}) + k_5 \log(h_{BS}) \log(d_{3D}) + k_6 \log(11.75 h_{UT})^2 \quad (4.18)$$

where $f$ is the carrier frequency, $d_{3D}$ is the 3D distance, $h_{UT}$ is the UE antenna height, $h_{bs}$ is the BS antenna height, and all $k'$s are independent factors which can be calibrated and the chosen values...
for the bounds and default solution are presented in Table 4.7, considering that the average street width and building height are 20 and 10 meters, respectively.

Table 4.7: Independent factors lower and upper bounds, and default values for Rural and Suburban NLoS model.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_0$</td>
<td>17</td>
<td>51</td>
<td>34.01</td>
</tr>
<tr>
<td>$k_1$</td>
<td>10</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>$k_2$</td>
<td>23</td>
<td>63</td>
<td>43.42</td>
</tr>
<tr>
<td>$k_3$</td>
<td>-25</td>
<td>-5</td>
<td>-15.07</td>
</tr>
<tr>
<td>$k_4$</td>
<td>185</td>
<td>555</td>
<td>370</td>
</tr>
<tr>
<td>$k_5$</td>
<td>-4.5</td>
<td>-1.5</td>
<td>-3.1</td>
</tr>
<tr>
<td>$k_6$</td>
<td>-4.8</td>
<td>-1.6</td>
<td>-3.2</td>
</tr>
</tbody>
</table>
Chapter 5

Results

5.1 Introduction

In this chapter, the main results of the optimizations made to the algorithm are presented. The footprint errors were tested, in order to select the best value for the surrounding cells, as well as the results for the new propagation model used, since it was optimized due to an error on the dependency of the received power with the frequency. The results for the optimization of the calibration model are presented, and also, the calibration and validation of the implemented propagation model. Even though this model is defined for 0.5 to 100 GHz [35, 36], in this work it is only calibrated and validated for frequencies from 800 MHz to 3.5 GHz. With the release of higher frequencies from the 5G technology, new sets of DTs samples should be measured and a new calibration and validation should be done.

Later in this chapter, the coverage prediction for Lisbon center, dense urban region, and for Vila Franca de Xira, suburban/rural region, are done. The implemented model capable of support frequencies from 0.5 to 100 GHz was used for the predictions. For each of these regions, the tested frequencies were 800 MHz and 3.5 GHz.

In order to predict the coverage, it is necessary to calculate the maximum cell range for the desired frequency bands, 800 MHz and 3.5 GHz. To estimate these values, the link budget for these mobile communications networks was done, following the recommendations in [37], so that the minimum requirements of the network at the cell edge would be a bit rate of 500 kbps for uplink, and 1 Mbps for downlink, for a coverage probability of 95%.

5.2 Optimization Results

5.2.1 Surrounding Cells Number

The study of the optimal surrounding cell number, is an important step because, despite considering more surrounding cells could be good to the algorithm due to the bigger amount of DTs, it also represents more processing time. Furthermore, simply considering more surrounding cells, may not assure
better results, it also depends on the available DTs number in the target cell. If they are considerable, surrounding cells DTs may add noise to the target cell DTs data.

In order to select the best value for the surrounding cells number, it was taken in mind, the errors of the resulting footprints in relation to the received power values obtained from the DTs, the number of DTs per bin, the calibration time and the necessary time for the cells parameters estimation, discussed in Section 3.4.2.

The simulation for these tests was applied in Lisbon center, with the same characteristics as in Section 4.2, but using values for the surrounding cells number between zero and fifty.

In Table 5.1, the results for the median absolute error, MAE and RMSE, are presented, for the different surrounding cells number. In Table 5.2, the results for the other tested factors, are presented.

Table 5.1: Median Absolute Error, MAE and RMSE for different surrounding cells number.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>4.088</td>
<td>4.924</td>
<td>6.273</td>
</tr>
<tr>
<td>40</td>
<td>4.365</td>
<td>5.007</td>
<td>6.309</td>
</tr>
<tr>
<td>30</td>
<td>4.335</td>
<td>4.899</td>
<td>6.179</td>
</tr>
<tr>
<td>20</td>
<td>3.743</td>
<td>4.662</td>
<td>5.837</td>
</tr>
<tr>
<td>10</td>
<td>3.825</td>
<td>4.563</td>
<td>5.827</td>
</tr>
<tr>
<td>5</td>
<td>3.762</td>
<td>4.515</td>
<td>5.692</td>
</tr>
<tr>
<td>1</td>
<td>3.615</td>
<td>4.351</td>
<td>5.562</td>
</tr>
<tr>
<td>0</td>
<td>3.507</td>
<td>4.335</td>
<td>5.471</td>
</tr>
</tbody>
</table>

Table 5.2: DTs per bin, calibration time and cells parameters estimation time for different surrounding cells number.

<table>
<thead>
<tr>
<th>SurroundingCells</th>
<th>DTs/Bin</th>
<th>CalibrationTime[ms]</th>
<th>ParametersTime[s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.670</td>
<td>11.368</td>
<td>8.939</td>
</tr>
<tr>
<td>40</td>
<td>0.597</td>
<td>10.079</td>
<td>7.157</td>
</tr>
<tr>
<td>30</td>
<td>0.505</td>
<td>8.351</td>
<td>5.378</td>
</tr>
<tr>
<td>20</td>
<td>0.401</td>
<td>6.116</td>
<td>4.002</td>
</tr>
<tr>
<td>10</td>
<td>0.258</td>
<td>3.876</td>
<td>1.957</td>
</tr>
<tr>
<td>5</td>
<td>0.161</td>
<td>2.453</td>
<td>1.122</td>
</tr>
<tr>
<td>1</td>
<td>0.0634</td>
<td>1.475</td>
<td>0.415</td>
</tr>
<tr>
<td>0</td>
<td>0.0288</td>
<td>1.367</td>
<td>0.258</td>
</tr>
</tbody>
</table>

These results show that with the increasing value for the surrounding cells number, the errors are higher, although they are all close. This means, that for this case in specific, Lisbon center, it is not necessary to use surrounding cells, as the cells in this network have a good amount of DTs for a good calibration of the model. However, this is normally not the case, in many other areas there is a low density of DTs measured per cell, and it is necessary to ensure that there is always a reasonable number of DTs.
for the calibration. For this reason, it is assumed that the ideal value for the surrounding cells number is twenty. This way, there is always enough DTs per bin for the calibration, even if the target cell has a low value of DTs measured, ensuring that the resulting footprint is similar to the result using the default value, fifty surrounding cells, but with a much faster running time of the algorithm.

To verify that the algorithm is working properly, for each of the above stated values for the surrounding cells number, it was plotted an histogram that shows the errors frequency and was also plotted the CDF for each of those surrounding cells number. All histograms have an approximately normal distribution and mean error value around zero dB, so it was concluded that the main reason for the errors is due to large-scale fading, as it also presents a normal probability distribution [38]. Also, all the CDFs have around 90% of the errors between [-10, 10] dB, confirming that the algorithm is working properly.

Figures 5.1 and 5.2, shows the histogram and the CDF, respectively, for twenty surrounding cells.
5.2.2 Path Loss Model Optimization Results

With the path loss model optimization, discussed in Section 4.3.1, the footprint errors were tested again. The simulation for this test was applied in Lisbon center, with the same characteristics as in Section 4.2, but using twenty surrounding cells. The error metrics estimated were also the same, the median of the absolute error, MAE and RMSE.

The results for the footprint errors with the new path loss model are presented in Table 5.3.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>4.334</td>
<td>6.446</td>
<td>8.231</td>
</tr>
</tbody>
</table>

Figure 5.3: Histogram for 20 surrounding cells with the new path loss model.

Figure 5.4: CDF for 20 surrounding cells with the new path loss model.
Figures 5.3 and 5.4, presents both the histogram and the CDF, respectively, using twenty surrounding cells, with only around 80% of the obtained errors, between [-10, 10] dB.

These results are significantly worse than the ones obtained in the initial path loss model. The reason for this is the number of cells that the initial calibration model could not solve for the new path model, presented in Table 5.4.

<table>
<thead>
<tr>
<th>Cellstested</th>
<th>Calibratedcells</th>
<th>Non calibratedcells</th>
</tr>
</thead>
<tbody>
<tr>
<td>470</td>
<td>360</td>
<td>110</td>
</tr>
</tbody>
</table>

In order to obtain better results, the calibration model was optimized, as discussed in Section 4.4.

### 5.2.3 Calibration Optimization Results

With the calibration model optimization, discussed in Section 4.4, the footprint errors were tested once again. The simulation for this test was applied in Lisbon center, also with the same characteristics as in Section 4.2, but using twenty surrounding cells. The error metrics estimated were the same, the median of the absolute error, MAE and RMSE.

With this new path loss model using the optimized calibration, the results for the footprint errors improved a lot for the cells that the NMath library could not solve the calibration and gave the default values.

Table 5.5 presents the errors for the different calibrations tested in the algorithm, confirming that the optimized solution is the one with better results.

<table>
<thead>
<tr>
<th></th>
<th>MedianError[dB]</th>
<th>MAE[dB]</th>
<th>RMSE[dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Calibration</td>
<td>10.028</td>
<td>11.154</td>
<td>13.659</td>
</tr>
<tr>
<td>NMath Library</td>
<td>4.334</td>
<td>6.446</td>
<td>8.231</td>
</tr>
<tr>
<td>Optimized Calibration</td>
<td>3.741</td>
<td>4.427</td>
<td>5.613</td>
</tr>
</tbody>
</table>

Figure 5.5, presents the CDFs for these previously tested cells, while the algorithm is running without calibration, with the calibration from the NMath library, and with the optimized calibration. An error percentage between [-10, 10] dB, of 50%, 80% and 90%, respectively, was obtained.

The histogram of the new path loss model, using the optimized calibration and twenty surrounding cells, is presented in Figure 5.6. It presents an approximately normal distribution and mean error value around zero dB, confirming once again, that the main reason for the errors is due to large-scale fading.
Figure 5.5: CDFs for different calibrations with the optimized path loss model and 20 surrounding cells.

Figure 5.6: CDFs for different calibrations with the optimized path loss model and 20 surrounding cells.
5.2.4 Calibration of the 0.5 to 100 GHz Propagation Model

In order to obtain a calibrated model for the various technologies, the use of DTs corresponding to those technologies is necessary. However, since drive tests are not available for the higher frequencies, such as the 3.5 GHz that will be analyzed in the coverage prediction, the calibration was done using available DTs from different frequencies at the same time.

For the urban environment case, the simulation for this test was applied in Lisbon center, with the same characteristics as in Section 4.2, but using twenty surrounding cells and the calibration used DTs with frequencies of 800, 1800 and 2600 MHz, simultaneously.

While for the rural environment, the simulation was applied in Vila Franca de Xira, covering a total area of 25.8 km$^2$. In this region, there are only twenty-two cells from the 4G technology, in the 800 MHz frequency, with around 20000 DTs. Twenty-two cells from the 3G technology were also used, in the 2100 MHz frequency, with around 12000 DTs. This was done in order to obtain DTs from 800 MHz and 2100 MHz for the calibration of the path loss model.

Table 5.6 presents the results for the median of the absolute error, MAE and RMSE, in Lisbon center. It was concluded that the model is well calibrated for the urban environment since for each frequency, a considerable number of cells were tested, and all errors are low, where the highest MAE is 5.09 dB for the 1800 MHz.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>236</td>
<td>3.58</td>
<td>4.63</td>
<td>4.99</td>
</tr>
<tr>
<td>1800</td>
<td>79</td>
<td>4.42</td>
<td>5.09</td>
<td>5.55</td>
</tr>
<tr>
<td>2600</td>
<td>155</td>
<td>3.36</td>
<td>3.78</td>
<td>4.59</td>
</tr>
</tbody>
</table>

Table 5.7 presents the results for the median of the absolute error, MAE and RMSE, in Vila Franca de Xira. Even though there is a low density of cells in this area, it was concluded that the model is well calibrated for the rural environment, since for each frequency all errors are acceptable, with the highest MAE of 6.67 dB for the 2100 MHz.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>22</td>
<td>5.87</td>
<td>6.26</td>
<td>3.88</td>
</tr>
<tr>
<td>2100</td>
<td>22</td>
<td>5.41</td>
<td>6.67</td>
<td>4.79</td>
</tr>
</tbody>
</table>

5.3 Link Budget for the 0.5 to 100 GHz Propagation Model

5.3.1 Methodology

In order to estimate the link budget for a network, with minimum requirements at the cell edge for a bit rate of 500 kbps for uplink and 1 Mbps for downlink, for a coverage probability of 95%, it was taken into
account the recommendations in [37]. The assumption that the network is restricted by uplink, was made. First, the maximum allowed path loss for uplink was estimated, then, from that value, the bit rate at the cell edge for downlink was calculated. If this bit rate is higher than the minimum requirements, 1 Mbps, the assumption is verified and the network is restricted by uplink, otherwise, it is restricted by downlink and the estimation its maximum allowed path loss is necessary.

To estimate the maximum allowed path loss for uplink, the following parameters are necessary:

- Bit Rate Requirement per resource block, for uplink and downlink, $R_{req,RB,UL}$ and $R_{req,RB,DL}$ respectively

$$R_{req,RB,UL}[kbps] = \frac{R_{req,UL}[kbps]}{n'_{RB}} \quad (5.1)$$

$$R_{req,RB,DL}[kbps] = \frac{R_{req,DL}[kbps]}{n'_{RB}} \quad (5.2)$$

where $R_{req,UL}$ is the required bit rate for uplink, 500 kbps, $R_{req,DL}$ is the required bit rate for downlink, 1 Mbps, and $n'_{RB}$ is the number of resource blocks that can be allocated to obtain that bit rate, a reasonable choice is 5, since with one resource block only, the noise rise becomes unrealistically high [37].

- Signal-to-Interference-plus-Noise Ratio (SINR), $\gamma$

$$\gamma[dB] = a_1[dB] - a_2[dB] \sqrt{\frac{\ln(\frac{a_0[kbps]}{R_{RB}[kbps]} - a_3[kbps])}{\ln(2)}} \quad (5.3)$$

where $a_0$, $a_1$, $a_2$ and $a_3$ are semi-empirical parameters with different values for uplink and downlink, the channel model, Extended Pedestrian A model (EPA), Extended Vehicular A model (EVA) and Extended Typical Urban model (ETU), and the type of antenna arrangement, Single-Input Multiple-Output (SIMO) 1x2, transmission diversity 2x2, and Open Loop Spatial Multiplexing (OLSM) 2x2. These values are presented in Tables 5.8 and 5.9, for uplink and downlink, respectively. It is assumed that the EVA model, since DTs are collected in a car, and transmission antennas with diversity 2x2, are used.

For the downlink, the parameters $a_0$ and $a_3$ have to be adjusted with regards to the control channel configuration:

$$a_0[kbps] = a_{0,max}[kbps] \times \left(1 - \frac{n_{PDCCH}}{14} - \frac{n_{ant}}{28} - \frac{48 - n_{ant}}{140n_{RB}}\right) \quad (5.4)$$
Table 5.9: Semi-Empirical Parameters for Downlink [37].

<table>
<thead>
<tr>
<th>Antenna arrangement</th>
<th>SIMO 1x2</th>
<th>Tx div 2x2</th>
<th>OLSM 2x2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPA 5</td>
<td>912.1</td>
<td>914.2</td>
<td>1583.8</td>
</tr>
<tr>
<td>EVA 70</td>
<td>912.4</td>
<td>913.8</td>
<td>1409.5</td>
</tr>
<tr>
<td>ETU 300</td>
<td>799.9</td>
<td>887.7</td>
<td>1162.8</td>
</tr>
<tr>
<td></td>
<td>27.00</td>
<td>27.17</td>
<td>34.03</td>
</tr>
<tr>
<td></td>
<td>27.34</td>
<td>27.70</td>
<td>34.99</td>
</tr>
<tr>
<td></td>
<td>27.75</td>
<td>27.90</td>
<td>31.93</td>
</tr>
<tr>
<td>a0,max[kbps]</td>
<td>16.01</td>
<td>15.38</td>
<td>18.37</td>
</tr>
<tr>
<td></td>
<td>15.34</td>
<td>15.49</td>
<td>18.16</td>
</tr>
<tr>
<td></td>
<td>-10.5</td>
<td>-16.2</td>
<td>-18.6</td>
</tr>
<tr>
<td>a3,max[kbps]</td>
<td>-4.4</td>
<td>-6.4</td>
<td>-10.2</td>
</tr>
<tr>
<td></td>
<td>-5.3</td>
<td>-7.3</td>
<td>-8.4</td>
</tr>
</tbody>
</table>

\[ a_3[kbps] = a_{3,max[kbps]} \times \left( 1 - \frac{n_{PDCCH}}{28} - \left( \frac{48 - n_{ant}}{140 n_{RB}} \right) \right) \]  \hspace{1cm} (5.5)

where \( a_{0,max} \) and \( a_{3,max} \) are the maximum values for \( a_0 \) and \( a_3 \), \( n_{PDCCH} \) is the number of allocated symbols for Physical Downlink Control Channel (PDCCH), 2 to 4 for 1.4 MHz and 1 to 3 for larger bandwidths, \( n_{ant} \) is the number of configured antenna ports, 2 for transmitter diversity 2x2, and \( n_{RB} \) is the total number of resource blocks for the deployed bandwidth, 50 for a bandwidth of 10 MHz.

- **Uplink Receiver sensitivity, \( S_{UL} \)**

\[ S_{UL}[dBm] = N_t[dBm/Hz] + N_f,BS[dB] + 10 \log(W_{RB}[Hz]) + \gamma[db] = N_{RB,UL}[dBm] + \gamma_{UL}[dB] \]  \hspace{1cm} (5.6)

where \( N_t \) is the thermal noise power density, -174 dBm/Hz, \( N_f,BS \) is the noise figure of the BS receiver, 5 dB [39], \( W_{RB} \) is the bandwidth that can be allocated per resource block, 180 kHz, and \( N_{RB,UL} \) is the uplink thermal noise per resource block.

- **Uplink Interference Margin, \( B_{IUL} \)**

\[ B_{IUL}[dB] = \frac{1}{1 - \gamma[db]} \times Q_{UL} \times F \]  \hspace{1cm} (5.7)

where \( Q_{UL} \) is the average uplink system load, 0.32, and \( F \) is the average ratio of path gains for interfering cells to those of the serving cell, 0.7.

- **Output Power of the User Equipment per Resource Block, \( P_{UE, RB} \)**

\[ P_{UE, RB}[dBm] = \frac{P_{UE}[dBm]}{n_{RB}} \]  \hspace{1cm} (5.8)

where \( P_{UE} \) is the output power of the user equipment, 23 dBm.

- **Maximum Allowed Path Loss, \( L_{pmax} \)**

\[ L_{pmax}[dB] = P_{UE, RB}[dBm] - S_{UL}[dBm] - B_{IUL}[dB] - B_{LN F}[dB] - L_{BL}[dB] - L_{CPL}[dB] - L_{BPL}[dB] + G_{0}[dB] - L_{j}[dB] \]  \hspace{1cm} (5.9)
where $B_{LN,F}$ is the log-normal fading margin, 2.9 dB for rural/suburban and 6.7 dB for dense urban with coverage probability of 95%, $L_{BL}$ is the body loss, 3 dB, $L_{CPL}$ is the car penetration loss, 8 dB, $L_{BPL}$ is the building penetration loss, 0 dB since it is outdoor, $G_a$ is the sum of the maximum gain in the forward direction of the BS and UE antenna gain, 17 dBi, and $L_j$ is the Tower Mounted Amplifier (TMA) insertion loss, 0 dB since it is not used.

After getting the maximum path loss, it is needed to verify if the assumption of uplink restriction is true by estimating the bit rate at the cell edge for downlink. For this estimation the following parameters are needed:

- **Output Power per Resource Block of the BS antenna, $P_{BS,RB}$**
  \[
  P_{BS,RB}[\text{dBm}] = \frac{P_{BS}[\text{dBm}]}{n_{RB}} \tag{5.10}
  \]
  where $P_{BS}$ is the output power of the BS, 46 dBm, and $n_{RB}$ is the total number of Resource Blocks (RBs), 50 for a bandwidth of 10 MHz.

- **Signal attenuation in downlink, corresponding to $L_{p_{\text{max}}}$, $L_{sa,cellrange}$**
  \[
  L_{sa,cellrange}[\text{dB}] = L_{p_{\text{max}}}[\text{dB}] + L_{BL}[\text{dB}] + L_{CPL}[\text{dB}] + L_{BPL}[\text{dB}] - G_a[\text{dB}] + L_j[\text{dB}] \tag{5.11}
  \]

- **Downlink Receiver Sensitivity, $S_{DL}$**
  \[
  S_{DL}[\text{dBm}] = N_{RB,DL}[\text{dBm}] + \gamma_{DL}[\text{dB}] \tag{5.12}
  \]
  where $N_{RB,DL}$ downlink thermal noise per resource block, and $\gamma_{DL}$ is the SINR for downlink.

- **Downlink thermal noise per resource block, $N_{RB,DL}$**
  \[
  N_{RB,DL}[\text{dBm}] = N_t[\text{dBm/Hz}] + N_{f,UE}[\text{dB}] + 10 \log(W_{RB}[\text{Hz}]) \tag{5.13}
  \]
  where $N_t$ is the thermal noise power density, -174 dBm/Hz, $N_{f,UE}$ is the noise figure of the UE receiver, 9 dB \[39\], $W_{RB}$ is the bandwidth per resource block, 180 kHz.

- **Downlink Interference Margin, $B_{IDL}$**
  \[
  B_{IDL}[\text{dB}] = 1 + \frac{P_{BS,RB}[\text{dBm}] \times Q_{DL} \times F_c}{N_{RB,DL}[\text{dBm}] \times L_{sa,cellrange}[\text{dB}]} \tag{5.14}
  \]
  where $Q_{DL}$ is the average downlink system load, 0.35, and $F_c$ is the average ratio between the received power from other cells to that of own cell at cell edge locations, 2.3.
• SINR for downlink, $\gamma_{DL}$

$$\gamma_{DL}[\text{dB}] = P_{BS, RB}[\text{dBm}] - L_{p_{\text{max}}}[\text{dB}] - N_{RB, DL}[\text{dBm}] - B_{IDL}[\text{dB}] - B_{LN}[\text{dB}]$$

$$- L_{BL}[\text{dB}] - L_{CPL}[\text{dB}] - L_{BPL}[\text{dB}] + G_{a}[\text{dB}] - L_{C}[\text{dB}] + G_{a}[\text{dBi}] - L_{j}[\text{dB}]$$

(5.15)

• Downlink bit rate per resource block, $R_{RB, DL}$

$$R_{RB, DL}[\text{kbps}] = \begin{cases} \max(0, a_3[\text{kbps}]) + (a_0[\text{kbps}] - a_3[\text{kbps}])e^{-ln(2)\left[\frac{\gamma_{DL}[\text{dB}]-a_1[\text{dB}]}{a_2[\text{dB}]}\right]} & \text{for } \gamma_{DL}[\text{dB}] < a_1[\text{dB}] \\ a_0[\text{kbps}] & \text{for } \gamma_{DL}[\text{dB}] \geq a_1[\text{dB}] \end{cases}$$

(5.16)

• Total downlink bit rate, $R_{DL}$

$$R_{DL}[\text{kbps}] = R_{RB, DL}[\text{kbps}] \times n_{RB}$$

(5.17)

where $n_{RB}$ is the total number of RB.

If the resulting bit rate for downlink, $R_{DL}$, is higher than the minimum required bit rate for downlink, 1 Mbps, then the assumption made that the uplink is the restrictive link is correct, otherwise, it is the downlink that restricts the network, if so, it is necessary to estimate a new maximum allowed path loss for this case.

This is done by backtracking the downlink link budget calculations [37]:

• The bit rate per resource block for downlink, $R_{req, RB, DL}$, is transformed into a SINR for downlink, $\gamma_{DL}$ using the Equation 5.3;

• The SINR required for the downlink is used in Equation 5.12, in order to obtain the sensitivity for downlink, $S_{DL}$, and can then be calculated the downlink thermal noise per resource block, $N_{RB, DL}$;

• $\gamma_{DL}$ and $N_{RB, DL}$ are then used in Equation 5.15, to calculate the maximum allowed path loss, $L_{p_{\text{max}}}$, using the initial downlink interference margin, $B_{IDL}$;

• A new signal attenuation, $L_{sa, cellrange}$, is derived using Equation 5.11;

• The new $L_{sa, cellrange}$ is applied to Equation 5.14 in order to obtain a new interference margin for downlink, $B_{IDL}$;

• Equations 5.15, 5.11 and 5.14 are then iterated until $L_{sa, cellrange}$ and $B_{IDL}$ are constant;

• Once $L_{sa, cellrange}$ is constant, it is converted to $L_{p_{\text{max}}}$ using one last time the Equation 5.15.

It is finally possible to calculate the maximum cell range through the path loss model being tested, using the maximum allowed path loss from the restrictive link, and resolving the equation of the path loss model in order to the distance from the BS to the UE.
Table 5.10: Budget Link for Lisbon center and Vila Franca de Xira

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Lisbon center</th>
<th>Vila Franca de Xira</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>$BW_{[MHz]}$</td>
<td>10</td>
</tr>
<tr>
<td>Number of RB</td>
<td>$n_{RB}$</td>
<td>50</td>
</tr>
<tr>
<td>Number of Allocated RBs</td>
<td>$n'_{RB}$</td>
<td>5</td>
</tr>
<tr>
<td>Uplink Required Bit Rate</td>
<td>$R_{req,UL}[kbps]$</td>
<td>500</td>
</tr>
<tr>
<td>Uplink Required Bit Rate per RB</td>
<td>$R_{req,UL}[kbps]$</td>
<td>100</td>
</tr>
<tr>
<td>BS Noise Figure</td>
<td>$N_{f,BS}[dB]$</td>
<td>5</td>
</tr>
<tr>
<td>UE Noise Figure</td>
<td>$N_{f,UE}[dB]$</td>
<td>9</td>
</tr>
<tr>
<td>Uplink System Load</td>
<td>$Q_{UL}$</td>
<td>0.32</td>
</tr>
<tr>
<td>Downlink System Load</td>
<td>$Q_{DL}$</td>
<td>0.35</td>
</tr>
<tr>
<td>Uplink System Load</td>
<td>$Q_{UL}$</td>
<td>0.32</td>
</tr>
<tr>
<td>Downlink System Load</td>
<td>$Q_{DL}$</td>
<td>0.35</td>
</tr>
<tr>
<td>Cell Edge F Factor</td>
<td>$F_c$</td>
<td>2.3</td>
</tr>
<tr>
<td>Thermal Noise</td>
<td>$N_{t}[dBm/Hz]$</td>
<td>-174</td>
</tr>
<tr>
<td>Bandwidth per RB</td>
<td>$W_{RB}[Hz]$</td>
<td>52.55</td>
</tr>
<tr>
<td>Uplink Thermal Noise per RB</td>
<td>$N_{RB,UL}[dBm]$</td>
<td>-116.45</td>
</tr>
<tr>
<td>Uplink SINR</td>
<td>$\gamma_{UL}[dB]$</td>
<td>3.57</td>
</tr>
<tr>
<td>Uplink Sensitivity</td>
<td>$S_{UL}[dBm]$</td>
<td>-112</td>
</tr>
<tr>
<td>Uplink Interference Margin</td>
<td>$B_{UL}[dB]$</td>
<td>3.1</td>
</tr>
<tr>
<td>UE Output Power</td>
<td>$P_{UE}[dBm]$</td>
<td>23</td>
</tr>
<tr>
<td>UE Output Power per RB</td>
<td>$P_{UE,RB}[dBm]$</td>
<td>16</td>
</tr>
<tr>
<td>Antenna Gains</td>
<td>$G_{a}[dB]$</td>
<td>17</td>
</tr>
<tr>
<td>Body Loss</td>
<td>$L_{BL}[dB]$</td>
<td>3</td>
</tr>
<tr>
<td>Building Penetration Loss</td>
<td>$L_{BPL}[dB]$</td>
<td>0</td>
</tr>
<tr>
<td>Car Penetration Loss</td>
<td>$L_{CPPL}[dB]$</td>
<td>8</td>
</tr>
<tr>
<td>TMA Insertion Loss</td>
<td>$L_{j}[dB]$</td>
<td>0</td>
</tr>
<tr>
<td>Fading Margin</td>
<td>$B_{LNF}[dB]$</td>
<td>6.7</td>
</tr>
<tr>
<td>Maximum Allowed Path Loss</td>
<td>$L_{pmax}[dB]$</td>
<td>125.1</td>
</tr>
<tr>
<td>Signal Attenuation at Cell Range</td>
<td>$L_{sa,cellrange}[dB]$</td>
<td>119.1</td>
</tr>
<tr>
<td>BS Output Power</td>
<td>$P_{BS}[dBm]$</td>
<td>46</td>
</tr>
<tr>
<td>BS Output Power per RB</td>
<td>$P_{BS,RB}[dBm]$</td>
<td>29</td>
</tr>
<tr>
<td>Downlink Thermal Noise per RB</td>
<td>$N_{RB,DL}[dBm]$</td>
<td>-112.4</td>
</tr>
<tr>
<td>Downlink Interference Margin</td>
<td>$B_{DL}[dB]$</td>
<td>21.4</td>
</tr>
<tr>
<td>Downlink Sensitivity</td>
<td>$S_{DL}[dBm]$</td>
<td>-118.2</td>
</tr>
<tr>
<td>Downlink SINR</td>
<td>$\gamma_{DL}[dB]$</td>
<td>-5.8</td>
</tr>
<tr>
<td>Downlink Bit Rate per RB</td>
<td>$R_{RB,DL}[kbps]$</td>
<td>22.36</td>
</tr>
<tr>
<td>Total Downlink Bit Rate</td>
<td>$R_{DL}[kbps]$</td>
<td>1117.98</td>
</tr>
</tbody>
</table>

5.3.2 Link Budget Results

Using the proposed method in Section 5.3, the link budget was done for Lisbon center and Vila Franca de Xira, using the propagation model for 0.5 to 100 GHz. For each region, the frequency bands of 800 MHz and 3.5 GHz were tested.

Table 5.10, presents the main results of the Link Budget study for both regions, assuming that the uplink is the restrictive link of the network, with minimum requirements of 500 kbps for uplink and 1 Mbps for downlink, with a coverage probability of 95%.

Through the inspection of the results, it was concluded that the assumption is correct, since the total bit rate for downlink, is superior to the requirements of the network for both cases, Lisbon center, and Vila Franca de Xira, with values around 1.1 and 2.4 Mbps, respectively.

As the assumption was correct, the resulting maximum allowed path loss for Lisbon center is 125.1 dB.
Table 5.11: Cell range for the different frequencies in both regions.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Cell Range</th>
<th>Inter-site distance</th>
<th>Area</th>
<th>Necessary BSs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lisbon center</td>
<td>Vila Franca de Xira</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GHz</td>
<td>0.8</td>
<td>3.5</td>
<td>0.8</td>
<td>3.5</td>
</tr>
<tr>
<td>GHz</td>
<td>802</td>
<td>471</td>
<td>1375</td>
<td>644</td>
</tr>
<tr>
<td>m</td>
<td>2063</td>
<td>966</td>
<td>986</td>
<td>26</td>
</tr>
<tr>
<td>m</td>
<td>26131677</td>
<td>25830411</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For Lisbon center, 18 BSs are necessary for 800 MHz and 52 BSs for 3.5 GHz, while for Vila Franca de Xira, 6 BSs are necessary for 800 MHz and 26 for 3.5 GHz.

Necessary BSs | 18 | 52 | 6 | 26

dB, and for Vila Franca de Xira is 128.9 dB. With these results, the estimation of the cell range for these two regions with the different frequencies was done.

For both regions, the NLoS case was assumed, as it is the worst-case scenario for the network prediction. With this in mind, Equation 4.12 was used for Lisbon center, and Equation 4.18 was used for Vila Franca de Xira. Both these equations were solved in order at the 3D distance between the BS and the UE. The results for both regions and for the different frequency bands are presented in Table 5.11.

For Lisbon center, the resulting cell range for 800 MHz was 802 meters, and for 3.5 GHz was 471 meters, meaning that for a well designed network, 18 and 52 BSs are necessary, respectively, to accomplish the minimum requirements of QoS.

As for Vila Franca de Xira, the resulting cell range for 800 MHz was 1375 meters, and for 3.5 GHz was 644 meters, meaning that 6 and 26 BSs, respectively, are necessary for a well designed network, to accomplish the minimum requirements of QoS.

5.4 Coverage Prediction for the 0.5 to 100 GHz Propagation Model

In order to obtain the coverage prediction for a given region, it is first set a bounding box for the equivalent area, and the respective terrain matrix is created. Then, the received power footprints of every cell inside the bounding box are calculated, for the frequency band that is being tested. Once every footprint is calculated, for each entry of the bounding box terrain matrix, it goes through the equivalent entry of each of the cells footprints, and keeps the higher value of the received power, as the final value for the coverage in that location. This results in a matrix for the set region, with the higher received power value for the network in that location, between the tested cells. Meaning that it takes the value of the best serving cell in each position.

5.4.1 Lisbon center Prediction

For the coverage prediction in Lisbon center, the NLoS case was assumed for the propagation model, because this is a dense urban region with an high density of buildings in all area.

Figures 5.7 and 5.8, presents the coverage prediction, for 800 MHz and 3.5 GHz, respectively.

Through the analysis of these figures, it is possible to see that the cell range is much higher for the 800 MHz than for the 3.5 GHz, just as expected from the link budget.

Figure 5.9, presents the CDFs of the received power level for the coverage area, for 800 MHz and 3.5 GHz. Through the inspection of the graph, it was concluded that both frequencies have around 100% of
Figure 5.7: Lisbon center coverage planning for 800 MHz.

Figure 5.8: Lisbon center coverage planning for 3.5 GHz.
its values higher than the minimum sensitivity level for downlink, -118.2 dBm, meaning that the network is well served in this area for both frequency bands, ensuring the necessary high levels of coverage and QoS.

This goes according to the link budget since it was predicted that the necessary number of BSs is 18 for 800 MHz, and 52 for 3.5 GHz, and in the given region it is being tested a network with 94 BSs.

5.4.2 Vila Franca de Xira Prediction

Figures 5.10 and 5.11, presents the coverage prediction in Vila Franca de Xira, for 800 MHz and 3.5 GHz, respectively.

Once again, through the inspection of these figures, it was concluded that the cell range is much higher for the 800 MHz than for the 3.5 GHz, also as expected from the link budget.

Figure 5.12 presents, for 800 MHz and 3.5 GHz, the CDFs of the received power level for the coverage area. As it is possible to see through the inspection of the CDFs graph, both frequencies have around 100% of its values above the minimum sensitivity level for downlink, -114.5 dBm, meaning that in this area, the network is also well served, for both frequency bands, ensuring the necessary high levels of coverage and QoS.

For the 800 MHz frequency, this goes according to the link budget, as the predicted number for necessary BSs was 6, and the network has a total of 9 BSs.

For the 3.5 GHz frequency, the results do not go according to the prediction in the link budget, as it was predicted that to ensure the minimum requirements for the network, it would be necessary a total of 26 BSs.

This is due to the values of each entry in the terrain elevation matrix, being the mean of the various points within that entry, it is not possible to calculate if there is LoS in relation to the buildings, it can only be calculated in relation to the terrain.

In order to verify this, it was done the visual representation of the LoS possibility for the cells in Vila
Figure 5.10: Vila Franca de Xira coverage planning for 800 MHz.

Figure 5.11: Vila Franca de Xira coverage planning for 3.5 GHz.
Franca de Xira. Figure 5.13 presents one of those cases, where the blue area is in LoS with the BS, while the red area is not. It was concluded that, this was not realistic, since there are a lot of buildings around the BS, and in between them, there is LoS with the BS.
Chapter 6

Conclusions

This chapter finalizes the work and it is organized in two sections. In the first section the summary of all work done is presented, while in the second section the possible future work directions are described.

6.1 Summary

The main goals of this thesis were to present, validate and optimize a tool capable of doing the coverage planning of a mobile network, and furthermore, the implementation of a propagation model for values between 0.5 and 100 GHz.

This work started by introducing the necessary theoretical knowledge, in Chapter 2, in order to understand the performed work. An overview of the LTE network was presented, along with the methods for data collection of the network performance, and the propagation models.

Chapter 3 addresses the RF Footprint Simulator that was used during this thesis development. The algorithm was described, along with the necessary input data and the processes main modules of operations. The algorithm resorts to DTs in order to calibrate the propagation model and have more realistic results. For calibration, a library that solved the constrained least squares problem was initially used.

In Chapter 4, the algorithm validations were done, and the implementations needed for its optimization were introduced. For validation, tests that estimated the error between the resulting footprints and the received power values from DTs, were done, where the available DT set for the target cell was divided in 80% calibration of the propagation model and the remaining 20% worked as the validation set for these tests. Using the initial propagation model with the default value for the surrounding cells number, fifty, it was calculated for 470 cells from Lisbon center, the median absolute error, MAE and RMSE, where it was obtained mean values for those cell of 4.088 dB, 4.924 dB, and 6.273 dB, respectively, thus concluding that the algorithm is working properly as the resulting errors are low.

After the errors test, the dependencies of the received power with the distance, frequency and antennas height, were analyzed, as well as the dependencies of the diffraction losses with these same factors. Only the evolution of the received power with the frequency was not working as expected. Higher values of frequencies should result in increased received power, which was not verified. In order to solve this
problem, the path loss model was changed.

Another optimization made was for the calibration model, the initial approach could not calibrate some of the tested cells, giving default values for the independent factors of the path loss model. To prevent this, it was implemented another calibration model, that solves the linear least squares problem.

Furthermore, in this chapter, it was presented the implementation of a new propagation model for frequencies between 0.5 and 100 GHz (where all mobile communications technologies are inserted, 2G, 3G, 4G and 5G). This model is an adaptation of the path loss model from 3GPP [35, 36].

Chapter 5, presents the results of the optimizations made to the algorithm as well as the coverage prediction for a dense urban region, Lisbon center, and a suburban/rural region, *Vila Franca de Xira.*

First, it was presented the optimization of the surrounding cells number. For values between 0 to 50 for the surrounding cells number, it was tested 470 cells from Lisbon center, the errors of the footprints, the number of DTs per bin, and times for the calibration and for the estimation of necessary cell parameters. Even though the best results for the errors were without surrounding cells, this only proved that in Lisbon center, the cells had enough DTs for a good calibration. However, this is normally not the case, because in many other areas there is a low density of DTs measured per cell. In order to ensure that there is always enough DTs for the calibration, it was assumed that the ideal value for the surrounding cells number was twenty. Providing similar results to the default value, and leading to an algorithm with a much faster running time.

After this, the results of the footprint errors of the new path loss model were presented. It was estimated the median absolute error, MAE and RMSE, and was obtained values of 4.334 dB, 6.446 dB and 8.231 dB. These results were significantly worse, and the reason for this was the number of cells that the initial calibration model could not solve for the new path model, which was the reason for the calibration optimization.

The calibration optimization results are then presented. The footprint errors were tested, using the new calibration. A comparison was made between the errors for the cells footprints, without calibration, using the initial approach for the calibration, and finally the optimized calibration. It was obtained an error percentage between [-10, 10] dB, of 50%, 80%, and 90%, respectively, proving that the optimized calibration is the one that presents the best results.

Afterward, it was calibrated and given validation to the implemented propagation model for the available frequencies, for both dense urban and rural cases. For Lisbon center, values for the MAEs of 4.63 dB, 5.09 dB, and 3.78 dB for the frequencies 800 MHz, 1800 MHz, and 2600 MHz respectively, were obtained. In *Vila Franca de Xira,* values of 6.26 dB and 6.67 dB were obtained for the MAEs, in the 800 MHz and 2100 MHz frequencies, respectively.

Lastly, in this chapter, the results of the link budget and the coverage prediction for Lisbon center and *Vila Franca de Xira* were presented, for the frequencies 800 MHz and 3.5 GHz. From the link budget, it was estimated that, for Lisbon center, in order to accomplish the minimum requirements of the network, the cell range for 800 MHz was 802 and for 3.5 GHz was 471 meters, leading to a minimum of 18 and 52 BSs, respectively. As for *Vila Franca de Xira,* the cell range obtained for 800 MHz was 1375 meters and for 3.5 GHz was 644 meters, leading to a minimum of 6 and 26 BSs, respectively.
Then, the coverage predictions for these regions were made. For Lisbon center, it was possible to conclude from the CDFs of the received power level of the coverage area, that for both frequencies, around 100% of the area had higher values than the minimum sensitivity level estimated, -118.2 dBm, meaning that the network is well served in this area for both frequencies, ensuring QoS. This goes according to the expected in the link budget since this area has more BSs than the minimum estimated.

For Vila Franca de Xira, it was possible to conclude, once again, from the CDFs of the received power level for the coverage area, that for both frequencies, around 100% of the area had higher values than the minimum sensitivity level estimated, -114.5 dBm. For the frequency of 3.5 GHz, this is not in accordance with the expected in the link budget, since in this area there are not enough BSs to ensure the minimum requirements. This result is due to the low resolution of the terrain elevation matrix, where the LoS possibility could not be well estimated.

6.2 Future Work

As future work, some improvements should be done. First, the RF Footprint Simulator should be tested for other regions, with different networks and different propagation characteristics. The module should be optimized, by implementing different path loss models, and depending on the characteristics of the regions, the one that best fits each case, would be used.

The terrain elevation file should also be improved, as it should have an higher resolution, in order to obtain a more realistic result of the LoS possibility, so that obstacles like buildings can be recognized as obstacles more precisely.

With the release of higher frequencies from the 5G technology, a new calibration and validation should be done for the implemented propagation model for frequencies from 0.5 to 100 GHz.

Also, an use case of geolocation can be developed, where the results from RF Footprint Simulator are used to estimate the position of a set of measurements from different cells (measurement report). A measurement report should have the received power value from at least two different cells. Then, the footprints of each of those cells are calculated, and finally, the position of the measurement report can be estimated, through the superimposed matrix of the resulting footprints and finding the entry that has the closest values from the measurement report.
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