Automatic Node Insertion in a Multi-Technology Transmission Network

Luis Fontes Amorim da Cunha

Thesis to obtain the Master of Science Degree in

Electrical and Computer Engineering

Supervisor(s): Professor António José Castelo Branco Rodrigues
Professor Pedro Manuel de Almeida Carvalho Vieira

Examination Committee
Chairperson: Professor José Eduardo Charters Ribeiro da Cunha Sanguino
Supervisor: Professor António José Castelo Branco Rodrigues
Member of the Committee: Professor Pedro Joaquim Amaro Sebastião

December 2019
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

First and above all, I would specially like to express my deepest appreciation to my supervisor, Doctor Pedro Vieira, for allowing me to develop this work. During the last months, I have greatly benefited from his advice, his insightful suggestions, and his extensive knowledge on telecommunications. While it was a privilege to develop a deep understanding of one of the most dynamic areas of technology which, I am sure, will be key to my future success. I would like to thank Celfinet for giving me the opportunity to develop this work in a company environment.

I would like to express my gratitude to Eng. Diogo Parracho, not only for the opportunity of studying a real-life engineering problem and adding value to its business. It is my vision that Engineering should be at the service of society and industry, hence I am proud that this has happened with this work.

I also thank to the all Research Team of Celfinet for their collaboration in obtaining the necessary information and tools for the development of the thesis, especially André Alves and Filipe Dias. To all my friends who accompanied me on this journey, such as Francisco Mota, Tomás Ferreira, Antonio Cardoso and many others.

I would also like to thank my supervisors Doctor António Rodrigues and Doctor Paula Queluz, for all the support and insight they provided during the development of this thesis. I would like to thank Instituto de Telecomunicações for providing me the required means for the completion of this dissertation.

Finally, I would like express my very profound gratitude to my parents for all the support and encouragement they have given me over the years, as this accomplishment would not have been possible without them. I would also like to thank my brother for always being there when I needed.
Abstract

The increasing complexity of mobile networks, which has been witnessed in recent years due to the increased demands on their performance, the growing number of subscribers and the existing number of access networks, makes it difficult for mobile operators not only to maintain, but also to optimize the performance of their networks. Telecom operators face serious challenges with their transmission network configuration and operation to ensure good Quality of Service (QoS). As a result, mobile operators are increasing efforts to create tools and procedures that are intended not only to assist radio engineers in the process of maintaining and optimizing networks mobile, but also to turn appropriate networks more autonomous. In order to meet the new requirements, it will be unavoidable to position and keep investing in new infrastructures in the uncovered areas, or to provide greater capacity in places with high traffic growth or with the emergence of new radio technologies such as the Fifth Generation (5G).

This thesis aims to develop an algorithm that optimizes the planning of a base station for a real telecom operator, taking into account the structure of the existing telecommunication network (locations, connections and traffic flow), maximizing QoS and minimizing Operational Expenditure (OPEX) and Capital Expenditure (CAPEX). This work is intended to be incorporated into a network planning and monitoring platform in order to provide an automatic process for introducing a base station. This process is intended to facilitate the operator’s choice when parameterizing technology, available bandwidth, geographic locations of transmission nodes and the cost associated with each transmission technology.

To create the structure of the network, a Python library called NetworkX was used, which allows the creation, manipulation and study of the dynamics of a structure and functions of complex networks. This library enable a computational method to calculate processing priorities based on a strict priority scheduling, as well as the application of the Dijkstra package, which is found in this library. The cost function, applied in Djisktra, meets the objective of the thesis, which is to find the solution that presents the best possible QoS, taking into consideration the latency (delay) in each path.

For all scenarios, the results obtained by the developed algorithm suggest the best possible links for each new transmission solution, associated with the lowest costs. Thus, the locations supporting the new base station were the closest to the Line of Sight (LoS), or the ones that required the smallest extent of optical fiber binding. The latencies associated with each service displayed for each scenario portray a good QoS for each service.

Keywords: Networking, Transmission, Insertion, Optimization, KPIs.
Resumo

O aumento da complexidade das redes móveis, que se tem verificado nos últimos anos, devido à maior exigência quanto ao seu desempenho, ao crescente número de assinantes e ao aumento de diferentes redes de acesso, torna mais difícil para as operadoras móveis não apenas manter, mas também otimizar o desempenho das suas redes. As operadoras de telecomunicações enfrentam sérios problemas relacionados com a configuração e operação da sua rede de transmissão, de modo a garantir uma boa Qualidade de Serviço (QoS). Como resultado, as operadoras de redes móveis têm concentrado cada vez mais esforços na criação de ferramentas e procedimentos que visam não apenas auxiliar os engenheiros de rádio no processo de manutenção e otimização das redes móveis, mas também tornar a própria rede mais autónoma. De modo a fazer face a estes requisitos, será inevitável posicionar e investir em novas infraestruturas nas áreas sem cobertura, ou fornecer maior capacidade nos locais com grande crescimento de tráfego e onde se perspetiva o surgimento de novas tecnologias de rádio como a Quinta Geração (5G).

Esta tese tem como objectivo o desenvolvimento de um algoritmo, que otimize o planeamento de uma estação base para qualquer operador real, tendo em conta a estrutura da rede de telecomunicações existente (localizações, ligações e tráfego presente), maximizando a QoS e minimizando o OPEX e o CAPEX. Esta ferramenta tem como finalidade ser incorporada numa plataforma de planeamento e monitorização da rede, de forma a proporcionar um processo de automatização na introdução de uma estação base. Este processo tem a finalidade de facilitar a escolha ao operador, parametrizando a tecnologia, largura de banda disponível, localizações geográficas dos nós de transmissão e o custo associado a cada tecnologia de transmissão.

Para conceber a estrutura da rede recorreu-se a uma biblioteca Python designada por NetworkX, que permite a criação, manipulação e estudo da dinâmica de uma estrutura e funções de redes complexas. Esta ferramenta possibilitou a utilização de um método computacional para o cálculo das latências de processamento baseado em strict priority scheduling, bem como a aplicação do pacote Dijkstra, que se encontra nessa biblioteca. A função custo, aplicada no Dijkstra, vai ao encontro do objectivo da tese, que passa por encontrar a solução que apresenta o melhor QoS possível, e para isto, a função tem em consideração a latência presente em cada caminho.

Para todos os cenários, os resultados obtidos pelo algoritmo desenvolvido sugerem as melhores ligações possíveis para cada nova solução de transmissão, associada aos menores custos. Desta forma, os locais que suportam a nova estação base eram os mais próximos com linha de vista, ou os que exigiam a menor extensão de ligação por fibra óptica. As latências associadas a cada serviço exibidas para cada cenário, retratam uma boa QoS para cada serviço.

Palavras-chave: Rede de Telecomunicações, Transmissão, Inserção, Otimização, KPIs.
# Contents

Acknowledgments ........................................................................................................... v
Abstract ......................................................................................................................... vii
Resumo ........................................................................................................................... ix
List of Tables .................................................................................................................... xv
List of Figures .................................................................................................................. xvii
List of Symbols ............................................................................................................... xix
Acronyms ......................................................................................................................... xix

1 Introduction .................................................................................................................. 1
   1.1 Motivation .............................................................................................................. 1
   1.2 Objectives .............................................................................................................. 1
   1.3 Thesis Outline ........................................................................................................ 2
   1.4 Publications .......................................................................................................... 2

2 Background ................................................................................................................... 3
   2.1 Hierarchical network ............................................................................................. 3
   2.2 General Characteristics of transport networks ..................................................... 5
       2.2.1 Connecting Methods ...................................................................................... 5
       2.2.2 Network layering .......................................................................................... 6
       2.2.3 Data Plane, Control Plane and Management Plane ...................................... 7
       2.2.4 Resilience ..................................................................................................... 7
       2.2.5 Quality of Service ....................................................................................... 8
       2.2.6 Traffic Engineering ...................................................................................... 8
   2.3 Transmission Network ........................................................................................... 9
       2.3.1 Microwave .................................................................................................... 9
       2.3.2 Optical Fiber ............................................................................................... 13
   2.4 Access network ...................................................................................................... 18
       2.4.1 GSM e 3G .................................................................................................. 18
       2.4.2 Long Term Evolution (LTE) ....................................................................... 22

3 Platform development .................................................................................................. 31
   3.1 Graphs Theory ...................................................................................................... 31
List of Tables

2.1 Comparison of the several layers characteristics on a telecommunication network [3]. . . 5
2.2 Assumptions in the calculation of Downlink (DL) throughput. . . . . . . . . . . . . . . 21
2.3 Standardized QCI characteristics. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 26
2.4 Transmission Bandwidth Configuration [Mbit/s], [23]. . . . . . . . . . . . . . . . . . . . . 29

3.1 Router characteristics by location type. . . . . . . . . . . . . . . . . . . . . . . . . . . . . 35
3.2 Priorities of each service. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 39
3.3 Environment rating due to population density. . . . . . . . . . . . . . . . . . . . . . . . . 39
3.4 KPI Division. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 44

4.1 Maximum delay per service. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 51
4.2 Example of a priority list and the delays associated with each service in a node. . . . . 53
4.3 Example of a priority list and the delays associated with each service in a edge. . . . . . 54
4.4 Speed at which the packet is transmitted considering the technology. . . . . . . . . . . 54

5.1 Services, volume and throughput that will be associated with the new Base Station. . . 63
5.2 Latencies associated with both transmission solution. . . . . . . . . . . . . . . . . . . . 64
5.3 Latencies associated with each transmission solution. . . . . . . . . . . . . . . . . . . . 66
5.4 Services that will be associated with the new Base Station. . . . . . . . . . . . . . . . . 66
5.5 Latencies associated with microwave solution. . . . . . . . . . . . . . . . . . . . . . . . 67
5.6 Services, Volumes and Throughput that will be associated with the new location. . . . 68
5.7 Latencies associated with microwave solution for each service. . . . . . . . . . . . . . . 69

A.1 Costs associated with new fiber optic connections. . . . . . . . . . . . . . . . . . . . . . 79
A.2 Costs associated with new microwave connections. . . . . . . . . . . . . . . . . . . . . . 79
# List of Figures

2.1 Hierarchical Network Design [1]. ......................................................... 4  
2.2 Functions of the three major planes [6]. ............................................. 7  
2.3 QoS parameters depending on user’s application, [7]. ........................ 9  
2.4 Microwave connection [8]. ................................................................. 10  
2.5 Explanation what z means. ................................................................. 11  
2.6 Elements of a microwave link. ............................................................. 13  
2.8 Optical Fiber attenuation compared with others services, [12]. .............. 14  
2.9 Direct Ethernet Transport overview, [13]. ........................................... 16  
2.10 Ethernet over Transport Network overview, [13]. ............................... 16  
2.11 Example of optical fiber connectors, [12]. .......................................... 17  
2.12 Elements of a fiber optic link. ............................................................ 18  
2.13 Universal Mobile Telecommunications System (UMTS) System architecture. ................................................................. 19  
2.14 Radio Interface Protocol Architecture, [16]. ...................................... 20  
2.15 Channelization Code Tree, [17]. ......................................................... 21  
2.16 LTE Network Architecture, [18]. ....................................................... 23  
2.17 Frequency domain view of the LTE multiple-access technologies. ......... 25  
2.18 LTE Protocol Stack Layers. ................................................................. 25  
2.19 Performance of radio signal, [23]. ...................................................... 27  
2.20 LTE frame structure, [24]. ................................................................. 28  
3.1 Breadth-first Search example [25]. ..................................................... 33  
3.2 Depth-first Search example [25]. ...................................................... 33  
3.3 Overview of the network. ................................................................. 36  
3.4 Example of supporting links. ............................................................. 37  
3.5 Example of request later, but scheduled first rather than lower priority tasks. .............. 38  
3.6 Comparison between geotype versus population density. ..................... 40  
3.7 Measure of busy hour on 2G. ............................................................ 42  
3.8 Measure of busy hour and base line on 4G. ........................................ 43  
3.9 Dispersion nodes computation. .......................................................... 44  
3.10 Load related to busy hour. ............................................................... 46
3.11 Load related to base line hour. .................................................. 46
3.12 Overview of the Optical fiber ducts. ........................................ 47
3.13 LoS profile between two locations. ........................................ 47

4.1 Overview of Insert Base Station algorithm. ................................. 56
4.2 Fiber Ducts Search algorithm flowchart. ................................. 57
4.3 Line of Sight Search algorithm flowchart. ............................... 58
4.4 Validation algorithm flowchart. ............................................. 59
4.5 Computation of node delay .................................................. 60
4.6 Output of delay node algorithm with same inputs of table above. ........ 60
4.7 Computation of transmission and queuing delay. ...................... 61
4.8 Output of delay edge algorithm with same inputs of table above. ........ 61

5.1 High capacity area. .......................................................... 64
5.2 Comparing the Core Routing of the two solutions. ...................... 65
5.3 Line of Sight profile connecting new Base Station to the supported node. .. 66
5.4 Zone that has low values of quality of service. ........................ 67
5.5 Area that present a bad QoS. ............................................. 68
5.6 Core Routing. .............................................................. 69
5.7 LoS profile. ............................................................ 69
5.8 Area with lacking coverage for the 2600 MHz frequency. ................. 70
5.9 Area where the new base station will be inserted. ..................... 70
5.10 Routing Core from new base station (BS) to Core from microwave solution. .... 70
5.11 LoS profile. .............................................................. 71
Acronyms

2G  Second Generation
3G  Third Generation
3GPP  Third Generation Partnership Project
4G  Fourth Generation
5G  Fifth Generation

ANACOM  Autoridade Nacional de Comunicações
ATM  Asynchronous Transfer Mode
BER  Bit Error Rate
BS  base station

CAPEX  Capital Expenditure
CE  Channel Element
CN  Core Network
CS  Circuit Switched

DCPCCH  Dedicated Physical Control Channel
DL  Downlink

DWDM  Dense Wavelength Division Multiplexing

E-UTRAN  Evolved UTRAN

ETSI  European Telecommunications Standards Institute

FDD  Frequency Division Duplex
FDMA  Frequency Division Multiple Access
FIFO  First-In, First-Out

GPRS  General Packet Radio Services

GSM  Global System for Mobile Communications

IMT-2000  International Mobile Communications 2000

IP  Internet Protocol

ITU  International Telecommunication Union

ITU-R  International Telecommunication Union Radiocommunication Sector

KPI  Key Performance Indicator

LoS  Line of Sight

LTE  Long Term Evolution

ME  Mobile Equipment

MNO  Mobile Network Operator

MTBF  Mean Time Between Failures

MTTF  Mean Time of Failure

MTTR  Mean Time to Repair

OFDM  Orthogonal Frequency Division Multiplexing

OFDMA  Orthogonal Frequency Division Multiple Access

OPEX  Operational Expenditure

OTN  Optical Transport Network

PIR  Peak Information Rate

PPP  Point-to-Point Protocol

PS  Packet Switched

PSTN  Public Switched Telephone Network

QoS  Quality of Service

RAN  Radio Access Network

RNC  Radio Network Controller
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>RNS</td>
<td>Radio Network Sub-System</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single Carrier Frequency Division Multiple Access</td>
</tr>
<tr>
<td>SDH</td>
<td>Synchronous Digital Hierarchy</td>
</tr>
<tr>
<td>SF</td>
<td>Spreading Factor</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TE</td>
<td>Traffic Engineering</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UL</td>
<td>Uplink</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>URSI</td>
<td>Union Radio Science International</td>
</tr>
<tr>
<td>USIM</td>
<td>UMTS Subscriber Identity Module</td>
</tr>
<tr>
<td>UTRAN</td>
<td>UMTS Terrestrial RAN</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wide-Band Code-Division Multiple Access</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

This chapter presents the motivation behind the developed work, as well as the objectives to be accomplished. The thesis outline is also included in this chapter and some scientific papers publications as well.

1.1 Motivation

As the complexity of mobile networks grows due to the increasing performance requirements, number of subscribers and existence of the different access networks, it becomes harder for the mobile network operators not only to maintain, but also to optimize the performance of those networks. Telecom operators face serious problems related to the configuration and operation of their transmission networks, to guarantee the desired QoS. As a result, mobile network operators are targeting the creation of tools and procedures that aim, not only to assist radio engineers in the process of maintaining and optimizing the mobile networks, but also making the network itself more autonomous.

At the same time, the constant Radio Access Network (RAN) enhancements, will lead to the need of providing large capabilities to maintain the required performance.

To meet these requirements, it will be inevitable to position and build new BS in areas without coverage, or to provide larger capacities to areas that need to face the traffic growth, or to deploy emergent new radio technologies such as 5G. This technology has small cells and macro cells in its architecture, that highly justifies the study of new BS.

This thesis focuses on applying traffic routing techniques, wired/wireless connection planning considering the location and morphology of the terrain, and assimilating knowledge on the configuration of a telecommunications network structure.

1.2 Objectives

This thesis aims to develop an algorithm that optimizes or plans a BS location for any real operator, taking into account an existing telecommunications network structure (locations, connections and traffic),
maximizing QoS and minimizing OPEX and CAPEX. This tool is intended to be incorporated into a network planning and monitoring platform, in order to provide an automated process for new BS location, facilitating the operators work.

It is expected that the algorithm output presents to the regular user or operator the best transmission solution for the new BS within the existing network when parameterizing the technology, available bandwidth, geographical locations of the transmission nodes and the cost associated with each transmission technology (fiber optics or microwave).

In order to achieve these results, it is essential to have a platform that contains this information. Hence, a database was used with real Mobile Network Operator (MNO) information.

Additionally, the work resulting from this thesis allows to view the network structure on the map, as well as the load at different times of the day, using the company's drive tests database.

1.3 Thesis Outline

This thesis is divided into six chapters. Chapter 2 presents a technical overview of the telecom network configuration, a general characteristics of access and core networks are described.

In chapter 3, the applied data pre-processing steps related with the whole data collection are presented. This chapter also shows how the platform that contains the network information and explains its structure.

Chapter 4 presents the proposed algorithms to accomplish the outlined objectives of this work, as well as the necessary background knowledge to develop the concerning methodology.

Chapter 5 includes the obtained results through the application of the proposed algorithm in Chapter 4. It includes the uses cases that demonstrate the different software outputs.

In Chapter 6, a summary of the work carried out in this thesis is presented and some conclusions are drawn. Lastly, future work is suggested.

1.4 Publications

The following scientific paper was written in the context of this work:

Chapter 2

Background

This chapter outlines the general concepts of configuration a telecommunications network, it is hierarchical network design and general characteristics of transport networks. Also describe possible access and transmissions networks.

2.1 Hierarchical network

A hierarchical design represents a network which is divided into three discrete layers, like Figure 2.1. Each hierarchical layer has well defined functions within the overall network architecture. This type of division helps the network designer to optimize and pick the suitable hardware and even software and define their roles for that particular network layer.

This hierarchical network design includes the following three layers:

- The backbone/core layer that provides bulk data transport, redundancy and connection to external networks;
- The distribution layer that provides policy-based connectivity and data aggregation;
- The local-access layer that provides workgroup/user access to the network.

The core layer is the network central element that serves as the gateway between the carrier's private network and the public network. It's where carriers employ in-line networking equipment to enforce QoS policies or bandwidth metering. Typically, in telecommunication networks, the term "core" is used by service providers and refers to the high capacity communication facilities that connect primary nodes. The core networks provide high speed and highly redundant forwarding services to transport packets between distribution-layer devices in different network regions, such as 10 Gigabit Ethernet or 100 Gigabit Ethernet. A core/backbone network provides paths for the information exchange between different sub-networks. Core/backbone networks usually have mesh topology that provides any-to-any connections among devices in the network. The facilities and devices used for the core networks are usually
routers and switches. The technologies used for the core facilities are mainly network and data-link layer technologies.

Core networks mostly offer the following features [2]:

- **Aggregation** - Core nodes offer the highest level of aggregation\(^1\) in a service provider network.
- **Authentication** - Equipment within the core network has the function to decide whether the user requesting service from the telecom network has the proper authorization.
- **Call control/Switching** - Decides the future course of a call based on the call signalling processing.
- **Charging** - Core network equipment is able to handle the collation and processing of charging data generated by multiple network nodes.
- **Service Invocation** - The core network performs the task of service invocation for its customers. Service invocation may occur in line (such as call forwarding) by the users or unconditionally (such as for call waiting). It's important to note that third-party networks/nodes may take part in actual service execution.
- **Gateways** - Shall be present in the core to access other networks. Gateway functionality is dependent on the type of network it interfaces with.

The distribution layer is the smart layer in the three-layer model where routing, filtering and QoS policies are managed. This layer combines the incoming data from the access layer and then the data is transmitted to the core layer, from where it is routed to its final destination.

The access layer is where local end users are allowed into the network. The access layer focuses in minimizing "cost-per-port". This layer is called the desktop layer because it focuses on connecting

---

\(^1\)Aggregation: applies to various methods of combining multiple network connections on parallel in order to increase throughput beyond what a single connection could sustain, and to provide redundancy in case one of the links should fail.
client nodes to the network, such as workstations. It is responsible for providing end user devices with connection to network resources it ensures that packets are delivered to end user devices. Access layer devices include hubs, multi-station access units and switches.

Each layer has its own characteristics showing a hierarchy, as shown Table 2.1.

<table>
<thead>
<tr>
<th>Subnetwork network</th>
<th>Total distance [km]</th>
<th>Span length [km]</th>
<th>Aggregation factor</th>
<th>Topologies</th>
<th>Bit-rates [Gbps]</th>
<th>Protocol variety</th>
<th>Other characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>domestic</td>
<td>≤ 0.1</td>
<td>≤ 0.1</td>
<td>none</td>
<td>almost all</td>
<td>≤ 1</td>
<td>high passive</td>
<td></td>
</tr>
<tr>
<td>access</td>
<td>≤ 20</td>
<td>≤ 20</td>
<td>high</td>
<td>almost all</td>
<td>≤ 2.5</td>
<td>high passive</td>
<td></td>
</tr>
<tr>
<td>metro</td>
<td>≤ 300</td>
<td>≤ 80</td>
<td>medium</td>
<td>ring</td>
<td>10</td>
<td>medium</td>
<td>urban areas</td>
</tr>
<tr>
<td>regional</td>
<td>≤ 600</td>
<td>≤ 80</td>
<td>medium</td>
<td>ring and others</td>
<td>10</td>
<td>medium</td>
<td>rural areas</td>
</tr>
<tr>
<td>core</td>
<td>≤ 5000</td>
<td>≤ 150</td>
<td>low</td>
<td>mesh</td>
<td>40</td>
<td>low</td>
<td>long distance</td>
</tr>
</tbody>
</table>

2.2 General Characteristics of transport networks

The traditional vision of telecommunication networks has been a smart combination of transmission and switching technologies. In comparison to the old analog network, digital technologies paving the way to packet-based networks can automate some functions.

This section addresses internet-working features that support backbone, distribution and access services. The following topics are discussed:

- Transfer information between nodes
- Network layering
- Data Plane, Control Plane and Management Plane
- Resilience
- QoS
- Traffic Engineering (TE)

2.2.1 Connecting Methods

Digital network can transfer information between nodes using two methods [4]:

- Circuit-Switched - create a temporary and dedicated link on a fixed bandwidth between communication nodes, until the call is complete. This method can guarantee quality but most of the bandwidth is wasted. Uses dedicated channels, thus, all packets are transmitted by the same path. Has three phases: circuit establishment, information transfer and circuit disconnect. A typically example is Synchronous Digital Hierarchy (SDH).
• Packet-Switched - allows users to equally share bandwidth, optimizing the resources, without concern about quality and latency. Packets travels independently on communications typically shared. Each node determines next transmission step for each packet. For example, Internet Protocol (IP) or Asynchronous Transfer Mode (ATM).

Packet switching is easier and more affordable than circuit switching because it is more efficiency due to statistical multiplexing.

2.2.2 Network layering

The telecommunication network have become increasingly complex, so a layer structure had to be developed. Each layer had to assume some responsibility for certain tasks, in a way that when the layers operate together, creates a complex but functional mesh.

Other advantage of layer stratification is that it allows each one to develop independently, in order to allow the insertion new technologies.

This representation allows to view the telecommunication network in a simple and easily understandable way [5]:

• Layer 1 - Physical layer - decide the transmission media used to connect devices with data-link layer. Most common technologies implementing are Ethernet, SDH and Optical Transport Network (OTN);

• Layer 2 - Data-link layer - define the protocol for flow control between two nodes. Provide data frames between them. Typical examples of this layer are Point-to-Point Protocol (PPP)\(^1\) or Ethernet MAC;

• Layer 3 - Network layer - the main task is to provide routing and traffic control. Support the functional and procedural means of transferring variable length data sequences (called packets) from one node to another connected in "different networks". The most common technology is the IP.

• Layer 4 - Transport layer - deals with the coordination of the data transfer between end systems and hosts;

• Layer 5 - Session layer - responsible for establishment of connection, maintenance of sessions, authentication and also ensures security;

• Layer 6 - Presentation layer - the data from the application layer is extracted here and manipulated as per the required format to transmit over the network;

• Layer 7 - Application layer - at the very top of the OSI Reference Model stack of layers which is implemented by the network applications. These applications produce the data, which has to be transferred over the network. This layer also serves as a window for the application services to access the network and for displaying the received information to the user.

\(^1\)Point-to-Point Protocol: Is a communication protocol of the data link layer that is used to transmit multi-protocol data between two directly connected (point-to-point) computers.
2.2.3 Data Plane, Control Plane and Management Plane

The network is also organized in three major planes, regarding its functions, which are:

- Data Plane - "Actually moving the packets based on what we learned" - forwards traffic to the next hop along the path to the selected destination network according to control plane logic;

- Control Plane - "Learning what we will do" - makes decisions about where traffic is sent. Control plane packets are processed by the router to update the routing table information, essential for automation. It is the signalling of the network;

- Management Plane - element that configures, monitors and provides management, monitoring and configuration services to all layers.

![Figure 2.2: Functions of the three major planes [6].](image)

2.2.4 Resilience

Resilience is the ability to provide and maintain an acceptable level of service when faults occur. In order to increase the resilience of a given communication network, the probable challenges and risks have to be identified and appropriate resilience metrics have to be defined, for the service to be protected. The usual method is to duplicate the network resources taking into account the network topology, traffic protection requirements and technology equipment. If the traffic protection is organized in advance it is called "protection", if not, it is called "restoration". If backup path restoration is not defined in advance, it requires a search after fail occurrence, meaning that it will take longer to restore the network.

The importance of network resilience is continuously increasing, as communication networks are becoming a fundamental component in critical infrastructures operations.

The resilience of a resource can be measured through:

- Mean Time of Failure (MTTF) - measure of reliability used for non-repairable systems. It represents the length of time that an item is expected to last in operation until it fails;

- Mean Time to Repair (MTTR) - refers to the amount of time required to repair a system and restore it to full functionality;
• Mean Time Between Failures (MTBF) - measures the predicted time that passes between one previous failure of a mechanical/electrical system to the next failure during normal operation. Or, the time between one system breakdown and the next;
• Maximum recovery time;
• Unavailability.

2.2.5 Quality of Service

QoS is a overall performance measurement of a service. Related aspects of the network service are often considered, such as packet loss, bit rate, throughput, transmission delay, availability, jitter (variance on latency), etc.

This measurements are defined by several parameters:

• Bit Error Rate (BER) - fraction of erroneous bits over the total number of transmitted bits;
• Peak Information Rate (PIR) - fraction of lost packets over the total number of packets transmitted;
• Latency - the time needed to carry information from the source to destination node;
• Jitter - Instability, the latency variation range;
• Service unavailability - the probability that the network service is not working;
• Set-up time - delay between the user application request time and the network service actual delivery time.

Network provide many services to transport data. Each user's application use a network service that characterizes a certain latency, as can be seen in Figure 2.3.

2.2.6 Traffic Engineering

In complex mesh networks, TE is very important due to its mechanism of dynamically analyzing and predicting the behavior of data transmitted over the network to manage the resources allocation accordingly, allowing optimization of network performance. TE encompasses the application of technology and scientific principles to measurement, characterization, modeling, and Internet traffic control.

This system is useful because it decreases the network vulnerabilities, service errors and congestions. A major objective of TE is to minimize or eliminate high-loss situations. In particular, the number of rejected messages or failed call attempts should be as close to zero as possible. Another goal of TE is to balance the QoS against network operating and maintenance costs.
2.3 Transmission Network

2.3.1 Microwave

Microwave is a way of transmitting data by electromagnetic radiation using high frequencies (on order of GHz), often used in long range communications. Propagation speed is close to the speed of light. Although it is easy and inexpensive to implement, it is very susceptible to magnetic, electronic and atmospheric phenomena.

It is possible to connect two networks using a wireless point-to-point connection. This connection works as if it were a connected wire, this is because two directional antennas are used. Thus, the radio waves are transmitted focused on the receiver and not scattered by a region. The antennas need to be perfectly aligned and therefore usually only work for straight-line communication, without obstacles, resulting in a signal-to-noise ratio. Mountain and roofs serve as basis for microwave transmission towers because they are most likely to have LoS (i.e. unobstructed) to another tower. The maximum range will depend on the antennas gain used and the possibility to add antennas (repeaters) to increase the connection range, or change the antenna direction. This allows microwave radio systems to transmit

<table>
<thead>
<tr>
<th>User application</th>
<th>QoS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max. latency (ms)</td>
</tr>
<tr>
<td>Storage</td>
<td>N.A.</td>
</tr>
<tr>
<td>Backup/restore</td>
<td></td>
</tr>
<tr>
<td>Storage on demand</td>
<td>10</td>
</tr>
<tr>
<td>Asynchronous mirroring</td>
<td>100</td>
</tr>
<tr>
<td>Synchronous mirroring</td>
<td>3</td>
</tr>
<tr>
<td>Grid computing</td>
<td></td>
</tr>
<tr>
<td>Compute grid</td>
<td>100</td>
</tr>
<tr>
<td>Data grid</td>
<td>500</td>
</tr>
<tr>
<td>Utility grid</td>
<td>200</td>
</tr>
<tr>
<td>Multimedia</td>
<td></td>
</tr>
<tr>
<td>Video on demand (entertain quality, similar to DVD)</td>
<td>2–20 s</td>
</tr>
<tr>
<td>Video broadcast (IP-TV), entertainment quality similar to DVD</td>
<td>2–20 s</td>
</tr>
<tr>
<td>Video download</td>
<td>2–20 s</td>
</tr>
<tr>
<td>Video chat (SIF quality, no real-time coding penalty)</td>
<td>400</td>
</tr>
<tr>
<td>Narrowband voice, data (VoIP, ...)</td>
<td>100–400</td>
</tr>
<tr>
<td>Telemedicine (diagnostic)</td>
<td>40–250</td>
</tr>
<tr>
<td>Gaming</td>
<td>50–75</td>
</tr>
<tr>
<td>Digital distribution, digital cinema</td>
<td>120</td>
</tr>
<tr>
<td>Video conference (PAL broadcast quality 2.0 real-time coding penalty)</td>
<td>100</td>
</tr>
</tbody>
</table>

Note: Latency is expressed in milliseconds with the exception of video on demand, video broadcast, and video download, where seconds are the unit.

Figure 2.3: QoS parameters depending on user’s application, [7].
thousands of data channels between two points, without relying on a physical medium (such as optical fibers or cable).

There are two types of microwave connection: terrestrial and satellite. The first is limited to about 80 km due to Earth’s curvature. For longer connections, passive (two back-to-back antennas or mirrors) or active (two antennas that receive, process and retransmit) repeaters are used. The second uses the geostationary satellite, orbiting about 36000 km from the Earth’s surface, as a repeater. It receives at one frequency, amplifies or repeats the signal and retransmits at another frequency. This connection is used for television, long-distance telephone calls and private networks. Figure 2.4, presents an example of each connection type:

![Microwave connection](image)

**Figure 2.4: Microwave connection [8].**

**Microwave System Design**

A simple one-way microwave link includes four major components: a transmitter, a receiver, antennas and transmission lines, as shown in Figure 2.6.

In a microwave link, the transmitter produces a signal that carries the information to be communicated. The information can be anything, such as a phone call, television or radio programs, text, images, web pages or a combination of those media. The transmitter has two fundamental functions: generating microwave energy at the required frequency and power level, and modulating it with the input signal for transmission.

The second part of the microwave system is a transmission line. This line carries the signal from the transmitter to the transmitter antenna and from the receiver antenna to the receiver, at link ends. It uses coaxial cables, called waveguides, that present some losses between the emitter to the emitter antenna \(a_{g,e}\) and from the receptor antenna to the receptor \(a_{g,r}\).

Antennas used are highly directional, which means they focus the transmitted and received energy from one specific direction. By concentrating the signal where it’s needed, allows communication over long distances using small amounts of power. These component can introduce some gain \(g_{ant}\) to the signal, which is calculated by using Equations 2.1 and 2.2, [9].
\[ g_{\text{ant}} = \frac{4 \pi A_e}{\lambda^2}. \] \hfill (2.1)

\[ A_e = \frac{\eta \pi D^2}{4[m]} \]. \hfill (2.2)

Where \( D \) is antenna diameter, \( \eta \) is efficiency of the antenna, usually in the order of 0.5, \( A_e \) is effective aperture (related to the physical area of the antenna) and \( \lambda \) is the wavelength.

The antenna emits the microwave signal from the transmission line into free space (electrical engineer’s term to the void between the transmitting and receiving antennas). This link between antennas is a vital element of this connection because is critical to the microwave link’s success. The losses of free space propagation must be taken account and can be determined by using Equation 2.3, expressed in logarithmic units, [9].

\[ L_{fs} = -10 \log\left(\frac{\lambda^2}{(4 \pi)^2 \cdot d^2[km]}\right) = 32.5 + 20 \log_{10} d[km] + 20 \log_{10} f[MHz]. \] \hfill (2.3)

Where \( d \) is the distance between the antennas and \( f \) is the signal frequency.

Man-made and natural obstacles might block or attenuate the signal. Flat terrain can create undesirable reflections and precipitation can absorb or scatter some of the microwave energy. Obstruction attenuation can cause considerable losses on the signal, thus, the calculation of the first radius of Fresnel ellipsoid is needed, expressed on Equation 2.4, [9].

\[ r_1 = \pm \sqrt{\frac{z \cdot (d - z)}{d} \cdot \lambda}. \] \hfill (2.4)

This calculation determines if some obstacle will attenuate or block the signal, where \( z \) is the distance from the antenna to point want to know the radius and \( d \) is the distance from both antennas, as shown in Figure 2.5.

\[ L[dB] = 6.4 + 20 \log(h_e + \sqrt{h_e^2 + 1}), h_e > -0.8. \] \hfill (2.5)
being,

\[ h_c = \sqrt{\frac{2 \times d}{\lambda \times d_1 \times d_2}} \times x . \]  

(2.6)

\[ x = \frac{(h_1 - h_{\text{obs}}) \times d_2 + (h_2 - h_{\text{obs}}) \times d_1}{d} . \]  

(2.7)

Where \( h_1, h_2 \) and \( h_{\text{obs}} \) is the height of transmitter, receiver and obstacle antenna respectively and \( d_1 \) and \( d_2 \) is the distance from obstacle to transmitter and receiver antenna respectively.

For rain attenuation, the International Telecommunication Union Radiocommunication Sector (ITU-R) proposes the following calculating method, [9]:

1. Obtain the precipitation \((R_{i0.01})\) intensity exceeded only 0.01% of time (in Continental Portugal is varies between 32 to 42 mm/h);

2. Calculate the attenuation coefficient (dB / Km) for \( R_{i0.01} \) where \( k \) and \( \beta \) depend on the frequency and polarization (usual values are tabulated);

\[ \gamma_r = k \times R_{i0.01}^\beta . \]  

(2.8)

3. Calculate the effective path length \((d_{e,f})\) from the actual link length \((d)\);

\[ d_{e,f} = \frac{d}{1 + 0.35 \times \exp(-0.015 \times R_{i0.01})} . \]  

(2.9)

4. Calculate the rain attenuation \((A_r^{(0.01)})\) not exceeded by more than 0.01% of the time;

\[ A_r^{(0.01)} = \gamma_r \times d_{e,f} . \]  

(2.10)

5. Calculate the attenuation \((A_r^{(p)})\) not exceeded more than \( p \)% of the time.

\[ A_r^{(p)} = A_r^{(0.01)} \times 0.12 \times p \times (0.546 + 0.043 \times \log_{10} p) . \]  

(2.11)

At the end of the link is the receiver. This component must be capable of detecting low energy levels, due to power loss on transmission.

**Power budget**

To design a link, all gains, attentions and powers, represented on Figure 2.6, must be considered, in order to determine the received power. For that, Equations 2.12 and 2.13 (expressed in logarithmic units), are needed.

\[ p_o = P_i \times g_{\text{ant},E} \times g_{\text{ant},R} \times a_{g,E} \times a_{g,R} \times I_f_s . \]  

(2.12)
Figure 2.6: Elements of a microwave link [8].

\[ P_o = P_i + G_{ant,E} + G_{ant,R} - A_{g,e} - A_{g,r} - L_{fs}. \]  \hspace{1cm} (2.13)

Where \( p_o \) and \( p_i \) are the power received and emitted, \( g_{ant,E} \) and \( g_{ant,R} \) are the gain of the transmit antenna and the gain of the receive antenna and \( a_{g,e} \) and \( a_{g,r} \) are the attenuations related to the transmitter and receiver, respectively.

If repeaters exist, each link’s free space attenuation must be taken into account, defined on Equation 2.14, [9].

\[ P_o = P_i + G_{ant,E} + G_{ant,R} + G_{rep} - A_{g,e} - A_{g,r} - L_{fs,rep-R} + L_{fs,E-rep}. \] \hspace{1cm} (2.14)

Engineers must have in mind the existing and potential problems when designing a microwave link, for example, the subjects already spoken like the precipitation probability and the terrain morphology (reflections and obstacles).

### 2.3.2 Optical Fiber

Optical fiber is used by many telecommunications companies to transmit telephone signals, Internet communication and cable television signals. It has great advantages over existing copper wire in long-distance and high-demand applications. However, infrastructure development within cities was relatively difficult and time consuming, and optical fiber systems were complex and expensive to install and operate. Due to these difficulties, optical fiber communication systems have primarily been installed in long-distance applications, where they can be used to their full transmission capacity, offsetting the increased cost. “By 2002, an intercontinental network of 250,000 km of submarine communications cable with a capacity of 2.56 Tbps was completed.”, [10].

Fiber optics are thin and made of pure glass, about human hair size. They are composed of three layers: Core, cladding and jacket, as can be seen in Figure 2.7. The first one is glass component and where the light propagates, the second maximizes the internal reflection inside core and its refraction index is less than the core. The last one provides protection to the core from both physical and environmental damage.

There are two types of optical fiber, [11]:

---

---
- Single mode - The core diameter is almost identical to the emitted light wavelength, so propagates along a single path;
- Multi mode
  - Step-index - Core and cladding has a uniform material but different refractive index between these two;
  - Graded-index - Core material has a different index as function of the radial distance from the center.

Figure 2.8: Optical Fiber attenuation compared with others services, [12].
Fiber characteristics

Data transmission through fiber optic cables is limited by attenuation and dispersion. The value of the bandwidth-distance product is considered the fiber characteristic. The maximum transmission distance is affected by several types of dispersion that occur in fibers. The bandwidth-distance product is typically limited by the phenomenon that the bit error rate rises sharply for too high data rates. It is helpful for comparing the performance of different types of fiber optics links.

Attenuation fiber ($\alpha$) is caused by a combination of material absorption (modern fibers has attenuation around 0.3 dB/km), Rayleigh scattering, Mie scattering and connection losses. Also physical stresses to the fiber, microscopic fluctuations in density and imperfect splitting techniques can cause attenuation.

For modern glass fiber, the maximum transmission distance is limited by dispersion, and not by material absorption, "... any effect wherein different components of the transmitted signal travel at different velocities in the fiber, arriving at different times at the receiver", [12]. Dispersion in optical fibers is caused by various factors, [11]:

- Inter-modal Dispersion - caused by the different axial speeds different of transverse modes (limits the performance of multi-mode fiber);
- Chromatic Dispersion - which occurs because the glass index varies slightly depending on the light wavelength (limits the performance of single-mode fiber). Can be removed by a dispersion compensator;
- Polarization Mode Dispersion - slight imperfections or distortions in a fiber can change the propagation velocities for the two polarizations;

The dispersion effect in fiber increases with bigger fiber lengths. Engineers are always looking at current limitations in order to improve fiber-optic communication, and several of these restrictions are currently being researched.

Advantages and Limitations

Advantages, [11]:

- Low attenuation - For 1550 nm, the attenuation coefficient is approximately 0.2 dB/km;
- Very high bandwidth (THz);
- Small size and low weight - The optical fibre cable cross-section area is $\frac{1}{10}$ of coaxial cable cross-section area and its weight is $\frac{1}{30}$ of coaxial cable weight;
- No electromagnetic interference - Silica ($SiO_2$) or plastic are insensitive to electromagnetic interference;
- Low security risk;
• Reduced cost - Optical fibres are made of purified glass (raw material is silica) or plastic.

Limitations, [11]:

• Limited by attenuation and dispersion.

Optical Fiber System Design

Modern fiber optic communication systems generally include an optical transmitter (transducer) to convert electrical signal into an optical bit stream suitable for transmission, a cable containing bundles of multiple optical fibers that is routed through underground conduits and buildings, multiple kinds of amplifiers, and an optical receiver to recover the original electrical signal. The transmitted data is typically digital information generated by computers, telephone systems and cable television companies. There are two different ways to pack the information:

• Direct Ethernet Transport - Puts native Ethernet frames directly on optical fibers, used on distances below 100 km.

![Direct Ethernet Transport overview](image)

Figure 2.9: Direct Ethernet Transport overview, [13].

• Ethernet over Transport Network - The Ethernet frames are encapsulated in other transport frames, used in long distances, hundred or thousands of kms.

![Ethernet over Transport Network overview](image)

Figure 2.10: Ethernet over Transport Network overview, [13].

Transducers

• Electrical-to-optical transducers, [11]:
  – Light Emitting Diode (LED) - is inexpensive, reliable but can support only lower bandwidth;
  – Laser Diode (LD) - provides high bandwidth and narrow spectrum.

• Optical-to-electric transducers, [11]:
  – PIN Diode - Silicone or InGaAs based PIN Diode operates well at low bandwidth;
  – Avalanche Diode - Silicone or InGaAs Diode with internal gain can work with high data rate.
Fiber connectors

A fiber optic splice establishes an optical connection between two individual optical fibers. Fiber optics connectors may be required to fix broken fiber connection or to tap the fiber for additional connections. The Figure 2.11 as some examples of these connectors and their losses ($A_c$):

![Fiber connectors](image)

**Figure 2.11: Example of optical fiber connectors, [12].**

Amplifiers

Since the transmission distance is limited by fiber attenuation and distortion, it is necessary to manage the light power to provide larger distances. First it was used opto-electronic repeaters, that convert the signal into a electrical signal, and then use a transmitter to send the signal again at higher intensity than it was received. However, because of high complexity with modern wavelength-division multiplexed signals and the cost of these repeaters, this was not possible. An alternative approach is to use optical amplifiers which amplify the optical signal directly without having to convert to the electrical domain. An optical amplifier can boost a wide band at once which can include hundreds of individual channels. In theory, the amplifier gain ($G$) is estimated through the attenuation that will exist in that fiber section, so:

$$G = \alpha \ast L + n \ast A_s + A_c.$$  \hspace{1cm} (2.15)

Where $\alpha$ is the attenuation referring to the optical fiber, $L$ its length and $A_s$ and $A_c$ are the attenuation of splitters and connectors, respectively.

Power budget limited link

For dimensioning a data transmission link, all the topics talked above need to be considered, such as fiber characteristics (attenuation and dispersion), optical fiber system (transducers, amplifiers, connectors), receiver sensitivity and system margin (normally is 3dB).

$$P_s = P_r + M_s + G + \alpha \ast L + n \ast A_s + A_c.$$ \hspace{1cm} (2.16)

Where $P_s$ and $P_r$ are the transmit and receive powers respectively. And $M_s$ is the system margin.
2.4 Access network

2.4.1 GSM e 3G

Parallel to the generalized implementation and evolution of the Second Generation (2G), International Telecommunication Union (ITU) started the process of defining the standard for Third Generation (3G) mobile systems, called International Mobile Communications 2000 (IMT-2000). After that, UMTS was created by European Telecommunications Standards Institute (ETSI) to be later developed by Third Generation Partnership Project (3GPP).

UMTS is seen as the successor of 2G mobile communications systems, such as the Global System for Mobile Communications (GSM) and 2G evolved systems or General Packet Radio Services (GPRS). 3G UMTS brings evolution and improvements to the level of capacity, transmission rates and new services, compared to the 2G system, such as:

- faster data speeds
- variable data rates to allow bandwidth
- asymmetric data rate support, in downlink and uplink, to transmit packet-switched traffic
- providing of QoS for various applications and services
- higher spectral efficiency

Unlike the 2G, which was developed primarily for voice transmission, the 3G was originated for data transfer.

Architecture

A UMTS network, taking into account that its functionalities and logical interfaces that interconnect them are well defined and specified by 3GPP standards, is composed of three groups, as you can see on Figure 2.13. These three groups are:

- User Equipment (UE) - interact with the user and the radio interface
- UMTS Terrestrial RAN (UTRAN) - radio functionalities
- Core Network (CN) - means of communication with external networks
There are some changes in the architecture. When compared to GSM, from the UE and UTRAN to protocol level, with the introduction of a new UTRAN interface.

The UE is the device available at the end-user. It has two modules: the Mobile Equipment (ME) and the UMTS Subscriber Identity Module (USIM). The ME is the device itself and the USIM is the SIM card, that contains the confidential data of each user.

UTRAN is composed of one or more Radio Network Sub-System (RNS). A RNS has one Radio Network Controller (RNC) and one or more NodeBs. The NodeB manages the data flow between the interface Iub and Uu. The RNC is responsible of controlling the NodeBs which are connected to it. UTRAN, establishes connectivity between the UE and the CN.

The CN responsibility is to switch and route the calls and also to act as the connection to external networks. It interconnects the radio access network to other external networks, such as the Public Switched Telephone Network (PSTN) and the Internet. The CN network is divided, mainly between the Circuit Switched (CS) and Packet Switched (PS) domains, since external networks and technologies are different.

The interfaces used to communicate between network elements are:

- CU - electric interface between USIM and ME;
- Uu - radio interface WCDMA responsible to connect the mobile part to the fixed part of the network. It connects the UE with the UTRAN.
- Iu - interface that associates the RAN to the CN;
- Iub - links the nodeB with RNC;
- Iur - interface responsible to assure the soft handover\(^1\) between RNCs.

\(^1\)Handover: A process that occurs when a mobile device is transferred from one cell to another without losing its connection. Ensures mobility.
Radio Interface

The UTRAN radio interface is divided into three protocol layers. The Figure 2.14 presents the layers and their interactions for UMTS, [16].

- Layer 1 - Physical layer;
- Layer 2 - Data-link layer (divided between Medium Access Control (MAC) and Radio Link Control (RLC));
- Layer 3 - Network layer.

Between the Physical layer and the Data Link layer, the transfer is done on the transport channels, and they are characterized by how and with what kind of characteristics data is transferred. Additionally, in the Data-link Layer, it contains logical channels, which are characterized by what type of data is transmitted.

Channelization Codes

UMTS uses Wide-Band Code-Division Multiple Access (WCDMA) technology as the transport mechanism in the radio interface, contrary to the methods used by the previous generation, which uses Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) technologies. In order to distinguish the users, WCDMA technology divide not in time or frequency but in code. This process has two phases: Spreading, consisting in order to spread the information to be transmitted through the available spectrum ($5 MHz$) and scrambling, randomly generated codes that provide the separation.

The Spreading Factor (SF) is the ratio between the chip rate and the information rate. In UMTS, the chip rate is equal to 3.84 Mchip/s. As in Figure 2.15, the available codes number depends on the
SF, which means that if it uses a SF of 4, only 4 codes are available to the users, but if the SF is 128, allows the allocation of 128 codes. So, the maximum codes number is a limitation for the maximum users number served at the same time. Moreover, a single user can use one or more codes. Each channelization code is defined by \( C_{ch, SF, k} \), where SF is the code spreading factor and \( k \) is the code number, between 0 and SF-1.

Each channelization code is defined by \( C_{ch, SF, k} \), where SF is the code spreading factor and \( k \) is the code number, between 0 and SF-1.

![Figure 2.15: Channelization Code Tree, [17].](image)

The number of available DL orthogonal codes within one scrambling code are limited by the spreading factor. With a spreading factor of N, the total number of orthogonal codes available is also N. To obtain the maximum data throughput, certain characteristics need to be known, that are presented on Table 2.2

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spreading Factor</td>
<td>128</td>
</tr>
<tr>
<td>Soft handover overhead</td>
<td>20%</td>
</tr>
<tr>
<td>Chip Rate</td>
<td>3.84 Mcps</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK (2 bits per symbol)</td>
</tr>
<tr>
<td>Common channel codes</td>
<td>10</td>
</tr>
<tr>
<td>Average DPCCH overhead</td>
<td>10%</td>
</tr>
<tr>
<td>Channel coding rate</td>
<td>( \frac{1}{3} ) with 30% puncturing</td>
</tr>
</tbody>
</table>

Using the Equation 2.17, the obtained throughput is 2.5 Mbps.

\[
R_b = R_c \times \frac{S_f - C_{CCH}}{S_f} \times \frac{1}{1 + O_{SH}} \times m \times O_D \times R_{CCH} \times \frac{1}{1 - p}. \tag{2.17}
\]

Where \( R_b \) is the obtained throughput, \( R_c \) is the chip rate, \( S_f \) is the spreading factor, \( C_{CCH} \) is the number of common channel codes, \( O_{SH} \) is the soft handover overhead, \( m \) is the modulation (bits per symbol), \( O_D \) is the average Dedicated Physical Control Channel (DCPCCH) overhead, \( R_{CCH} \) is the channel coding rate and \( p \) the puncturing used.

21
**Capacity**

The Channel Element (CE) is a measure of the required resource allocation in the Node B necessary to provide capacity for one voice channel, including control plane and signalling. The number of required CEs for a certain user depends on the traffic type of the services in using. The more number of CEs available on a certain Node B, the more capacity is available for users. The amount of CEs can be optimized to fit the current need depending on the type of users and the amount of users using different services.

**2.4.2 Long Term Evolution (LTE)**

The Long Term Evolution (LTE) is a Fourth Generation (4G) mobile communications technology, also developed by 3GPP, resulting of 2G/3G access technologies evolution. This broadband radio system provides a high-rate, low latency packet-switched optimized system. The emergence of the 4G of mobile networks marks a major change in communications, as it is a completely new mobile communication system. Packet-only networks were implemented, placing data services as the main business of mobile operators, the All-IP concept. In short, the LTE specifies higher energy and spectral efficiency, lower latency, channel bandwidth flexibility, cost reduction and compatibility with other network generations.

LTE can be operated in Frequency Division Duplex (FDD) or Time Division Duplex (TDD) mode, also referred to as LTE FDD and TD-LTE. The DL in LTE uses the Orthogonal Frequency Division Multiple Access (OFDMA) as its multiple access scheme and the Uplink (UL) uses Single Carrier Frequency Division Multiple Access (SC-FDMA). Both solutions provide orthogonality between users, reducing interference and increasing network capacity. The main aspects of LTE technology are:

- New multiple access schemes based on OFDMA for LTE-FDD and LTE-TDD;
- Support for Multiple-Input, Multiple-Output (MIMO) antenna technology;
- New control and data channels;
- New network architecture and protocols (two nodes, IP-based).

**Architecture**

LTE, unlike UMTS, does not support CS connections. Because it is based on IP, with the transition of networks combining CS and PS, the system architecture became simpler.

As such, the LTE concept consists of the radio access network, Evolved UTRAN (E-UTRAN), and the core network, Evolved Packet Core (EPC), characterized by simplicity. Since the packets are processed and forwarded in the EPC core, improves the transmission rate and the latency time.

Figure 2.16 shows the architecture of an LTE network, including its elements and the standardized interfaces.

The EPC is responsible for UE overall control and bearers establishment. The main logical nodes are:
- Policy Control and Charging Rules Function (PCRF) - responsible for policy control decision-making, as well as controlling the flow-based charging functionalities in the Policy Control Enforcement Function (PCEF), which resides in the PDN-GW;

- Home Subscriber Server (HSS) - central database that contains information about all the operator’s network subscribers;

- Serving Gateway (SGW) - Serves as the local mobility anchor for the data bearers when the UE moves between eNodeBs;

- Mobility Management Entity (MME) - Controls the mobile’s high-level operation with signalling messages and Home Subscriber Server (HSS);

- Packet Data Network Gateway (PDN-GW) - Responsible for IP address allocation for the UE. Is also important for the filtering of downlink user IP packets into the different QoS-based (bearers).

- E-SMLC (not shown in Figure 2.16) - Calculates the best server eNodeB based on received measures, and determines UE speed and achieved accuracy.

While the CN consists of many logical nodes, the access network is made up of essentially just one node, the Evolved Node B (eNodeB), which connects to the UEs. Each of these network elements is inter-connected by standardized interfaces in order to allow multivendor interoperability, which are:

- X2 - To perform handovers between eNodeBs and management of load and interference;

- S1 - Interface between the core and the radio access networks;

- S11 - Performs the signaling exchange between the SGW and the MME;

- S6a - Allows the subscriber transfer and data authentication between the MME and the HSS;

- S5/S8 - Performs the user plan connection and its management between SGW and PDN-GW;
• SGi - Interface between the PDN-GW and the external networks, allowing, for example, Internet access;

• S7 - Allows the QoS QoS policies transfer and tax rules.

The E-UTRAN, simply consists of a eNodeBs network and is responsible for managing multiple cells and for all radio-related functions, which are, [19]:

• Radio Resource Management (RRM) - Covers all radio bearers related functions, such as radio bearer control, radio admission control, radio mobility control, scheduling and dynamic resources allocation for UEs in both UL and DL;

• Header Compression - Helps to ensure efficient use of the radio interface by compressing the IP packet headers, which could otherwise represent a significant overhead;

• Security - All data sent over the radio interface is encrypted;

• Positioning - The E-UTRAN provides the necessary measurements and other data to the E-SMLC and assists it in finding the UE position;

• Connectivity to the EPC - Consists of the signalling towards the MME and the bearer path towards the SGW.

As a result of eNodeBs having such functionalities allows tight interaction between the different protocol layers of the radio access network, thus reducing latency and improving efficiency. Such distributed control reduce costs and avoid "single points of failure".

The protocols running between the eNodeBs and the UE are known as the Access Stratum (AS) protocols.

To achieve the extensive range of requirements, outlined above, is only possible due to advances in the underlying mobile radio technology. As an overview, three fundamental technologies, that have shaped LTE radio interface design, outline worthy, are: multicarrier technology, multiple-antenna technology, and the application of packet-switching to the radio interface.

**Multicarrier Technology**

For multiple access in LTE it was adopted OFDMA for the DL and SC-FDMA for the UL. Both of these schemes allows a new dimension of flexibility in the system, as you can see in Figure 2.17.

To provide a multiple-access scheme, OFDMA extends the multicarrier technology of Orthogonal Frequency Division Multiplexing (OFDM). While OFDM subdivides the bandwidth available for signal transmission multiple of narrow band subcarriers, arranged to be mutually orthogonal, which either individually or in groups can carry independent information streams. However in OFDMA, this available bandwidth subdivision is exploited in sharing the subcarriers among multiple users.

SC-FDMA, provides a multiple-access technology which has much in common with OFDMA, in particular the flexibility in the frequency domain, and the incorporation of a guard interval at the start of each
transmitted symbol to facilitate low complexity frequency domain equalization, at the receiver. Peak-to-Average Power Ratio (PAPR) of OFDM is difficult to tolerate for the transmitter of the mobile terminal, in the uplink.

**Radio Interface**

As said above, LTE has been designed as a completely packet-oriented multiservice system. This philosophy is applied across all the layers of the protocol stack. Below is a more elaborated diagram of E-UTRAN Protocol Stack:

![LTE Protocol Stack Layers](image)

The information flows between the different layers are known as channels, which are distinguished by the kind of information they carry and by the way in which the information is processed.

- **Logical Channels** - Define *what type* of information is transmitted over the air. Data and signalling messages are carried on logical channels between the RLC and MAC protocols;
• Transport Channels - Define how is something transmitted over the air. Data and signalling messages are carried on transport channels between the MAC and the physical layer.

• Physical Channels - Define where is something transmitted over the air. Data and signalling messages are carried on physical channels of the physical layer.

Quality of Service

LTE architecture supports hard QoS, with end-to-end quality of service and Guaranteed Bit Rate (GBR) for radio bearers. Each Service Data Flow (SDF) is associated with one and only one QoS Class Identifier (QCI). QoS is a natural fit because the LTE MAC is fully scheduled. The QCI priority determines the order in which the data packets are manipulated, that is to say that if two data flows arrive at the same time for being processed, the flow that presents a QCI with lower priority is processed first, so that it has a shorter delay. Priority defines the importance of the respective data stream, for example, the voice service has a higher priority (less value) than a video streaming service, because it is more serious for a user to notice a delay in conversation than when watching a streaming video.

EPS bearers provide one-to-one correspondence with RLC radio bearers and provide support for Traffic Flow Templates (TFT). There are four types of EPS bearers:

• GBR Bearer - Resources permanently allocated by admission control;
• Non-GBR Bearer - No admission control;
• Dedicated Bearer - Associated with specific TFT (GBR or Non-GBR)
• Default Bearer - Non-GBR, catch-all for unassigned traffic

Table 2.3 exemplifies some QCI characteristics, each with its associated QoS parameters and a well-defined usage purpose. The characteristics describe the packet forwarding treatment that an SDF aggregate receives edge-to-edge between the UE and the PCRF.

<table>
<thead>
<tr>
<th>QCI</th>
<th>Resource Type</th>
<th>Priority Level</th>
<th>Packet Delay Budget (ms)</th>
<th>Packet Error Loss Rate</th>
<th>Example services</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GBR</td>
<td>2</td>
<td>100</td>
<td>$10^{-2}$</td>
<td>Conversational Voice</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>4</td>
<td>150</td>
<td>$10^{-3}$</td>
<td>Conversational Video (Live Streaming)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>3</td>
<td>50</td>
<td>$10^{-3}$</td>
<td>Real Time Gaming</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>4</td>
<td>300</td>
<td>$10^{-6}$</td>
<td>Buffered Streaming</td>
</tr>
<tr>
<td>65</td>
<td></td>
<td>0.7</td>
<td>75</td>
<td>$10^{-2}$</td>
<td>Mission Critical user plane Push To Talk voice</td>
</tr>
<tr>
<td>66</td>
<td></td>
<td>20</td>
<td>100</td>
<td>$10^{-2}$</td>
<td>Non-Mission-Critical user plane Push To Talk voice</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>2.5</td>
<td>50</td>
<td>$10^{-2}$</td>
<td>V2X messages</td>
</tr>
<tr>
<td>5</td>
<td>Non-GBR</td>
<td>1</td>
<td>100</td>
<td>$10^{-6}$</td>
<td>IMS Signalling</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>6</td>
<td>300</td>
<td>$10^{-6}$</td>
<td>TCP-based (www, e-mail, chat, ftp, p2p file sharing, progressive video, etc)</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>7</td>
<td>100</td>
<td>$10^{-3}$</td>
<td>Live Streaming, Interactive Gaming</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>8</td>
<td>300</td>
<td>$10^{-6}$</td>
<td>TCP-based (www, e-mail, chat, ftp, p2p file sharing, progressive video, etc)</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>9</td>
<td>300</td>
<td>$10^{-6}$</td>
<td>TCP-based (www, e-mail, chat, ftp, p2p file sharing, progressive video, etc)</td>
</tr>
<tr>
<td>69</td>
<td></td>
<td>0.5</td>
<td>60</td>
<td>$10^{-6}$</td>
<td>Mission Critical delay sensitive signalling</td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>5.5</td>
<td>200</td>
<td>$10^{-6}$</td>
<td>Mission Critical Data</td>
</tr>
<tr>
<td>79</td>
<td></td>
<td>6.5</td>
<td>50</td>
<td>$10^{-2}$</td>
<td>V2X messages</td>
</tr>
</tbody>
</table>

26
Capacity

The radio signal quality is affected by several factors such as signal path loss or diffraction (that reduce the power density of the signal) and space loss (which affects the subscriber’s signal as he moves away from the transmitting base station). The Figure 2.19 suits an example of environment challenges and the performance of radio signal through that threats.

(a) Radio environment challenges
(b) Data throughput adjusted based on radio conditions

Figure 2.19: Performance of radio signal, [23].

The better the quality of signal received, the better the performance and throughput achieved by the subscriber. These factors affect the performance of radio transmission and have originated the development of new adaptive modulation schemes and techniques, which aim to even for the environmental factors, delivering more capacity and better range in a noisy environment full of obstacles.

One example of these sophisticated techniques is adaptive modulation. Adaptive modulation provides a trade-off between robustness of digital encoding and delivered bit rate, in order to balance throughput with error resilience, dynamically based on the current RF channel conditions reported by the UE in Measurement Reports. When the signal strength is good, the modulation switch to a less robust encoding (higher bit rate). But on the other hand, when the strength is weak the modulation switch to a more robust encoding (less bit rate) due to multi-path reflections. Due to OFDM signal, it is possible to choose between three types of modulation: Quadrature Phase-Shift Keying (QPSK or 4-QAM) 2 bits per symbol, 16-Quadrature Amplitude Modulation (16-QAM) 4 bits per symbol and 64-QAM 6 bits per symbol.

Other alternative is the use of multiple antennas at both the transmitter or receiver to improve performance. That technology scheme is called Multiple-input and Multiple-output (MIMO).

3GPP has defined bandwidth channels for LTE, being the three more used the: 5, 10 e 20 MHz. The smallest modulation structure in LTE is the Resource Element (RE), as can be verified on Figure 2.20.

Analyzing Figure 2.20 and knowing the number of RBs of each channels, it is possible to deduct the number of REs for the channel, in one subframe (1ms). For example, for channel bandwidth of 5 MHz [24]:

27
12_{\text{Subcarriers}} \times 7_{\text{Symbols of OFDMA}} \times 25_{\text{RBs}} \times 2_{\text{Slots}} = 4200_{\text{REs}}. \quad (2.18)

Assuming the modulation QPSK without codification, the bit rate is:

\[
2_{\text{Bits/symbol}} \times \frac{4200_{\text{REs}}}{1_{\text{ms}}} = 8.4_{\text{Mbps}}. \quad (2.19)
\]

Solving the Equations 2.18 and 2.19, we can obtain the number of REs and theoretical values of throughput, in DL, for each typically wide-bands, as shown in Table 2.4.

It is necessary to subtract the related overhead with signaling, synchronization and coding, it is estimated to be about the 25% the maximum bit-rate (throughput), under ideal conditions, considering the channel 5 MHz, 64-QAM and MIMO 4x4, can be given by:

\[
0.75 \times 100.8 = 75.6_{\text{Mbps}}. \quad (2.20)
\]
Table 2.4: Transmission Bandwidth Configuration [Mbit/s], [23].

<table>
<thead>
<tr>
<th>Channel Bandwidth (MHz)</th>
<th>5</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum of Resource Blocks</td>
<td>25</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Maximum Occupied Bandwidth (MHz)</td>
<td>4.5</td>
<td>9.0</td>
<td>18.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modulation</th>
<th>SISO</th>
<th>MIMO 2x2</th>
<th>MIMO 4x4</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>8.4</td>
<td>16.8</td>
<td>33.6</td>
</tr>
<tr>
<td>16-QAM</td>
<td>16.8</td>
<td>33.6</td>
<td>67.2</td>
</tr>
<tr>
<td>64-QAM</td>
<td>25.2</td>
<td>50.4</td>
<td>100.8</td>
</tr>
<tr>
<td>QPSK</td>
<td>16.8</td>
<td>33.6</td>
<td>67.2</td>
</tr>
<tr>
<td>16-QAM</td>
<td>33.6</td>
<td>67.2</td>
<td>134.4</td>
</tr>
<tr>
<td>64-QAM</td>
<td>50.4</td>
<td>100.8</td>
<td>201.6</td>
</tr>
<tr>
<td>QPSK</td>
<td>33.6</td>
<td>67.2</td>
<td>134.4</td>
</tr>
<tr>
<td>16-QAM</td>
<td>67.2</td>
<td>134.4</td>
<td>268.8</td>
</tr>
<tr>
<td>64-QAM</td>
<td>100.8</td>
<td>201.6</td>
<td>403.2</td>
</tr>
</tbody>
</table>
Chapter 3

Platform development

On this Chapter introduces the developed platform and the necessary and implemented tools that supported the development and testing of the software for the thesis. The Chapter begins by giving a brief review of graph theory, as graphs were fundamental in the creation of the platform especially the information of locations and relationship between them (connections). Next, the structure of the telecommunications network, the information gathered from the Celfinet company database and some necessary choices and tools were exposed.

3.1 Graphs Theory

This mathematics field is used to study relationships between the objects of a set. Usually represented by a graph $G = (V(G), A(G))$, a diagram in which the vertices are represented by points and the edges by lines joining adjacent vertices, configuring the imagined relation. Several problems can be represented by graphs:

- Trajectories between cities;
- Routing of vehicles;
- Site Map of a site;
- Computer network;
- Telecommunications network.

In mathematics and computer science, connectivity is one of the basic concepts of graph theory. It is a subject strongly linked to the theory of network flow problems. The graph connectivity is an important measure of the robustness of a network.

Over the years, telecommunications networks have been forming a complex topology, not only in number of nodes and inter-connectors but also in communication protocols. On the other hand, the networks were expanded for technical needs, and some of them, such as optical fiber, according to
geography. The mobile communication networks present part of the topology with dynamic configuration because of the mobile terminals. Thus, network typologies display properties according to the configuration, and it is possible to improve their performance by knowing it.

The focus extends beyond the network structure to an understanding of the relationship between structure and dynamics. The dynamics of information traffic flow, in complex networks, has been studied and the issue of traffic congestion has become very important, requiring efficient handling.

### 3.1.1 Terminology

A graph is an ordered pair \((V, A)\), where \(V\) is an arbitrary set and \(A\) is a subset of \(V^{(2)}\), the set of all unordered pairs of \(V\). Being the vertex elements \(V\) and edge elements \(A\). Consider two vertices \(u\) and \(v\) and an edge connecting them denoted \(uv\) or \(vu\). When two vertices are points on the same edge, they are said to be neighbors or adjacent. The number of vertices is denoted by \(n\) and the number of edges per \(m\). The degree of a vertex is defined as the number of incident edges.

A path between two vertices \(v_1\) and \(v_2\) of a graph is the edges sequence of the path leaving in \(v_1\) in the direction of \(v_2\) and are said ends of the path. The path length is its edges number. Graphs can have weights associated with their edges, represented by a number, labeling each edge. In this case, the path length between two vertices is the edges weights sum that compose the path.

### 3.1.2 Digraphs and Multigraph

A graph is said to be a digraph when the connections direction between the vertices is considered. In this case the directed edge is called arc.

A multigraph is where between two vertices has more than one relation, this means that has more than one edge connecting these two vertices.

### 3.1.3 Value graphs

A network is a graph in which a real number is associated with the connections. This number is often referred to as binding weight. This classification is given according to the need, or, of the flow indication in the vertices. In practice this number can represent:

- Cost;
- Distance;
- Time;
- Broadcast Reliability;
- Failure Probability;
- Capacity.
3.1.4 Search in graphs

There are two ways to cover all the vertices of a graph, usually called search.

- Breadth-first Search (BFS) - In this way, start from an initial vertex and goes through all its neighbors, one by one, and then crosses the neighbors of each one of its neighbors, in the order that was visited in the previous step;

![Breadth-first Search example](image)

- Depth-first Search (DFS) - Starting from an initial vertex, this algorithm visits the vertices one by one to the "deeper son" that can be reached, and after descending in the hierarchy, passes the next child.

![Depth-first Search example](image)

3.1.5 Computational representation

There are several structures that can be used to store the information of a graph or digraph.

- Matrix of adjacencies - is an array $M$ of Dimension $|V| \times |V|$ in which the element $M_{i,j}$ will be equal to 1 if there is an edge from $i$ to $j$ or 0, otherwise;

![Matrix of adjacencies](image)
• List of adjacencies - It stores for each vertex $u$ of $v$ a list of all the vertices $v$ for which there is an edge $uv$;

• List of edges - uses two vectors with $|A|$ elements to store the edges of the edges belonging to $A$;

• Matrix of incidences - For a digraph is a matrix $M$ of dimension $|V| \times |A|$ where each element follows the equation:

$$m_{ij} = \begin{cases} +1, & \text{if } v_i \text{ is the initial vertex of } a_j \\ -1, & \text{if } v_i \text{ is the final vertex of } a_j \\ 0, & \text{otherwise} \end{cases}$$

(3.1)

In the case of non-directed graphs it is equal to the adjacency matrix;

• List of edges and vertices - are the simplest form of representation of a graph. Two lists are maintained, one with all the vertices of the graph and the other with all the edges and their ends.

### 3.1.6 Minimum path

As previously stated, the length of a valued path is the costs sum of traversing each edge and in an unvalued graph is equal to the number of edges that compose it. The minimum path problem is the optimization of the cost of crossing a graph between two vertices.

The most popular algorithms for determining the minimum cost are:

• Bellman-Ford - Minimum path search algorithm of weighted graph whose edges can have a negative cost, unlike Dijkstra, although a slow algorithm;

• Dijkstra - Minimum path search algorithm of a weighted graph, directed or not with positive weighted edges;

• A* - Path search algorithm through combinations of heuristic approximations;

• Johnson - Minimum path search algorithm, allows some edges to have negative numbers, but negative cycles should not exist.

### 3.2 Network Structure

In order to enable the construction of a complex telecommunication structure, Python programming language was used, since it offers various libraries. These libraries are algorithms collection to simplify the process of programming and removing the need of reprogramming the most used. The most important library to highlight, is the NetworkX, [26]. This is a package for the creation, manipulation, and study of the structure (graphs), dynamics, and functions of complex networks. In the graph, the vertex or node represents a location, that can be a data center or base station, and an edge represents a connection between two locations (that can be physical or logical), that can be linked by two different technologies: optical fiber or microwave.
Both elements of the graph have characterizing attributes. A real database was used that contains all the necessary information to characterize network elements.

### 3.2.1 Network Hierarchy

The network structure considers a hierarchy split according to its role and potentialities. So, it is organized in three different types of layers or levels.

- Transport or Core;
- Aggregation;
- Access.

Its differences are in the implemented equipment. The higher the level of the hierarchy the better the performance, intelligence and capacity of the equipment. The database about this topic did not contain information about all routers/switches on all locations, but was consistent with those who had, i.e., locations with that information presented the same equipment to the same level. Due to the lack of information about the router type in some locations, was assumed to be the same as another router of same level that contain this information. Each router is associated with a maximum capacity (bits per second), a number of ports and a respective capacity for each port, as can be analyzed on Figure 3.1.

<table>
<thead>
<tr>
<th>Location Type</th>
<th>Equipment</th>
<th>Bit rate [bits/sec]</th>
<th>Ports</th>
<th>Bit rate per port [bits/sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>CISCO ASR 9010</td>
<td>$14 \times 10^{12}$</td>
<td>140</td>
<td>$1 \times 10^{11}$</td>
</tr>
<tr>
<td>Aggregation</td>
<td>CISCO ASR-920</td>
<td>$480 \times 10^{9}$</td>
<td>48</td>
<td>$10 \times 10^{9}$</td>
</tr>
<tr>
<td>Access</td>
<td>CISCO ASR-907</td>
<td>$64 \times 10^{9}$</td>
<td>16</td>
<td>$4 \times 10^{9}$</td>
</tr>
</tbody>
</table>

It's important to mention that each location can have more than one router, meaning more capacity in that location.

JavaScript, HTML language and the Openstreetmap API was used for building a representation of the network. Thus, the notion of geographical location is clearer to interpret and explicit, as can be inspected in Figure 3.3.

The nodes shown in red represent locations that are in inoperative state, i.e., are not working, hence it is impossible to forward traffic through those nodes.

### 3.2.2 Nodes attributes

In addition to increase demands for lower latency, data centers share a unique challenge in that the majority of data center traffic stays within the data center as workload processing is distributed across multiple compute nodes. Modern data centers are optimizing their network architecture to support distributed, virtualized computing by connecting every switch to each other, a trend known as hyper-scale
computing. One of the underlying technologies that makes hyper-scale computing commercially attractive is high-speed Ethernet.

This graph component is associated with the following information:

- Location name;
- Location coordinates - longitude and latitude;
- Network type - Transport, Aggregation or Access;
- Bit rate Available;
- Load - percentage of use;
- Free ports;
- Priority queue;
Environment rating - dense urban, urban or rural;

Status - in service, turned off or in planning.

These attributes help to redirect the traffic data through the network. Each edge will be associated with a cost related to these equivalent or proposed attributes. That is, it is assumed that this graph has as its characteristic value graph as already explained in the Subsection 3.1.3.

3.2.3 Edges attributes

Similarly to the nodes, the edges diverge depending on the technology used or on the medium in which traffic flows (fiber optics and microwaves), and also on their type of connection, which can be physical or logical.

- Physical - Associated with one type of technology and can support the logic;
- Logic - Supported by physicals and depend on them. If the physicals, for some reason, are turned off, the logic will also be turned off;
  - Channels - Multiplexing virtual circuits that are associated with a physical medium. Such as various wavelengths in Dense Wavelength Division Multiplexing (DWDM);
  - Services - It is associated with capacities reserved for private clients, where there is no information about the traffic that flows there.

In Figure 3.4, we can observe that channel 1 is supported by physical link 1 and 2 and channel 2 is supported only by physical link 3. Service 1 is supported by all channels (1 and 2). If any link (physical or channel) went off, the supported ones also go down.

![Figure 3.4: Example of supporting links.](image)

This graph component is related to the following data:

- Source and target - where and where are you going;
- Network type - Transport, Aggregation or Access;
- Technology - Optical fiber or microwave;
- Connection Identification;
- Bandwidth Available;
• Load - percentage of use;
• Support - which channels or services support;
• Priority queue;
• Status - in service, turned off or in planning.

It is important to label the edge with a connection identification because between two nodes there may be more than one link. It is also critical to know which technology is used because each one is associated with different transmission media and bit rates, causing different latencies. These attributes also help to redirect the network traffic data to the high level nodes.

3.2.4 Priority queue

Priority queuing is crucial to calculate system latencies. Different types of traffic need different QoS standards. For real-time applications, it is important that average delay and delay-jitter are bounded, while for non real-time applications, the throughput and loss ratio are the restrictive parameters. In order to guarantee acceptable delay boundaries to delay-sensitive traffic (such as voice/video), several scheduling schemes – for switches and routers – have been proposed and analyzed, each with their own specific algorithmic and computational complexity. The algorithm that sets the worst case scenario is the strict priority scheduling, [28]. With this scheduling, as long as delay-sensitive (or high-priority) packets are present in the queuing system, high priority traffic is served. Delay-insensitive packets can thus only be transmitted when no delay-sensitive traffic is present in the system. As already mentioned, this is the most drastic way to meet the QoS constraints of delay-sensitive traffic, but also the easiest to implement.

The earliest request (task) may not be the most important request, as it is shown in Figure 3.5. It is different from standard queues such as First-In, First-Out (FIFO). A higher priority is typically assigned to a more important task. This is why the traffic in higher priority queues is always scheduled ahead of the traffic in the lower priority queues. This algorithm may carry bandwidth starvation for lower priority traffic, when there is an excessive amount of high-priority traffic.

Figure 3.5: Example of request later, but scheduled first rather than lower priority tasks, [29].

Considering a scenario in which a service provider, in order to carry traffic, might have to comply with certain regulations. For example, such regulation might be that no traffic should be dropped no matter
how congested the network might be. That can be supported by using strict priority queuing in which traffic is placed in a high-priority queue without any limitation on the bandwidth consumed.

As already said, each service is related to a priority that is presented on Table 3.2, which was given taking account the existing services and its sensibility to the delay.

<table>
<thead>
<tr>
<th>Service</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOS</td>
<td>1</td>
</tr>
<tr>
<td>Leased</td>
<td>2</td>
</tr>
<tr>
<td>Voice</td>
<td>3</td>
</tr>
<tr>
<td>Streaming</td>
<td>4</td>
</tr>
<tr>
<td>HTTP</td>
<td>5</td>
</tr>
<tr>
<td>Download</td>
<td>6</td>
</tr>
</tbody>
</table>

### 3.2.5 Environment rating

In order to classify a node according to its environment (dense urban, urban, suburban or rural), the Python library was again used. A package called Geocoding which receives geographic coordinates as input, returns the parish, district and the country corresponding to those coordinates. Then the population density per parish was looked up ([30]) and subsequently the environment classified according to the Portuguese communications regulatory authority, Autoridade Nacional de Comunicações (ANACOM), as it can observed on the follow Table 3.3, was applied.

<table>
<thead>
<tr>
<th>Geotype</th>
<th>Population density [pop/km²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense urban</td>
<td>(d &gt; 14000)</td>
</tr>
<tr>
<td>Urban</td>
<td>(1100 &gt; d &gt; 14000)</td>
</tr>
<tr>
<td>Suburban</td>
<td>(100 &gt; d &gt; 1100)</td>
</tr>
<tr>
<td>Rural</td>
<td>(d &lt; 100)</td>
</tr>
</tbody>
</table>

After classifying and labeling all locations, the following step was its verification, since the population density values obtained were somewhat outdated. For this, it is essential to make a comparison with another credible institution such as Lisbon Metropolitan Area. This comparison can be analyzed in the Figure 3.6.
(a) Classification taking account the Table 3.3 considering population density in the parish.

(b) Reference for comparison [32].

Figure 3.6: Comparison between geotype versus population density.

By observing the Figure 3.6 it is possible to recognize that it was well rated, since the zones with more inhabitants (display more yellow dots, Figure 3.6 b ) are classified as dense urban and urban and consequently the zones with less inhabitants are classified as suburban and rural. These designation was helpful to the following topic.

### 3.3 Traffic Modeling

This Section has four phases:

- Load the existing Key Performance Indicators (KPIs);
- Classify BSs without KPIs data according to its environment;
- Load the dispersion nodes (node through which you can go more than one way);
- Generate traffic to higher nodes and edges.

KPIs are referent to the different parameters values which evaluate network performance, used by the operators as a measure to know how good or bad the services are being carried out. The network has three major components (Core, Aggregation and Access), as already mentioned, and each of these components have their own KPIs which affect the performance of the network as a whole.

The database contained several KPIs, total volume and throughput from uplink and downlink, from different dates and hours and different technology (2G and 4G) for each location. Analyzing the existing KPIs, it was possible to identify the busy hour and baseline hour, where the traffic volume is higher and its opposite, respectively.

Since the database contained multiple dates, the current hourly traffic was averaged, that is, the total traffic per hour was totaled and divided by the number of locations. On the following Figure 3.7 and 3.8, we can monitor the baseline hour and the busy hour on both technologies, 2G and 4G.
Predictably the time with the most traffic was 6PM and the lowest was at 5AM. As can be concluded, the 13th of December presents the largest data volume and the lowest was 24th of December.
(a) Estimates the hour with average largest/lowest amount of 4G data transmitted.

(b) Estimates the date with the largest amount of transmitted 4G data referenced at 1PM.

(c) Estimates the date with the smallest amount of transmitted 4G data referenced at 6AM.

Figure 3.8: Measure of busy hour and base line on 4G.

For 4G KPIs data, the time with the most traffic was 1PM and the lowest was at 6AM. As can be concluded, the 15th of May presents the largest data volume and the lowest was 7th of May.

One of the biggest issues was the lack of KPIs data for each node and edges, which would add a
major obstacle in the algorithm development. In order to overcome this, it was necessary to associate each available KPI to the corresponding node and consequently to the environmental classification, mentioned above, Sub-chapter 3.2.5. Therefore, BSs (access nodes) that do not had these data were assigned with KPIs from similar nodes according to their environmental classification.

After associating KPIs with access nodes, the 2G and 4G KPIs data were broken down into services, as defined on Table 3.4, considering the Ericsson Mobility Report, [33], that measure the traffic impact of different application categories.

<table>
<thead>
<tr>
<th>Services</th>
<th>2G</th>
<th>4G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>HTTP</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Download</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Video-Streaming</td>
<td></td>
<td>60</td>
</tr>
</tbody>
</table>

Afterwards, KPIs for dispersion nodes were computed, exemplified in more detail in Figure 3.9.

![Dispersion nodes computation.](image)

Analyzing the Figure 3.9, the KPIs of dispersion nodes are the sum of nodes KPIs of lower/equal hierarchy. It can be concluded that node 4, 6 and 7 will be the dispersion nodes. The Equation 3.2 shows the equations to calculate the dispersion nodes, taking Figure 3.9 into account.
\[ \begin{align*}
\text{node}1 + \text{node}2 &= \text{node}3 \\
b + c &= e \\
a + d &= f \\
\text{node}3 &= \text{node}4 \\
\text{node}5 &= \text{node}6
\end{align*} \]

(3.2)

For flooding this data to other highest nodes and links, data transmission between dispersion nodes was performed randomly, allowing the KPIs to be distributed throughout the network.

The KPIs distribution has benefited from the algorithm known as Dijkstra (mentioned in Subsection 3.1.6), already implemented in NetworkX package, being used the “bidirectional” version for performance reasons, [34]. This algorithm has as input parameters: the graph, which is the graph structure that contains all network information, the source (the dispersion node that contains KPIs) and the destination (another dispersion node that contains KPIs). Also requires a cost function that is related with each edge, as already explained in the two Subsections 3.1.3 and 3.2.2. The algorithm returns the chosen path, connections and nodes, which is subsequently associated with the referent KPIs.

Although the choice was random, the KPIs data was fairly and evenly distributed across the network. For such, the cost function used was defined as shown in Equation 3.3.

\[
\text{cost} = \frac{1}{Bw\text{Available}} \times \text{weight}_{Bw} + \text{Latency} \times \text{weight}_{La}.
\]

(3.3)

If one connections node state is not operating or still planned, it will have high cost (infinity), so that it won't be considered. If connections have unavailable bandwidth (available bandwidth equal to zero), they will be handled equally. By analyzing the cost function from Equation 3.3 it is possible to verify that, the higher the latency or the lower the available bandwidth, the higher the cost. This means a lower probability of being selected. Latency calculation will be presented in the following Subsection 4.4.

The bandwidth and latency weights (\(\text{weight}_{Bw}\) and \(\text{weight}_{La}\)), in Equation 3.3 were preset to 10% and 90%, respectively, aiming the thesis objective to give more importance to the path with the lowest possible latency, to maximize the QoS. As such, bandwidth will serve as a tiebreaker, that is, if there are two paths with the same latency, the algorithm will choose the one with the most available bandwidth.

As already mentioned in Subsection 3.2.2, for these four phases it was used the busy hour and base line hour traffic to flood KPIs data to all edges and nodes. Being possible to analyze and visualize the network with different loads at different times of day, as shown in Figures 3.10 and 3.11, respectively.

As can be seen in Figure 3.10, representing traffic at busy hour, it has a higher load than Figure 3.11, representing traffic at base line hour. It can be concluded that, there are more reddish and orange connections on first Figure than in the second. Even for those links that have not changed color, many have a higher load too, just not enough to change color. That is, the links and nodes are more loaded with services.

With this visualization and analysis, it can be concluded that this step was successfully completed.
3.4 Morphology

Important data for a node insertion tool is to access the terrain morphology and optical fiber ducts. This data is crucial for inserting a new node, since it is necessary to know if the node has LoS or if there are optical fiber ducts that interconnect to an existent node on the network.

To obtain this information, regarding the optical fiber ducts, it was used a tool provided by Celfinet, that already contained this data. It was necessary to perform this migration, which was successfully done as shown in the Figure 3.12.

This data was saved on a graph to facilitate its access and handling. On this graph, the nodes represent the visit box (brown points), where there is access to the ducts, and edges (brown links) represent the links between visits box that contains the distance as an attribute.

Regarding the terrain morphology, a terrain geodata file which contains this information was explored and successfully inserted in the platform, as can be seen in Figure 3.13.
Figure 3.12: Overview of the Optical fiber ducts.

Figure 3.13: LoS profile between two locations.
Chapter 4

Base Station Insertion algorithm

Telecommunications have been growing, mainly the RANs that allowed the appearance of mobile phones, and practically the extinction of corded phones. This growth has led to the development of the RAN sector which has led to 2G, 3G, 4G and recently 5G, which is in testing situations. The last one requires large capacities and high processing levels. This will lead to a great need to provide large capacity to covered areas and to cover non covered ones. This will inevitably point to the growth of locations and their planning, which is how to connect to the communications network structure. As mentioned in Chapter 1, the algorithm aims to automate the insertion of a base station in a telecommunications network. This computing demands several parameters to be checked. It is necessary to check if there are fiber optic conducts and/or any LoS that connects this new node to the network. Moreover, it is essential to verify whether there are some network nodes that can hold the new incoming traffic, generated by the new base station.

The Base Station Insertion algorithm brings some optimization in a BS planning, which informs which location supports the new BS and costs associated with each technology (optical fiber or microwave).

Therefore, the need to introduce a new Base Station location may be due to:

- Zone with lack of coverage;
- Zone that needs increased capacity because it is congested;
- Zone that needs capacity to improve QoS;
- Implementation of new locations due to new application technology.

Introducing a location today is quite complex as a number of checks and validations has to be done. These consist on several steps:

- Verification of existing fiber ducts in the area with connection to network locations;
- Line of sight verification for network locations;
- Validation of the node that supports the new one.
It is mandatory to provide the coordinates of the location giving the required coverage, as well as the expected or maximum traffic capacities and volume that will be obtained in the coverage zone. For this the algorithm with the coordinates of the new location uses a database, already referred to in Subsection 3.2.2, which contains the KPIs read from some BSs and associates them with the new location for the area.

As output, the program will provide the necessary alarms and their solution for each technology. In the case of possible solution will be presented:

- The node which supports the new one;
- The traffic of each service and its routing latencies to the Core.
- Cost associated with the new link.

Eventuality an alarm needs to be reported, the algorithm is instructed to do so, either:

- There is no fiber ducts near the new node;
- There is no fiber ducts connection of the new node to the network;
- There are no line of sight with other locations;
- Location X cannot support incoming services;
- Location X does not contain enough ports for new connection;
- Location X does not support expected throughput.

After presenting the transmissions solutions, regular user or operator can chose which technologies want to interconnect the new location to the network.

Next, the flowchart of the proposed algorithm for problem optimization will be presented.

### 4.1 Fiber Ducts Search algorithm

In order to search for fiber optic ducts, it was used the graph containing their information, already described in the Subsection 3.4. The algorithm looks for manholes in the ducts with a maximum distance of 100 meters from the coordinates that were given as input of the new location, considering that the costs provided by the company Celfinet for the opening of the road are limited to that distance. If it does not found any manholes for that maximum distance, the algorithm shows that there are no optical fibers in the zone. If it finds, the algorithm will check if this conduit connects with other(s) network location(s). If so, it creates a list saving in ascending order of the fiber optic length needed to make this connection. This order is to ensure that the cost shown is as low as possible. In the possibility of not finding a link with another network location, the algorithm reports that there is no connection with another location.

After looking for fiber optic ducts it is necessary to validate the node on which it supports the new one, *i.e.*, it is essential to verify that traffic flows to the Core, satisfying certain requirements. For this it was suggested another algorithm exposed in Subsection 4.3, Validation algorithm.
Subsequent to validation, if it verifies, the costs associated with the fiber optic connection, which will be presented on Sub-chapter 4.5, will be reported.

Following is a flowchart for a better understanding of how this algorithm works, Figure 4.2.

### 4.2 Line of Sight Search algorithm

As already mentioned in Section 3.4, the platform contains the terrain morphology. This algorithm generates a list in ascending order of geographical distance from all locations that have LoS with a maximum radius of 25 km referring to the coordinates that were given as input to the new location. This maximum distance was again provided by Celfinet Operations department.

To have LoS it is imposed that the Fresnel ellipsoid is not obstructed by more than 40%, [35]. The frequency used for Fresnel ellipsoid calculation is in the C band, the most common frequency range for telecommunication communication.

The calculation for LoS takes into account the curvature of the Earth to block long distance transmissions. The algorithm considers the Spherical Earth model, making the necessary adjustments to the heights of the transmitter and receiver antennas, Equation 4.1. It is widely used in practice and is the value of $K = \frac{4}{3}$ as a reference to normal atmospheric conditions [36].

\[
\begin{align*}
    r_e &= K \times 6370 [\text{km}] \\
    h'_1 &= h_1 - \frac{d_1^2}{2r_e} \\
    h'_2 &= h_2 - \frac{d_2^2}{2r_e}
\end{align*}
\]  

(4.1)

Where $r_e$ is the Earth equivalent radius, $h'_1$ and $h'_2$ the equivalent heights of the transmitter and receiver, respectively and $h_1$ and $h_2$ the real heights of the transmitter and receiver, respectively. Of course that if the distances are small comparing with the heights of the Spherical Earth model, it can be approximated to the Flat Earth model.

If there is no LoS for a network node, the algorithm reports the situation. In the circumstances of existing it is essential to validate the node containing LoS, if the expected traffic associated to the new location reaches the Core fulfilling its requirements. To verify these, an algorithm exposed in the Subsection 4.3 is suggested, Validation algorithm.

Then, if validation takes place, the costs associated with the microwave connection will be determined, presented on Sub-chapter 4.5.

Next, a flowchart will be shown for a better understanding of how this algorithm works, Figure 4.3.

### 4.3 Validation algorithm

As discussed on the introduction of this Chapter, the goal is to provide the cheapest solution for each technology, so the existent node that connects to the new may differ between each technology. However,
validation is performed the same way.

For the already existent and connecting node it is essential to verify some check-list, namely:

- Verify that the support node has port for the new connection;
- Validate that the port capacity supports the new connection, that is, if the port capacity is greater than the whole throughput of the new node (i.e, sum of all services bit rates);
- Find a path to the Core that supports all traffic associated with the new connection;
- Confirm that the Core node can flow the services to another Core node;
- Inspect if the final latencies of each service are within the standards.

The suggested check-list is done through the Core, because it is the top of the network hierarchy and because it is in a ring topology. This routing will be explained below.

**Core Routing**

This process uses an algorithm already mentioned in Section 3.3 with for the purpose of generating network traffic. It is explored here for the purpose of routing all services that the new node contains in priority order, (Table 3.2). This routing takes into account this order, so that services with the highest priority, that is, the most sensitive to latency or with lower default values, are processed first.

On this occasion the Core nodes are not chosen randomly, but by jump order, i.e, the amount of links traveled to reach this hierarchy. After routing is performed from the new node to the nearest Core node, a final check is performed whether final latency is within the service’s default maximum delay, see Table 4.1, to come across a good QoS.

<table>
<thead>
<tr>
<th>Service</th>
<th>Maximum delay [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>100</td>
</tr>
<tr>
<td>Streaming</td>
<td>150</td>
</tr>
<tr>
<td>HTTP</td>
<td>300</td>
</tr>
<tr>
<td>Download</td>
<td>300</td>
</tr>
</tbody>
</table>

In the event that all conditions are not met for all services, an alarm is sent that the support node cannot stand and moves to the next nearest support node. If the Core node cannot flow traffic to another node, it reports an alarm and moves to the next nearest node.

The path chosen for each service uses the Dijkstra algorithm that takes into account the following cost function, see Equation 4.2, same as Equation 3.3 but with a different characteristic. Since Core Routing is an upward hierarchical path, if the path has downward links it gives an additional cost and is less likely to be chosen.

\[
\text{cost} = \frac{1}{BwAvailable} \ast \text{weight}_{Bw} + \text{Latency} \ast \text{weight}_{La} + \text{Hierarchy}.
\]  

(4.2)
In order to better understand the Validation algorithm and its checks, a flowchart will be shown in Figure 4.4.

### 4.4 Delays computation

As mentioned in Subsection 2.2.5, QoS is an important measure and it is related to the latency of each service. A service transmission may be affected by the intervention of two graph components (nodes and edges), at data transmission level, propagation and queues, as explained in Subsection 3.2.4 as function of its priority. This Subsection also states that there are several complex computational algorithms taking priority into account, referencing the strict priority scheduling, [28].

Next will be presented the computation methods for the latencies calculation for the two components of the graph.

#### 4.4.1 Node Delay computation

Node inherent latency is related to processing the volume of each service and the wait time to be served. As mentioned already, the node obeys a priority order per door, that is, it will first serve the highest service and so on. If there are two services of equal importance, the order will consider a FIFO approach.

When answering a service, the node dispose all its full capacity per door to process it and so on to the next. When the node serves the next service, latency is affected by the previous one.

Thus, the formula representing the calculation related to the node latencies is Equation 4.3:

\[
delay_{node}[n] = \begin{cases} 
\frac{Volume[n]}{Capacity_{node}}, & \text{if } n = 1 \\
\frac{Volume[n]}{Capacity_{node}} + delay_{node}[n - 1], & \text{if } n > 1 
\end{cases}
\]  

The node has as its attribute a total capacity $Capacity_{node}$ in bits per second per door. It also has a priority queue where $n$ represents the place of service in the queue, i.e., how many services have higher priority than it. $Volume[n]$ represents the package volume in bits for that service.

**Flowchart**

For a better understanding, below is a flowchart of the implemented algorithm, Figure 4.5.

**Example**

Below, in Table 4.2, an example of a priority list of a node with full capacity per door $Capacity_{node}$ with 4 [Gbit/s] and the latencies associated with each service.
Table 4.2: Example of a priority list and the delays associated with each service in a node.

<table>
<thead>
<tr>
<th>Service</th>
<th>Priority</th>
<th>n</th>
<th>Volume [bits]</th>
<th>Formula</th>
<th>delay_{node}[n] [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>2</td>
<td>1</td>
<td>1200</td>
<td>$\frac{\text{Volume}[1]}{\text{Capacity}_{node}}$</td>
<td>$3 \times 10^{-7}$</td>
</tr>
<tr>
<td>Voice</td>
<td>2</td>
<td>2</td>
<td>1200</td>
<td>$\frac{\text{Volume}[2]}{\text{Capacity}<em>{node}} + \text{delay}</em>{node}[1]$</td>
<td>$3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Streaming</td>
<td>3</td>
<td>3</td>
<td>3600</td>
<td>$\frac{\text{Volume}[3]}{\text{Capacity}<em>{node}} + \text{delay}</em>{node}[2]$</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>HTTP</td>
<td>4</td>
<td>4</td>
<td>2000</td>
<td>$\frac{\text{Volume}[4]}{\text{Capacity}<em>{node}} + \text{delay}</em>{node}[3]$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>Download</td>
<td>5</td>
<td>5</td>
<td>5000</td>
<td>$\frac{\text{Volume}[5]}{\text{Capacity}<em>{node}} + \text{delay}</em>{node}[4]$</td>
<td>$3.25 \times 10^{-4}$</td>
</tr>
<tr>
<td>Download</td>
<td>5</td>
<td>6</td>
<td>6000</td>
<td>$\frac{\text{Volume}[6]}{\text{Capacity}<em>{node}} + \text{delay}</em>{node}[5]$</td>
<td>$4.75 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Comparing values in Table 4.2 with the node delay algorithm output, Figure 4.6, is being assigned the correct latencies for each service.

### 4.4.2 Edge Delay computation

The implicit latency to the edge is related to the volume processing of each service, the waiting time to be answered and its transmission. Like the node, and as stated in Subsection 3.2.3, the edge also has a priority list. But its processing is distinct. Unlike the node, the edge instead of using its full capacity uses the throughput associated with each service ($\text{BitRate}[n]$) taking into account the available edge bandwidth ($\text{BwAvailable}[n]$). In the event that the available bandwidth is greater than the service’s throughput, the service use the requested throughput, serving the next service by comparing the next service’s throughput and the remaining bandwidth. If the available bandwidth is lower, only available bandwidth is used until the first service being processed goes out ($\text{DelayFPS}$). If the packet is not fully processed and already has available bandwidth for the requested throughput, use the requested. Therefore, more than one service can be processed at the same time.

**Flowchart**

For a better understanding, below is a flowchart of the implemented algorithm for computation of process and queuing delay ($\text{delay}_{transmission}$), Figure 4.7.

**Example**

To help the understanding how to calculate the processing and queuing delay ($\text{delay}_{transmission}$), on Table 4.3. The edge has full capacity $100[kbits/s]$. Initially the available bandwidth is at full capacity because busy bit rate is zero.

Comparing Table 4.3 with the edge delay algorithm output, Figure 4.8, is being assigned the correct latencies for each service.
Table 4.3: Example of a priority list and the delays associated with each service in an edge.

<table>
<thead>
<tr>
<th>Service</th>
<th>Priority</th>
<th>n</th>
<th>Volume [bits]</th>
<th>Bit Rate [bits/s]</th>
<th>Bandwidth Available [bits/s]</th>
<th>Formula</th>
<th>( \text{delay}_{\text{process}}[n] ) [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>2</td>
<td>1</td>
<td>1200</td>
<td>64000</td>
<td>100000</td>
<td>( \frac{\text{Volume}[n]}{\text{Bandwidth}[n]} )</td>
<td>18.75</td>
</tr>
<tr>
<td>Voice</td>
<td>2</td>
<td>2</td>
<td>1200</td>
<td>30000</td>
<td>36000</td>
<td>( \frac{\text{Volume}[n]}{\text{Bandwidth}[n]} )</td>
<td>40</td>
</tr>
<tr>
<td>Download</td>
<td>5</td>
<td>3</td>
<td>4000</td>
<td>10000</td>
<td>6000</td>
<td>( \frac{\text{Volume}[n] - \text{delay}_{\text{process}}[1] \times 6000}{\text{Bandwidth}[n]} )</td>
<td>408.50</td>
</tr>
<tr>
<td>Download</td>
<td>5</td>
<td>4</td>
<td>6000</td>
<td>15000</td>
<td>0</td>
<td>( \frac{\text{Volume}[n]}{\text{Bandwidth}[n]} + \text{delay}_{\text{process}}[1] )</td>
<td>418.75</td>
</tr>
</tbody>
</table>

Other delay associated to the edge

There is one more edge-related delay, which is service propagation. This depends on the type of technology associated with the edge, i.e., whether the transmission medium is fiber optic or microwave, that is as an attribute of the edge as already referenced in Subsection 3.2.3. Transmission media are associated with different transmission speeds, translating to different latencies.

Table 4.4: Speed at which the packet is transmitted considering the technology.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave</td>
<td>( \simeq 3 \times 10^8 )</td>
</tr>
<tr>
<td>Optical fiber</td>
<td>( \simeq 3 \times 10^8 \div 1.45 )</td>
</tr>
</tbody>
</table>

Remembering that the speed in the optical fiber is refracted. The fiber is composed of silica which has a refractive index of 1.45, [12].

This delay is also dependent on the distance, i.e., the bigger the distance of the link in geographic terms, bigger its value. The following formula, Equation 4.4, expresses the calculations that represent this delay.

\[
\text{delay}_{\text{propagation}} = \frac{\text{Distance}}{\text{Velocity}}. \quad (4.4)
\]

Thus the latency correlated with the edge (\( \text{delay}_{\text{edge}} \)) has the following interpretation, Equation 4.5.

\[
\text{delay}_{\text{edge}} = \text{delay}_{\text{transmission}} + \text{delay}_{\text{propagation}}. \quad (4.5)
\]

This final formula, Equation 4.5, encompasses all latencies associated with the edges. The processing and queue delay, shown on Figure 4.7, plus the transmission delay, on Equation 4.4.

4.5 CAPEX and OPEX

It was provided by the Celfinet Operations department, the values associated with each operation and for each transmission technology. This translate to the costs associated with each planning being as realistic as possible.

The costs related to a new fiber optic connection are associated:

- The required fiber optic length;
• Performing single mode fiber optic fusion on cable already terminated on join;

• Mobilization of a team;

• Fiber optic cable installation;

• Excavation and construction of ditches;

• Construction of manholes.

On Annex A.1 are the values associated with each operation. The Fiber Ducts Search algorithm, take these values into account and calculates a estimated cost of the new connection for when planning a new location.

The associated cost, analogous with microwave solutions, depends on the throughput of all traffic flowing over the new link. In the annex A.2 are the values associated with this type of technology and the possible different microwave technologies.

The Line of Sight Search algorithm provides an estimate of the cost of the new connection when planning a new location.
Figure 4.1: Overview of Insert Base Station algorithm.
Figure 4.2: Fiber Ducts Search algorithm flowchart.
Figure 4.3: Line of Sight Search algorithm flowchart.
Figure 4.4: Validation algorithm flowchart.
Figure 4.5: Computation of node delay.

\[
delay[n] = \frac{\text{Volume}[n]}{\text{Capacity}_{\text{node}}} + \text{delay}[n-1].
\]

\[ n = n + 1 \]

Figure 4.6: Output of delay node algorithm with same inputs of Table 4.2.

<table>
<thead>
<tr>
<th>Service</th>
<th>Queue</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Voice</td>
<td>1</td>
<td>3.000000e-07</td>
</tr>
<tr>
<td>1 Voice</td>
<td>2</td>
<td>6.000000e-07</td>
</tr>
<tr>
<td>2 Streaming</td>
<td>3</td>
<td>1.500000e-06</td>
</tr>
<tr>
<td>3 HTTP</td>
<td>4</td>
<td>2.000000e-06</td>
</tr>
<tr>
<td>4 Download</td>
<td>5</td>
<td>3.250000e-06</td>
</tr>
<tr>
<td>5 Download</td>
<td>6</td>
<td>4.750000e-06</td>
</tr>
</tbody>
</table>
Figure 4.7: Computation of process and queuing delay ($delay_{transmission}$).

<table>
<thead>
<tr>
<th>Service</th>
<th>Queue</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Voice</td>
<td>0.01875</td>
</tr>
<tr>
<td>1</td>
<td>Voice</td>
<td>0.04000</td>
</tr>
<tr>
<td>2</td>
<td>Download</td>
<td>0.40750</td>
</tr>
<tr>
<td>3</td>
<td>Download</td>
<td>0.41875</td>
</tr>
</tbody>
</table>

Figure 4.8: Output of delay edge algorithm with same inputs of Table 4.3.
Chapter 5

Use cases

In this Chapter, the result are organized into use cases. The main purpose is to show different outcomes of the proposed algorithm presented earlier. For that, in each use case it is explained a brief context situation regarding the need for insertion and planning of a new BS.

It should be noted that the results considered busy hour, since it is the time period when the network has the highest data traffic, which translates to the worst quality of service and congested connections, eventually justifying the planning of a new BS and therefore the usefulness of the proposed algorithm.

5.1 High capacity area

5.1.1 Problem Description

The area shown in Figure 5.1 during the busy hour is a high capacity (loaded) area. It can be observed that the transmissions links are mostly orange, which is expectable in an urban area.

Adding one more BS, in the zone identified in Figure 5.1 with a purple circle, will increase capacity in that area, which will relieve existing connections. To achieve this, the proposed algorithm was used after being provided the necessary inputs.

Then, the algorithm uses the database containing the received KPIs from the existing BSs in that area, and uses them for the new BS. Those found, the volume and throughput for each service are presented in Table 5.1.

<table>
<thead>
<tr>
<th>Services</th>
<th>Volume [bits]</th>
<th>Throughput [kbits/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>606.0</td>
<td>37.02</td>
</tr>
<tr>
<td>HTTP</td>
<td>454.5</td>
<td>18.51</td>
</tr>
<tr>
<td>Download</td>
<td>202.0</td>
<td>6.17</td>
</tr>
</tbody>
</table>
5.1.2 Solution

As already mentioned in the Section 4, the algorithm presents two possible solutions: the optical fiber solution and then the microwave solution.

As shown in Table 5.2, the latencies of each service, from the path taken to the Core in each solution, meet the default values for each service in Sub-chapter 4.3, Table 4.1.

Table 5.2: Latencies associated with both transmission solution.

<table>
<thead>
<tr>
<th>Services</th>
<th>Optical Fiber [ms]</th>
<th>Microwave [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>49.1</td>
<td>32.8</td>
</tr>
<tr>
<td>HTTP</td>
<td>73.7</td>
<td>49.1</td>
</tr>
<tr>
<td>Download</td>
<td>98.3</td>
<td>65.5</td>
</tr>
</tbody>
</table>

It is noticeable that the latencies associated with the microwave solution are lower than the latencies associated with the optical fiber solution. This happens because the nodes supporting the new inserted BS are different for both solutions. As stated earlier, the LoS algorithm tests the geographically closer nodes, while the Fiber Ducts Search algorithm tests node’ locations that will require less optical fiber cable. In addition, the path taken to the Core in the microwave solution travels fewer edges than the optical fiber solution. The Core routing fiber optical and Microwave scenarios are presented in Figure 5.2, respectively.

The software displays the LoS profile from the new base station to the supporting node considering the microwave link presented in Figure 5.3. As can be inspected, the Fresnel ellipsoid is completely free for all the radio link.

The encoun optical fiber solution has a cost 3.47 times higher than the microwave solution. The new
microwave connection has a length of 363 meters, while the optical fiber connection has a length of 200.80 meters. In more detail, Annex B.1 as the report on the application of this use case.

As noted in Sub-chapter 3.3, the network contains base line hour traffic that allows you to compare the final latencies of each service associated with the new base station during that time of day. In the following Table 5.3 it is possible to notice the traffic that is in that zone during the time with less traffic and the latencies associated with each service for each transmission technology.

As expected, the latencies associated with each service during the lowest traffic time of day are lower.
5.2 Zone with poor Quality of Service

5.2.1 Problem Description

As stated in the Sector 4, adding a BS is a solution when the network faces weak QoS levels in a certain area. The presence of a new location will relieve the others, giving more capacity to the coverage area that translates into better QoS.

Once again, the database of the Celfinet company was used, in which it was possible to view the performed drive-test. When analyzing this database, it was observed that there was a zone that presented very low values of QoS, as can be observed in Figure 5.4.

The addition of a location in the identified zone from Figure 5.5 is essential to increase the coverage capacity in that area, thereby improving the values of QoS. For this we used the proposed algorithm and designed providing the necessary inputs. These are in Appendix B.2.

Again, the algorithm uses the database containing the KPIs received from existing locations in that area, and considers them as expected traffic on the new BS. These expected volume and throughput for each service are presented in Table 5.4.

Table 5.4: Services that will be associated with the new BS.

<table>
<thead>
<tr>
<th>Services</th>
<th>Volume ([\text{bits}])</th>
<th>Throughput ([\text{kbits/s}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>5859.1</td>
<td>61.10</td>
</tr>
<tr>
<td>HTTP</td>
<td>5443.6</td>
<td>30.55</td>
</tr>
<tr>
<td>Download</td>
<td>2419.4</td>
<td>10.18</td>
</tr>
</tbody>
</table>

Table 5.3: Latencies associated with each transmission solution.

<table>
<thead>
<tr>
<th>Services</th>
<th>Volume ([\text{bits}])</th>
<th>Throughput ([\text{kbits/s}])</th>
<th>Latencies ([\text{ms}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>23.7</td>
<td>20.81</td>
<td>3.4</td>
</tr>
<tr>
<td>HTTP</td>
<td>17.8</td>
<td>10.41</td>
<td>5.1</td>
</tr>
<tr>
<td>Download</td>
<td>7.9</td>
<td>3.47</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Figure 5.3: LoS profile connecting new BS to the supported node.
5.2.2 Solution

The Fiber Ducts Search algorithm, already described in Subsection 4.1, alarms that the new location is not near of fiber optic ducts. That said there is no solution for this technology.

Regarding the Line of Sight algorithm in this use case, it has several alarms. When testing the new BS with supporting locations A and D, identified in Figure 5.6, service latencies do not meet the default values when performing Core Routing. The latency associated with the Voice service had a value of \(237\text{ms}\). This latency corresponds to a bad QoS.

The algorithm also shows that the new location does not have LoS for locations B and C, also marked in Figure 5.6. However, it does provide a viable solution in which the latencies for each service presented in Figure 5.5, satisfy the default values found in the Sub-chapter 4.3, Table 4.1.

Table 5.5: Latencies associated with microwave solution.

<table>
<thead>
<tr>
<th>Services</th>
<th>Latencies [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>96.7</td>
</tr>
<tr>
<td>HTTP</td>
<td>178.0</td>
</tr>
<tr>
<td>Download</td>
<td>238.0</td>
</tr>
</tbody>
</table>

Together with the targeted services latencies, the algorithm displays the new connection in Figure 5.6 and the LoS profile of the new link in Figure 5.7.

In more detail, Annex B.2 present the report on the application of this use case.
5.3 Zone with lack of coverage

5.3.1 Problem Description

Figure 5.8 shows the lack of coverage (zone with the blue dots) at the frequency of 2600 MHz. This frequency is the most used for increasing capacity purposes. Regarding coverage, there are other frequencies that guarantee it in that area.

However, to improve capacity, QoS and to ensure longer continuity at the 2600 MHz frequency, a new BS is proposed in that area, marked in Figure 5.9.

Initially, the algorithm relies on the database to gather the collected KPIs in that area, through the existing locations where are described in the Table 5.2.

<table>
<thead>
<tr>
<th>Services</th>
<th>Volume [bits]</th>
<th>Throughput [kbits/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>260.3</td>
<td>16.65</td>
</tr>
<tr>
<td>Streaming</td>
<td>26620.2</td>
<td>7048.29</td>
</tr>
<tr>
<td>HTTP</td>
<td>5324.0</td>
<td>149.81</td>
</tr>
<tr>
<td>Download</td>
<td>86.8</td>
<td>2.77</td>
</tr>
</tbody>
</table>

5.3.2 Solution

The Fiber Ducts Search algorithm indicates that the new BS is not near to fiber optic ducts. That said, it has no solutions for this technology.

On the other hand, the LoS algorithm presents a workable microwave solution with the new connection and path taken by routed services to the core, shown in Figure 5.10.
One can see from the following Figure 5.11, there is LoS between the new location and the base station that supports this new site.

The latencies given in Table 5.7 satisfy the default values found in the Sub-chapter 4.3, Table 4.1, for each service.

<table>
<thead>
<tr>
<th>Services</th>
<th>Latencies [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>47.0</td>
</tr>
<tr>
<td>Streaming</td>
<td>11.9</td>
</tr>
<tr>
<td>HTTP</td>
<td>107.2</td>
</tr>
<tr>
<td>Download</td>
<td>99.7</td>
</tr>
</tbody>
</table>

In more detail, full report on the application of this use case is presented on Annex B.3.
Figure 5.8: Area with lacking coverage for the 2600 MHz frequency.

Figure 5.9: Area where the new base station will be inserted.

Figure 5.10: Routing Core from new BS to Core from microwave solution.
Figure 5.11: LoS profile.
Chapter 6

Conclusions

This chapter is divided into two sections. In Section 6.1, a summary of the work carried throughout this thesis is presented and the main conclusions are drawn. Section 6.2 provides an insight about the possible steps that can be taken to further improve and evaluate the presented methodology.

6.1 Summary

The main purpose of this thesis was to develop an algorithm that will allow Telecom operators to improve network configuration and transmission, in order to assure good QoS. The algorithm is able to add a new BS by defining the best transmission solution, dependent on the used technology, available bandwidth, geographical locations of the transmission nodes while keeping good QoS at the minimum cost.

In addition, real databases were used to allow access to network readings at different times of the day, and to allow network visualization at different traffic loads.

Chapter 2 provides a technical overview of configuration a telecommunication network. And general features of access and core networks.

Chapter 3 present the data preprocessing steps applied related to the whole real data collection. This chapter also show how the platform that contains the network was made and define its structure. Also mention that was some lack of information and explain how was extrapolated.

This was possible due to the Python library called NetworkX. This library is used for creation, manipulation and study of the structure dynamics and functions of complex networks. The development of network structure was essential to the design of the software presented on Chapter 4.

Chapter 4 describes the concepts, techniques and the proposed algorithms to developed the software to accomplish the outlined objectives of this work, as well as the knowledge background necessary to develop that methodology.

The proposed method for computational the processing delays was substantiated on strict priority scheduling, where each service as own priority according to its sensibility for QoS. So the lower the default value for good QoS, the higher its priority.

The suggested algorithm for Core Routing was also based on a Python package from NetworkX
library, called Djisktra. The cost function adopted was designed around the purpose of the thesis, which had to parameterize the path with better QoS, selecting the path with the lowest latency.

The estimated OPEX and CAPEX had real values practiced by the Celfinet company for comparison of each technology to be as real as possible. One of the goals of this thesis was to find a better solution to minimize their costs.

Chapter 5 consist on the results obtained through the application of the proposed algorithm in Chapter 4. It includes the necessary uses cases that demonstrate the different software outputs. Three different situations that need the planning and optimization of a new location were presented. In this chapter, the targets considered for using the software were also presented.

For all scenarios, the results obtained from the simulations, provide the best possible links for each transmission solution associated with the lowest costs, i.e., the locations supporting the new BS had LoS and optical fiber cable size under budget. The presented latencies for scenario, portray a good QoS for each service. The different latencies are due to the volume size and throughput associated with each service, given that the available bandwidth on each link was sufficient. Regarding the latency associated with each node, it is negligible, as it uses its full capacity per port to process one service at a time, translating into very low latency.

Lastly, the first scenario shows the difference in latencies when testing the insertion of the new node at different times of the day (busy hour and base line hour).

In conclusion, the purpose of the thesis was achieved by showing the importance of an automated and fast software tool for defining new BS, and how operators can benefit from it, without doing the usual manual process.

## 6.2 Future Work

In terms of future work for the proposed methodology, it would be interesting to add the possibility aggregation and transport locations, which are more complex, contains larger capacities, support more connections and can drive a network restructuring to balance traffic. Furthermore, the probability for a resilient solution is also of relevant study, i.e., the aggregation and transport locations normally has more than one connection supporting them (redundancy).

Another feature is considering new transmission solutions between locations such as millimeter waves.
Bibliography


Appendix A

Tables

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cost [euros]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FO cable</td>
<td>1.60</td>
</tr>
<tr>
<td>Fiber Optic Fusion</td>
<td>20.2</td>
</tr>
<tr>
<td>Team Mobilization</td>
<td>328.64</td>
</tr>
<tr>
<td>FO cable installation</td>
<td>0.72</td>
</tr>
<tr>
<td>Ditch construction</td>
<td>31.39</td>
</tr>
<tr>
<td>Manhole construction</td>
<td>520.83</td>
</tr>
<tr>
<td>Excavation</td>
<td>34.68</td>
</tr>
</tbody>
</table>

Table A.1: Costs associated with new fiber optic connections.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mikrotik</td>
<td>40</td>
<td>12</td>
<td>3500</td>
</tr>
<tr>
<td>Airmux</td>
<td>100</td>
<td>12</td>
<td>3500</td>
</tr>
<tr>
<td>RTN</td>
<td>180</td>
<td>25</td>
<td>4000</td>
</tr>
</tbody>
</table>

Table A.2: Costs associated with new microwave connections.
Appendix B

Use cases reports

B.1 High capacity area Report

<table>
<thead>
<tr>
<th>ID:</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location:</td>
<td>XY</td>
</tr>
<tr>
<td>Coordinates:</td>
<td>(X, Y)</td>
</tr>
</tbody>
</table>

KPIs associated:

<table>
<thead>
<tr>
<th>Service</th>
<th>Volume [bits]</th>
<th>Throughput [bits/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>606</td>
<td>37021.2</td>
</tr>
<tr>
<td>HTTP</td>
<td>454.5</td>
<td>18310.6</td>
</tr>
<tr>
<td>Download</td>
<td>202</td>
<td>6170.2</td>
</tr>
</tbody>
</table>

Reason: High capacity area

Transmission solution: Optical Fiber

Alarms: 5_FO

Supported Location:

<table>
<thead>
<tr>
<th>Latencies:</th>
<th>Latencies [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>49.1</td>
</tr>
<tr>
<td>HTTP</td>
<td>73.7</td>
</tr>
<tr>
<td>Download</td>
<td>98.8</td>
</tr>
</tbody>
</table>

Distance of new connection: 200.80 metros
<table>
<thead>
<tr>
<th>Capacity of new link:</th>
<th>4 Gbits/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated cost:</td>
<td></td>
</tr>
<tr>
<td>New configuration:</td>
<td></td>
</tr>
</tbody>
</table>

Colors Representation:
- Core
- Aggregation
- Access
- In planning
- New
- Path
- Optical fiber ducts
Transmission solution: Microwave

Alarms: 

Supported Location: S_MW

Latencies:

<table>
<thead>
<tr>
<th>Service</th>
<th>Latencies [ ms ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>32.8</td>
</tr>
<tr>
<td>HTTP</td>
<td>49.1</td>
</tr>
<tr>
<td>Download</td>
<td>65.5</td>
</tr>
</tbody>
</table>

Distance of new connection: 363 metros

Capacity of new link: 40 Mbits/s

Estimated cost: 

New configuration:
Line of Sight Profile

Link Profile

Height above sea level [m]

Distance [m]
B.2 Area with poor Quality of Service Report

Report

ID: 2
Location: XY
Coordinates: (X, Y)

KPIs associated:

<table>
<thead>
<tr>
<th>Service</th>
<th>Volume [bits]</th>
<th>Throughput [bits/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>5859.1</td>
<td>61103</td>
</tr>
<tr>
<td>HTTP</td>
<td>5443.6</td>
<td>30551.85</td>
</tr>
<tr>
<td>Download</td>
<td>2419.38</td>
<td>10183.95</td>
</tr>
</tbody>
</table>

Reason: Area with poor Quality of Service

Transmission solution: Optical Fiber

Alarms:
- New node do not have connection to fiber ducts.
Transmission solution: Microwave

Alarms:
- Services do not fulfill the default values to location A.
- Do not have Line of Sight to B.
- Do not have Line of Sight to C.
- Services do not fulfill the default values to location D.

Supported Location: S

Latencies:

<table>
<thead>
<tr>
<th>Service</th>
<th>Latencies [ ms ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>96.7</td>
</tr>
<tr>
<td>HTTP</td>
<td>178</td>
</tr>
<tr>
<td>Download</td>
<td>238</td>
</tr>
</tbody>
</table>

Distance of new connection: 2010 metros

Capacity of new link: 40 Mbits/s

Estimated cost:

New configuration:
Line of Sight Profile

![Graph of Line of Sight Profile](image)
B.3 Area with lack of coverage Report

Report

ID: 3
Location: XY
Coordinates: (X, Y)

KPIs associated:

<table>
<thead>
<tr>
<th>Service</th>
<th>Volume [bits]</th>
<th>Throughput [bits/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>260,257</td>
<td>15647.15</td>
</tr>
<tr>
<td>Streaming</td>
<td>26620.21</td>
<td>7048287.54</td>
</tr>
<tr>
<td>HTTP</td>
<td>5324.04</td>
<td>149810.77</td>
</tr>
<tr>
<td>Download</td>
<td>86.76</td>
<td>2774.53</td>
</tr>
</tbody>
</table>

Reason: Area with lack of coverage

Transmission solution: Optical Fiber

Alarms:
- New node do not have connection to fiber ducts.
Transmission solution: Microwave

Alarms:

Supported locations:

Latencies:

<table>
<thead>
<tr>
<th>Service</th>
<th>Latencies [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>46.86</td>
</tr>
<tr>
<td>Streaming</td>
<td>11.9</td>
</tr>
<tr>
<td>HTTP</td>
<td>107.21</td>
</tr>
<tr>
<td>Download</td>
<td>99.2</td>
</tr>
</tbody>
</table>

Distance of new connection: 337 metres

Capacity of new link: 40 Mbit/s

Estimated cost:

New configurations:

![Map of locations with different colors representing different configurations](image)

![Line of Sight Profile](image)