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Departamento de
Eletrónica, Telecomunicações e Informática

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Desenvolvimento de Heurísticas para o Dimensionamento de Redes Óticas Transparentes

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e Telecomunicações, realizada sob a orientação científica do Doutor Armando Humberto Moreira Nolasco Pinto, Professor Associado do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro e coorientação empresarial do Doutor Rui Manuel Dias Morais, Doutor em Engenharia Eletrotécnica pela Universidade de Aveiro, coordenador de atividades de investigação em optimização de redes na Infinera Portugal. Tendo como instituição de acolhimento o Instituto de Telecomunicações - Pólo de Aveiro.

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Aos meus pais e à minha irmã por todo o apoio incondicional.

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Palavras-chave

CAPEX, heurísticas, redes óticas de transporte transparentes, camada lógica, camada física, algoritmos, escalonamento, encaminhamento, agregação, sobrevivência, programação linear inteira

Resumo

Nesta dissertação foram desenvolvidas, implementadas e validadas heurísticas para o dimensionamento de redes óticas de transporte transparentes. Foi criada uma plataforma genérica para o desenvolvimento e a implementação das heurísticas baseada em duas entidades principais: um gestor de recursos da camada lógica e um gestor de recursos da camada física. Esta estrutura foi desenhada de modo a poder ser usada para testar uma grande variedade de heurísticas. No âmbito desta tese foram desenvolvidas heuristicas considerando o escalonamento dos pedidos baseados na quantidade de tráfego de cada pedido. Foram ainda desenvolvidos algoritmos para o encaminhamento, a atribuição de comprimentos de onda e agregação dos pedidos de tráfego. O objetivo das heurísticas passa pelo dimensionamento de uma rede, onde recorrendo-se a um mínimo possível de recursos, e portanto, minimizando o CAPEX da rede, se tenta garantir o encaminhamento total do tráfego. Por uma questão de simplificidade apenas foram consideradas redes sem sobrevivência, no entanto, a plataforma é suficientemente genérica para permitir a inclusão de sobrevivência. Tendo também em conta a referida vertente económica, foi elaborado um estudo detalhado e comparativo, tendo em foco o CAPEX da rede, com o objetivo de validar a qualidade das soluções fornecidas pelas heurísticas desenvolvidas tendo por base os valores obtidos através de um modelo baseado em programação linear inteira. Finalmente, são partilhadas e discutidas algumas conclusões e direções para o desenvolvimento de trabalho futuro.

Keywords CAPEX, heuristics, transparent optical networks, logical layer, physical layer, algorithms, scheduling, routing, grooming, survivability, integer linear programming

Abstract In this dissertation a set of heuristic algorithms was developed, implemented and validated for the dimensioning of transparent optical networks. A generic platform was also created in order to allow the heuristics development and implementation, based on two main entities: a logical layer manager and a physical layer manager. The referred structure was designed in order to allow the test of a vast variety of heuristic algorithms. Within the scope of this dissertation were developed traffic scheduling algorithms based on the individual traffic quantity of each request. In addition, some routing, grooming and wavelength assignment algorithms were also developed. The main goal of these heuristics is is to dimension networks, while recurring to the minimum possible amount of resources, thus minimizing the CAPEX of the network, while also trying to guarantee the total traffic routing. For simplicity reasons only the case of networks without survivabilty was treated, although the platform is sufficiently generic to allow its inclusion in future work. Regarding the economic aspects, a detailed and comparative study was conducted, focusing on the networks CAPEX, in order to validate and assess the quality of the solutions provided by the heuristics developed based on the solutions given by an integer linear programming model. Finally, some conclusions and possible future work are discussed.

Table of contents

List of figures

List of tables

List of acronyms

CAPEX Capital Expenditure

EXC Electrical Cross Connector

ILP Integer Linear Programming
IP Internet Protocol
IPS Input Parameters System

OADM Optical Add/Drop Multiplexer
ODU Optical Data Unit
O-E-O Optical-Electronic-Optical
OLT Optical Line Terminal
OPEX Operational Expenditure
OXC Optical Cross Connector

QoS Quality of Service

WDM Wavelength Division Multiplexing

Chapter 1

Introduction

The main objective of a network is to provide communications between two or more desired endpoints. But over time, as networks have become larger and more complex so did their functions grown as well, in such a manner, that nowadays they may also include traffic integrity and survivability aspects and also network management and performance monitoring [1]. Until recently in the history of mankind, communications were very limited, for instance by geographical proximity as messages were transported by messengers or couriers, who either walked or were transported by domesticated animals, or were sent through fire, smoke or sound signals, but in this particular cases just confirming prearranged messages. In the new telecommunications era this master-to-servant relationship was eradicated, replacing the service of a messenger by mechanical telegraphs, followed by copper wires and electromagnetic waves and most lately by the revolutionary optical fibers. These advances dramatically reduced the time required to transport messages, accelerated business transactions, and so in a manner improved human relationships by allowing real-time worldwide communications [1].

Networks are in its essence, very complex engineering systems with many variables to take into account. More precisely, an optical network is a type of data communication network built with optical fiber technology and is composed of fiber optic cables that carry channels of light, combined with equipment deployed along the fibers to process it. Major breakthrough technologies development has been followed by the evolution of optical networks. For instance, one of the earliest technological advances was the ability to carry multiple channels of light on a single fiber optic cable, where each light stream is carried at a different optical frequency and multiplexed into a single fiber, the so called Wavelength Division Multiplexing (WDM) [2]. Until recently, telecommunication networks have been an intelligent combination of transmission and switching technologies, and even if transmission and switching are still the basic building blocks of any network, their fundamentals nowadays cover a much complex and broader scope mainly due to the arise of digital technologies which introduced packet switched networks, which proved to have superior performance regarding various aspects such as connection time, reliability, economy, flexibility and much more [3]. In this last, there is a dynamic allocation of the transmission bandwidth, allowing many users to share the same transmission line and thus reducing the wastage of available bandwidth resources, in contrast to old circuit switched networks where the same was pre-allocated.

A common way to geographically divide telecommunication networks is in access, metro and core networks, being the last two almost entirely based on optical fiber technology, although the penetration of optical fiber communications in the access segment is progressing at an astonishing rate [4]. Access networks usually connect directly to end users, providing interfaces that operate at bit-rates suitable to support various different applications and typically cover a small geographical area, spanning the last tens of kilometers to the end user [5]. On the other hand, metro networks aggregate traffic from several access networks and carry it between major cities, countries or continents. Finally, core networks who are also named transport or backbone networks cover an even larger geographical area, typically thousands of kilometer, and may be shared among millions of customers [2][6].

Devices and connection demands to the Internet have been growing unbelievably fast mainly due to the expansion of optical fiber to customers homes, the increased bandwidth of new mobile technologies, video traffic, and business virtual private networks with remote access to huge databases, which also translates in a growth in Internet-based applications [2][7]. Each year, various new devices in different form factors with increased capabilities and intelligence are introduced and adopted in the market. All of this results in a major increase of Internet Protocol (IP) traffic as we can see in figure 1.1. In response, as operators are undergoing a heavy pressure to reduce the cost per bit transported, they have been investing in a widespread of upgrades to their metro and backbone networks, introducing new technologies, to greatly enhance their capacity and reduce expenses. Currently carriers are demanding WDM optical networking technologies that provide both low Capital Expenditure (CAPEX) and low Operational Expenditure (OPEX) and as almost all traffic is transported through optical networks the operators are very interested in reducing the cost per transported bit as much as possible without compromising the Quality of Service (QoS) [2].

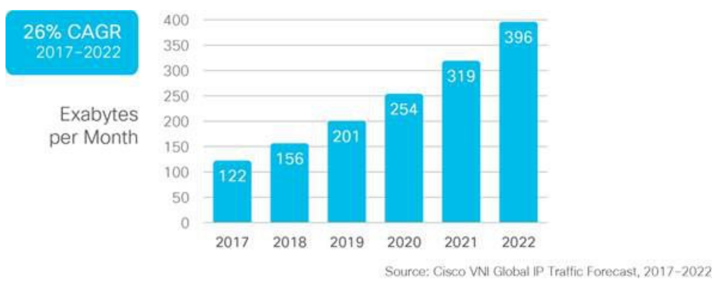

Figure 1.1: Cisco forecasts per month of IP traffic from 2017 until 2022 [8].

1.1 Motivation

The widespread of telecommunications worldwide is the result of the ability to place in the market services at lower prices easily affordable by the masses. The cost factor is therefore, a major enabling issue in the telecommunications industry and tend to have a strong influence in all engineering and administrative decisions, once it directly affects the competitiveness of system vendors and network operators [6]. Network planning tasks such as, how to route and protect traffic in a network or how to bundle different traffic into the same wavelengths, must usually be performed or at least assisted by software tools, the so-called network planning tools. This happens because of the extreme difficulty to make a fast and scalable manual planning to a large and complex telecommunication network [2]. Thus, network planning tools are extremely important as they are used in the various stages of the telecommunications business, namely, in the budgeting, implementation and operation stages enabling the optimization of the available resources and significant cost savings [9]. Currently, there exists various commercial network planning tools but as they usually take into account specialized implementation constraints or proprietary technology to those companies, they are usually not available for public research and comparative studies [10]. In this context, the development of methodologies and optimization tools for transport networks planning is being intensively investigated in academia environments. Therefore, arose the interest and opportunity to develop a global platform that serves as a planning tool created along this dissertation, which is meant for academic and educational research purposes. Additionally, some heuristic algorithms were developed from scratch, implemented and validated in that same platform, offering near optimal solutions in shortest periods of time (for highly complex problems) when compared with other methods, for instance the Integer Linear Programming (ILP) models. These algorithms often need to balance solution quality and scalability, as this last criterion poses a problem for ILP based algorithms, which are known to scale poorly with the problem size, the less complex heuristic algorithms can be considered as a great advantage.

1.2 Objectives

Due to the importance of transport network planning and dimensioning, this dissertation aims to achieve the following main objectives:

1. Elaborate a generic framework for optical transport networks dimensioning based on heuristics.

2. Implement the framework recurring to the NetXPTO-NetPlanner simulator.

3. Develop heuristic algorithms for transparent networks.

4. Elaborate an economic comparative study and validate the heuristics with ILP and analytical results.

1.3 Dissertation outline

This dissertation is organized in 7 chapters. Chapter 2 serves the purpose of a state-of-the-art review on optical transport networks dimensioning. The chapter introduces and explains the main concepts and notions used throughout the dissertation, it starts by giving a general description of the architecture and possible topologies of optical networks as well as a description of the reference and realistic networks and the different traffic scenarios defined. The remaining of the chapter is devoted to the detailed description of the models used for CAPEX estimations, namely the analytical, the ILP and the Heuristic. Chapter 3 is composed of several sections, where a general description of the created generic framework is presented as well as of each of the individual entities that it is comprised of. Afterwards, in chapter 4, is taken an approach on the practical implementation of the created platform through NetXPTO-Netplanner simulator, the set of variables and inputs used is extensively detailed as well as the functionalities and features provided. In chapter 5 the implemented heuristic algorithms are explored and other possible alternatives to the strategies adopted are provided. Some charts representing the pseudo code behind the routing, grooming and wavelength assignment are also present in this chapter. Chapter 6 contains the results obtained throughout this dissertation for both the reference and the realistic networks. Also in this chapter a comparative analysis is performed with the results obtained wit different methods. Finally, in chapter 7 some conclusions and suggestions for future research directions are provided.

1.4 Major Achievements

The list of main objectives and contributions achieved during this dissertation are presented below:

1. Creation of a generic framework for optical networks dimensioning.
2. Implementation of the framework over the NetXPTO-Netplanner simulator, resulting in an operational platform.
3. Successful testing and validation of the developed heuristic algorithms.

Chapter 2

Optical Transparent Networks Dimensioning

The scope of this chapter resides on the elaboration of a state-of-the-art review relatively to optical transport networks. This chapter is composed of 5 subsections, the first 2.1 provides a generic description on optical transport networks and addresses the main constituting components, the second 2.2 refers and provides a brief description on the different topologies in a network, the third 2.3 is an approach on the various methods of calculating the CAPEX of a network and the last two describe both the reference and the realistic networks considered for the various types of dimensioning processes, 2.4 and 2.5, respectively.

2.1 Network Architecture

In the modern telecommunications era, networks are a vast and highly multidisciplinary field of study as it shall be seen further along this dissertation. As it was mentioned in the previous chapter, traffic requirements have been growing unbelievably fast in the last few decades and so an efficient and well structured network becomes a priority of even greater importance over time once the direct consequence is the minimization of required network components, thus, lowering the respective CAPEX of the network.

In the transparent transport mode, which will be the transport mode studied, signals remain in the optical domain from their source till the destination node, traveling in a defined route through one or more optical channels that together constitute a high-bandwidth end-to-end circuit, i.e., a lightpath [11]. Therefore, a single-hop grooming scheme is used as intermediate nodes do not perform wavelength conversions and so the requests must be assigned with the same wavelength on all the links of the used path [12]. This is known as the wavelength continuity constraint and implies that the utilization of the same wavelength channels is restricted to the client signals with the same endpoints [9]. Also in this transport mode the so called electro-optic bottleneck is eliminated as this method allows information transfer rates to reach closer values to those allowed by optical devices, which are significantly beyond the rates achievable in an Optical-Electronic-Optical (O-E-O) network [13]. Electrical regeneration is also not present, and as such the quality of the optical signals degrade as they traverse the optical components along the route limiting the maximum transmission length of the signals in the optical domain without regeneration [9]. Regarding the network economic aspects, the dimensioning of a telecommunications network involves identifying the required resources and their respective quantities [14]. As both setting up and operating large telecommunications infrastructures require large amounts of money any network investment must be carefully evaluated [15]. These costs can be divided into two major branches: the CAPEX and the OPEX. The first will be analyzed more closely during this dissertation and can be sub-divided into the cost of buying and installing the equipment as well as setting up the infrastructures and the second represents an expense a network company incurs through its normal operations, which can include rent, inventory costs, insurance, and funds allocated for research and development [6][16].

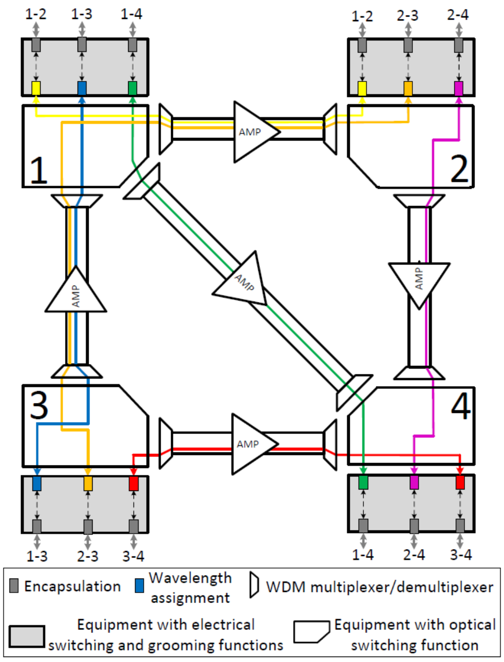

Figure 2.1: Example of an all-optical network with 4 nodes [9].

Above in figure 2.1 an example of a four nodes all-optical network is shown where a single-hop grooming technique is used and O-E-O conversions only happen at end nodes. Also, the grooming of client signals is restricted to services with the same end-points [9].

An optical transport network can be seen as set of bidirectional links connecting nodes [9]. Links and nodes are interconnected through compatible interfaces in order to form a topology. Therefore, a network topology can be described as the arrangement of nodes and links, and are usually represented as a graph.

2.1.1 Links

Physical point-to-point connections ensured by transmission systems between a pair of adjacent nodes, thus guaranteeing the transmission of WDM signals between them [7]. Links can be composed by one or more transmission systems where each one usually comprises one pair of unidirectional optical fibers ensuring a bidirectional connection between the nodes [9]. The optical fiber is the medium where the optical signal is transmitted and is capable of transporting data on wavelengths [17]. In networks capable of allowing the transiting traffic to remain in the optical domain, as it is the case, it must be considered another important property of the transmission systems which is the optical reach, the maximum distance a signal can be transmitted in the optical domain before it degrades to a level where it is required optical amplification of the signal, in order to allow a correct detection of the same in the receptor [2]. The distance between each amplification stage is typically denominated span.

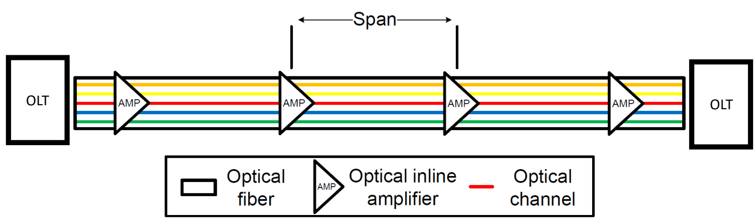

Figure 2.2: Schematic of a link containing an optical fiber, inline optical amplifiers and OLT terminals [9].

2.1.2 Nodes

Nodes are multirack systems that usually perform six main functions being them as it follows: encapsulation, electrical switching, deterministic or statistical multiplexing (grooming), wavelength assignment, optical switching and finally optical multiplexing. All of these tasks require a substantial amount of hardware making the nodes one of the most expensive components of the network [6]. Moreover, as in all-optical networks the transiting traffic can potentially remain in the optical domain from source to destination, crossing through the node rather than be electronically processed, technology had to be developed in order to enable this so called optical bypass. This process would imply a significant reduction in the amount of required nodal electronic equipment, thus reducing the monetary value needed to implement it. The three major network elements that are capable of optical bypass are the Optical Add/Drop Multiplexer (OADM), the multi-degree OADM and the all-optical switch [2]. In optical networks, nodes consist mainly of three different blocks: modules, shelves and racks. The independent modules are attached to shelves in order to allow backplane communication and possess a required number of ports and other different components that perform functions on both the optical and the electrical domains, such as, optical and electrical switching, encapsulation, grooming and wavelength assignment. Regarding the shelves they provide a common infrastructure to the modules and are attached into racks which consist in frames for mounting multiple shelves and provide power and cooling to the system [9]. Ports can be defined as bidirectional optical connectors used to interconnect two modules using a pair of fibers. Each type of module occupies a given number of slots, which are the minimum unit space in a shelf and some of those slots in the shelf are reserved for the control modules which are required for operation, administration, and management tasks of the system.

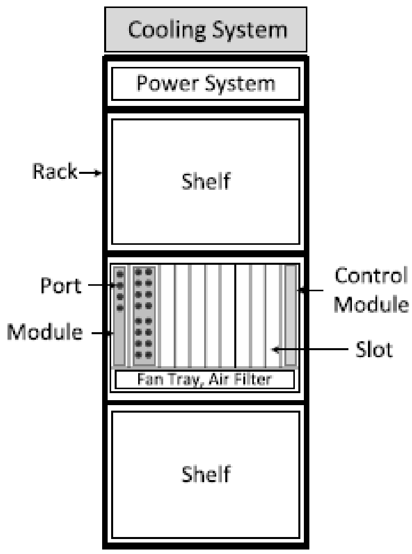

Figure 2.3: Schematic of a node structure containing modules, shelves and a rack. [18].

2.2 Network Topologies

2.2.1 Physical Topology

The pattern that represents and characterizes the layout of an optical network, i.e., the physical disposition of nodes and the connections between them. A physical network topology can be modeled as a graph which is a mathematical structure made of a set of vertices, representing nodes, and a set of edges, representing links. Graphs are usually represented pictorially using dots and arcs to represent vertices and edges, respectively, or by adjacency matrices. An adjacency matrix is a matrix containing only zeros and ones and where the position of the ones specify which vertices are directly connected to which other vertices [15].

2.2.2 Logical Topology

Represents how the components of an optical network are connected. Each node may be either optically connected to each other, or only optically connected to adjacent or suitable nodes. This leads to a situation where different transport modes are possible to exist, namely, the opaque, the transparent and the translucent [19]. In this dissertation the focus will be on the transparent transport mode. Likewise the physical topology, previously referred, it can also represented as a graph or through adjacency matrices.

2.3 Capital Expenditure Estimation

In this section is intended to provide the general equations used in order to make CAPEX calculations. As networks are mainly comprised of nodes and links in order to calculate the total network cost it has to be considered the sum of these two components costs. The CAPEX value of a network, C_C, in monetary units (e.g. euros, or dollars), can be expressed by equation 2.1

$$C_C = C_L + C_N \tag{2.1}$$

where

- $C_L \rightarrow$ Links setup cost in monetary units (e.g. euros, or dollars)
- $C_N \rightarrow$ Nodes setup cost in monetary units (e.g. euros, or dollars)

Below in this section are proposed and described the models used to calculate the CAPEX of the network. These calculations are made based on the transparent transport mode without survivability case.

2.3.1 Links Cost

First lets focus on the cost of the links part, C_L, in monetary units (e.g. euros, or dollars). Links can be implemented with one or more transmission systems, whose cost is directly impacted by three major components, the costs regarding the Optical Line Terminal (OLT), the optical regeneration stages and the optical fiber. However, this last component can be discarded as it usually appears as an operational expense instead of a capital expenditure since it is commom practice in the telecommunications area for operators to lease fiber-optic cables instead of installing them [6]. In this dissertation each existent link is considered to possess just one bidirectional transmission system.

In order to calculate the cost of the links, we can use use equation 2.2.

$$C_L = \sum_{i=1}^{N} \sum_{j=i+1}^{N} L_{ij} \left(2\gamma_0^{OLT} + 2\gamma_1^{OLT} W_{ij} + 2N_{ij}^{R} c^{R} \right) \tag{2.2}$$

where

- $i \rightarrow$ Index for start node of a physical link
- $j \rightarrow$ Index for end node of a physical link
- $N \rightarrow$ Total number of nodes, N $\in \mathbb{N}$
- $L_{ij} \rightarrow$ Binary variable indicating if link between the nodes i and j is used, $L_{ij} \in 0, 1$
- $\gamma_0^{OLT} \rightarrow$ OLT base cost in monetary units (e.g. euros, or dollars)
- $\gamma_1^{OLT} \rightarrow$ OLT optical channels linear cost factor in monetary units (e.g. euros, or dollars)
- $W_{ij} \rightarrow$ Total number of optical channels in link i j
- $N_{ij}^{R} \rightarrow$ Number of optical amplifiers in link i j
- $c^{R} \rightarrow$ Unidirectional optical amplifiers cost in monetary units (e.g. euros, or dollars)

The number of amplifiers for each link can be calculated by equation 2.3

$$N_{ij}^{R} = \left(\left\lceil \frac{len_{ij}}{span} \right\rceil - 1 \right) \tag{2.3}$$

where the variable len_{ij} is the length of link ij in kilometers and the $span$ is the distance between amplification stages, also in kilometers [15].

2.3.2 Nodes Cost

Regarding the nodes part of the costs, in transparent network nodes it is necessary to consider both the optical and the electrical parts, as it can be seen below in figure 2.4. The channels that just go through the node are switched in the optical domain and the channels that are local to the node are processed in the electrical domain, with the switching being performed in the wavelength-domain [15]. So, as the nodes have an electrical part, the Electrical Cross Connector (EXC), and an optical part, the Optical Cross Connector (OXC), it becomes obvious that the cost of the nodes, C_N, is given by the sum of these two parts, thus, obtaining the equation 2.4

$$C_N = C_{EXC} + C_{OXC} \tag{2.4}$$

where

- $C_{EXC} \rightarrow$ Electrical node cost in monetary units (e.g. euros, or dollars)
- $C_{OXC} \rightarrow$ Optical node cost in monetary units (e.g. euros, or dollars)

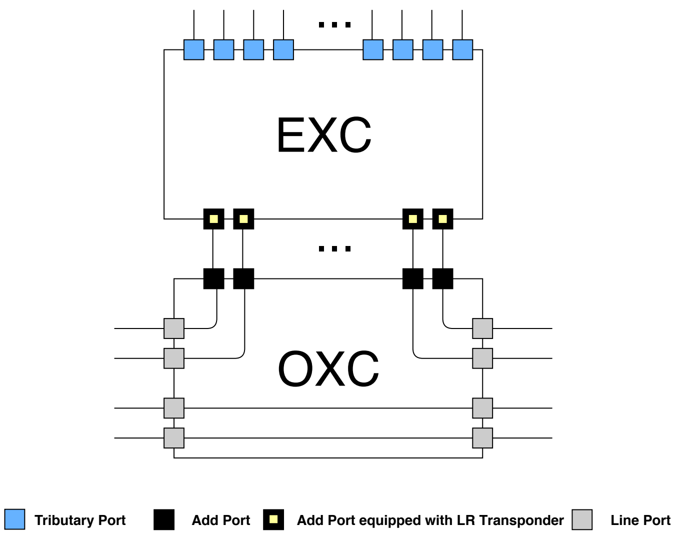

Figure 2.4: Electrical and optical node structure.

The electric cost is than the sum of the fixed cost of the electrical connection with the total cost of all the electric ports. Therefore, the electric cost in monetary units (e.g. euros, or dollars), C_{EXC}, is given by equation 2.5 [7].

$$C_{EXC} = \sum_{n=1}^{N} N_{exc,n} \left(\gamma_{e0} + \sum_{c=-1}^{B} \gamma_{e1,c} P_{exc,c,n} \right) \tag{2.5}$$

where

- $N \rightarrow$ Total number of nodes, N $\in \mathbb{N}$
- $N_{exc,n} \rightarrow$ Binary variable indicating if node n is used, $N_{exc,n} \in 0, 1$
- $\gamma_{e0} \rightarrow$ EXC base cost in monetary units (e.g. euros, or dollars)
- $\gamma_{e1,c} \rightarrow$ EXC port cost in monetary units (e.g. euros, or dollars) with bit-rate B and with a given transceiver reach
- $P_{exc,c,n} \rightarrow$ Number of ports of the electrical switch of node n
- $B \rightarrow$ A natural number corresponding to the maximum index of short-reach ports, see table 2.1

Index	Bit rate
-1	100 Gbits/s line bit-rate (long-reach port)
0	1.25 Gbits/s tributary bit-rate (short-reach port)
1	2.5 Gbits/s tributary bit-rate (short-reach port)
2	10 Gbits/s tributary bit-rate (short-reach port)
3	40 Gbits/s tributary bit-rate (short-reach port)
4	100 Gbits/s tributary bit-rate (short-reach port)

Table 2.1: Table containing indexes and the corresponding bit rates.

The following equation 2.6 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n, [7]. It can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{2.6}$$

where $D_{nd,c}$ are the client demands between nodes n and d with bit rate c.

In this case there is the following particularity:

- When n=d the value of client demands is always zero, i.e, $D_{nn,c} = 0$

On the other hand, the equation 2.7 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e. the number of add ports of node n, [7]. It can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} \lambda_{nj} \tag{2.7}$$

where λ_{nj} is the number of optical channels between node n and node j.

In relation to the optical part, C_{oxc}, once again the optical cost is the sum of the fixed cost of the optical connection with the total cost of all the optical ports. Therefore the optical cost in monetary units (e.g. euros, or dollars), C_{OXC}, is given by equation 2.8 [7].

$$C_{OXC} = \sum_{n=1}^{N} N_{oxc,n} \Big(\gamma_{o0} + \gamma_{o1} P_{oxc,n} \Big) \tag{2.8}$$

where

- $N \rightarrow$ Total number of nodes, N $\in \mathbb{N}$
- $N_{oxc,n} \rightarrow$ Binary variable indicating if node n is used, $N_{oxc,n} \in 0, 1$
- $\gamma_{o0} \rightarrow$ OXC base cost in monetary units (e.g. euros, or dollars)
- $\gamma_{o1} \rightarrow$ OXC optical channels linear traffic cost in monetary units (e.g. euros, or dollars)
- $P_{oxc,n} \rightarrow$ Number of ports of the optical switch of node n

The following equation refers to the number of ports in the optical switch of node n, $P_{oxc,n}$, i.e. the number of line ports and the number of adding ports of node n [7]. It can be calculated as

$$P_{oxc,n} = P_{line,n} + P_{add,n} \tag{2.9}$$

which is equivalent to the equation 2.10 expressed below.

$$P_{oxc,n} = \sum_{j=1}^{N} f_{nj}^{od} + \sum_{j=1}^{N} \lambda_{nj} \tag{2.10}$$

where f_{nj}^{od} refers to the number of line ports for all demand pairs (od) and λ_{nj} refers to the number of add ports.

2.3.3 Capital Expenditure Models

The values obtained for the CAPEX of the tested networks will most probably vary for the exact same traffic scenario considering the model used (analytical, ILP or heuristic) since the calculated values for variable $P_{exc,c,n}$ and $P_{oxc,n}$ will always depend upon the mode of transport used and on the routing and grooming strategies, which differ according to the model used. In order to make these calculations, it will also be needed to take into account the costs of the equipment used, which are presented in table 2.2, and will represent the steady variables of the problem.

	Symbol	Cost
OLT base cost	γ_0^{OLT}	15 000 €
OLT optical channels linear cost factor	γ_1^{OLT}	5 000 €
Unidirectional optical amplifier	c^R	2 000 €
EXC base cost	γ_{e0}	10 000 €
OXC base cost	γ_{o0}	20 000 €
Long reach transponder	γ_{e1}	100 €/Gbit/s
EXC traffic linear factor cost	γ_{e2}	100 €/Gbit/s
OXC optical channels linear traffic cost	γ_{o1}	2 500 €/port

Table 2.2: Table of costs used to calculate the CAPEX [6].

Analytical Model

The analytical approach is used when a statistical approximation is required not existing the need for exact and precise values. This estimation becomes useful for cases where there is lack of some information, for example the number of demands to process or the topology of the network, or when the routing and/or grooming processes are unknown.

In this section the calculations are made in an analytical way in order to get a different point of view while expecting similar results. Having this said, the CAPEX in monetary units, C_C is again given by the equation 2.1.

For this calculation first let's focus on the cost of the links. Where to calculate the cost of the Links, C_L, it is used the equation 2.11

$$C_L = \left(2L\gamma_0^{OLT}\right) + \left(2L\gamma_1^{OLT} < w >\right) + \left(2N^R c^R\right) \tag{2.11}$$

where

- $\gamma_0^{OLT} \rightarrow$ OLT base cost cost in monetary units (e.g. euros, or dollars)
- $L \rightarrow$ Number of bidirectional links
- $\gamma_1^{OLT} \rightarrow$ OLT optical channels linear cost in monetary units (e.g. euros, or dollars)
- $< w > \rightarrow$ Average number of optical channels
- $N^R \rightarrow$ Total number of unidirectional optical amplifiers
- $c^R \rightarrow$ Unidirectional optical amplifiers cost in monetary units (e.g. euros, or dollars)

Looking at the equation 2.11 it becomes obvious that practically all the values of the variables used are known, only missing the number of optical amplifiers and the average number of optical channels [15].

Through the equation 2.12 we can calculated the number of optical amplifiers, N^R, as

$$N^R = \sum_{l=1}^{L} \left(\left\lceil \frac{len_l}{span} \right\rceil - 1 \right) \tag{2.12}$$

where len_l is the length of link l and $span$ is the distance between amplifiers, again assumed to be of 100 km [15].

The average number of optical channels can be calculated as it follows, through equation 2.13 [7].

$$< w > = \left(\frac{\lceil D < h > \rceil}{L_u} \right) (1 + < k >) \tag{2.13}$$

where D is the number of unidirectional demands, L_u is the number of unidirectional links and $< k >$ is the survivability coefficient. And finally the number of unidirectional demands can be calculated as

$$D = \left(\frac{1}{2} \right) (1 + \xi) \left(\frac{T_1}{\tau} \right) \tag{2.14}$$

where ξ is the grooming coefficient, T_1 is the total unidirectional traffic and τ is the line bit rate, assumed to be 100 Gbit/s [7].

Taking into account the particularities of the transparent transport mode it will be assumed the following values:

- $\xi = 1.25$
- $< k > = 0$ (there is no survivability)

It will be assumed that the grooming coefficient has value 1.25 and that the survivability coefficient is zero because it is not considered survivability.

Relatively to the cost of the nodes, it can be expressed as in equation 2.4, being the electrical cost of the nodes, C_{exc}, given by equation 2.15.

$$C_{exc} = N\left(\gamma_{e0} + (\gamma_{e1}\tau < P_{exc} >)\right) + \gamma_{e2}\ P_{trib} \tag{2.15}$$

where:

- $N \rightarrow$ Number of nodes
- $\gamma_{e0} \rightarrow$ EXC base cost in monetary units (e.g. euros, or dollars)
- $\gamma_{e1} \rightarrow$ Long reach transponder cost in monetary units (e.g. euros, or dollars)
- $\gamma_{e2} \rightarrow$ EXC traffic linear factor cost in monetary units (e.g. euros, or dollars)
- $\tau \rightarrow$ Line bit rate
- $< P_{exc} > \rightarrow$ Average number of ports of the electrical switch
- $P_{trib} \rightarrow$ Total number of tributary ports

In relation to the optical part, C_{oxc}, the optical cost of the nodes is given by equation 2.16

$$C_{oxc} = N \times \left(\gamma_{o0} + (\gamma_{o1} < P_{oxc} >)\right) \tag{2.16}$$

where:

- $N \rightarrow$ Number of nodes
- $\gamma_{o0} \rightarrow$ OXC base cost in monetary units (e.g. euros, or dollars)
- $\gamma_{o1} \rightarrow$ OXC optical channels linear traffic cost in monetary units (e.g. euros, or dollars)
- $< P_{oxc} > \rightarrow$ Average number of ports of the optical switch

Regarding the equation 2.15 it becomes obvious that all the variables are already known with the exception of the number of tributary ports, P_{trib}, that can be calculated through the

ODU's matrices referred below in sections 2.4 and 2.5 and the average number of ports of the electrical switch, $< P_{exc} >$, that can be calculated as

$$< P_{exc} > = < d > \tag{2.17}$$

Finally the average number of ports of the optical switch, $< P_{oxc} >$, can be calculated as

$$< P_{oxc} > = < d > [1 + (1 + < k >) < h >] \tag{2.18}$$

where $< d >$ is the average number of demands, $< k >$ is the survivability coefficient and $< h >$ is the average number of hops. Taking all of these in account it becomes possible to calculate the approximated values for the CAPEX of a network.

ILP Model

ILP models are usually applied into optimization problems, where a given function is intended to maximize or minimize, based on a set of constraints [19]. More precisely in the telecommunications area, ILP models are used to design networks describing real components and their capabilities through a set of linear equations and inequalities, making use of only integer values [7]. Despite the quality of the solutions obtained through the ILP models, as dimensioning a real network involves a large number of variables and computational resources, the results of the ILP models can take days, months or even years once the range of solutions is enormous. The equations given in the previous sections 2.3.1 and 2.3.2 will be utilized here to make the CAPEX calculations. Furthermore, all transport modes require the routing of the demands, but in the case of the ILP models it is assumed that the routing is performed by the ILP model instead of feeding it with candidate paths. The ILP models will differ from the heuristic models since they will search every other possible resolution of the problem in order to find the optimal solution. In order to use this model, proposed in a previous dissertation, a set of constraints presented in Morais [9] and Esteves [7] must be ensured.

Heuristic Model

Here a search for an acceptable near optimal solution is conducted, based on strategic and intelligent decisions. Although the same equations applied before in subsections 2.3.1 and 2.3.2 are still valid, the difference towards the ILP models resides in the fact that, while using heuristic approaches a set of specific algorithms has to be implemented for routing and grooming purposes and as such not all of the possible scenarios are considered once the algorithms are not wide enough, making this a faster and less complex method but also less accurate.

2.4 Reference Network

In this section will be described the reference network used throughout the dissertation to test the heuristic algorithms developed and to obtain solutions. Both the physical topology and traffic matrices for the three scenarios of traffic are specified below.

2.4.1 Physical Topology

As it is possible to see in figure 2.5 for this specific case the reference network consists in 6 nodes interconnected by 8 bidirectional links. It is also important to know the average length of the links and for that purpose it will be necessary to define the distances of each individual link.

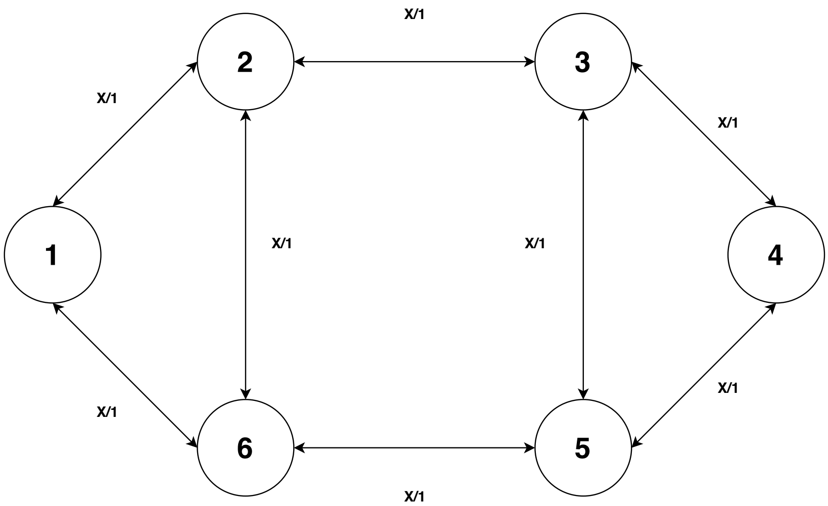

Figure 2.5: Reference network physical topology graph representation.

Node	**1**	**2**	**3**	**4**	**5**	**6**
1	0	1	0	0	0	1
2	1	0	1	0	0	1
3	0	1	0	1	1	0
4	0	0	1	0	1	0
5	0	0	1	1	0	1
6	1	1	0	0	1	0

Table 2.3: Reference network physical topology adjacency matrix.

Above in figure 2.5 and table 2.3 the physical topology of the reference network is specified as a graph and in an adjacency matrix, respectively. Below we have the distance matrix that contains the actual values of distance, expressed in kilometers (km), between node sites. The values will remain the same for every traffic scenario tested and the traffic matrix must be symmetric.

$$Dist = \begin{bmatrix} 0 & 350 & 0 & 0 & 0 & 150 \\ 350 & 0 & 350 & 0 & 0 & 150 \\ 0 & 350 & 0 & 250 & 50 & 0 \\ 0 & 0 & 250 & 0 & 150 & 0 \\ 0 & 0 & 50 & 150 & 0 & 550 \\ 150 & 150 & 0 & 0 & 550 & 0 \end{bmatrix}$$

In table 2.4 we have the global variables that characterize the reference network.

Constant	Description	Value
N	Number of nodes	6
L	Number of bidirectional links	8
$<\delta>$	Node degree	2.667
<len>	Mean link length (km)	250
<h>	Mean number of hops for working paths	1.533
<h'>	Mean number of hops for backup paths	2.467

Table 2.4: Table of reference network values.

2.4.2 Logical Topology

The logical topology of a network depends directly of the transport mode used.

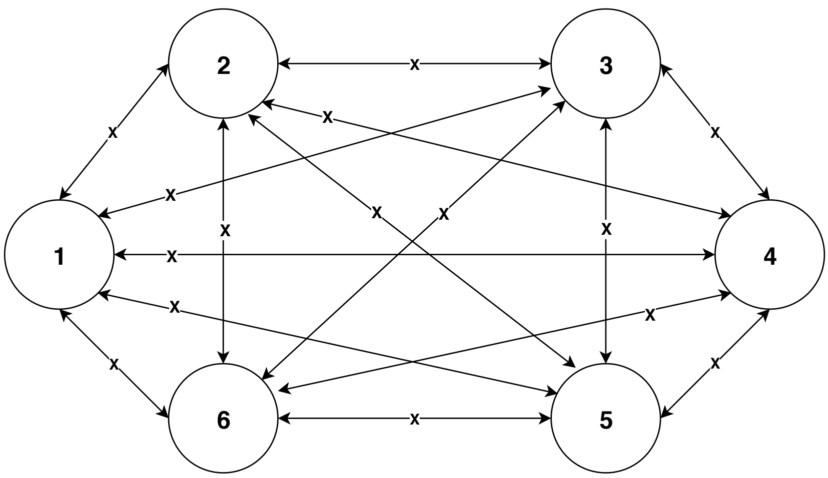

Figure 2.6: Reference network logical topology graph representation.

For this specific case, as only the transparent transport mode is considered, the resultant logical topology is represented in figure 2.6. Like the previous, it is comprised of the same 6 nodes which in this case are directly connected, on an upper logical layer, to every other node.

2.4.3 Traffic Matrices

Three different scenarios of traffic (low, medium and high) were designed in order to better understand the later results. Each of the scenarios are composed of 5 matrices of different Optical Data Unit (ODU) frame types, namely, the ODU0 corresponding to 1.25 Gbit/s, the ODU1 corresponding to 2.5 Gbit/s, the ODU2 corresponding to 10 Gbit/s, the ODU3 corresponding to 40 Gbit/s and finally the ODU4 thaht corresponds to 100 Gbit/s. The matrices for all cases are symmetric, meaning that the traffic sent, for example, from node 1 to node 2 is the same as the traffic sent from node 2 to 1. Since in this case all the traffic requests are known the network traffic is said to be static.

Low Traffic Scenario

In this case, it was chosen to have a total unidirectional traffic of 2 Tbit/s. That amount of traffic was distributed through the different ODU type matrices as it can be seen below.

$$ODU0 = \begin{bmatrix} 0 & 10 & 2 & 6 & 2 & 6 \\ 10 & 0 & 0 & 2 & 10 & 0 \\ 2 & 0 & 0 & 2 & 8 & 2 \\ 6 & 2 & 2 & 0 & 2 & 2 \\ 2 & 10 & 8 & 2 & 0 & 6 \\ 6 & 0 & 2 & 2 & 6 & 0 \end{bmatrix} \quad ODU1 = \begin{bmatrix} 0 & 4 & 8 & 4 & 0 & 10 \\ 4 & 0 & 0 & 6 & 2 & 2 \\ 8 & 0 & 0 & 2 & 2 & 0 \\ 4 & 6 & 2 & 0 & 2 & 6 \\ 0 & 2 & 2 & 2 & 0 & 2 \\ 10 & 2 & 0 & 6 & 2 & 0 \end{bmatrix}$$

$$ODU2 = \begin{bmatrix} 0 & 2 & 2 & 2 & 0 & 0 \\ 2 & 0 & 0 & 0 & 2 & 0 \\ 2 & 0 & 0 & 2 & 2 & 0 \\ 2 & 0 & 2 & 0 & 2 & 0 \\ 0 & 2 & 2 & 2 & 0 & 2 \\ 0 & 0 & 0 & 0 & 2 & 0 \end{bmatrix} \quad ODU3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 2 \\ 0 & 2 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ODU4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 \\ 0 & 2 & 0 & 0 & 2 & 0 \end{bmatrix}$$

Through these matrices it becomes possible to calculate the total network traffic for the low traffic scenario:
$T_1^0 = 120\text{x}1.25 = 150$ Gbits/s $T_1^1 = 100\text{x}2.5 = 250$ Gbits/s $T_1^2 = 32\text{x}10 = 320$ Gbits/s

$T_1^3 = 12\text{x}40 = 480$ Gbits/s $T_1^4 = 8\text{x}100 = 800$ Gbits/s

$T_1 = 150 + 250 + 320 + 480 + 800 = 2000$ Gbits/s $T = 1000/2 =$ **1 Tbits/s**

Where the variable T_1^x represents the unidirectional traffic of the ODUx, for example, T_1^0 represents the unidirectional traffic of the ODU0 and T_1^1 represents the unidirectional traffic of the ODU1. The variable T_1 represents the total of unidirectional traffic that is injected into the network. Finally, the variable T represents the total of bidirectional traffic.

Medium Traffic Scenario

In this case it was chosen to have a total unidirectional traffic of 10 Tbit/s. That amount of traffic was distributed through the different ODU type matrices as it can be seen below.

$$ODU0 = \begin{bmatrix} 0 & 50 & 10 & 30 & 10 & 30 \\ 50 & 0 & 0 & 10 & 50 & 0 \\ 10 & 0 & 0 & 10 & 40 & 10 \\ 30 & 10 & 10 & 0 & 10 & 10 \\ 10 & 50 & 40 & 10 & 0 & 30 \\ 30 & 0 & 10 & 10 & 30 & 0 \end{bmatrix} \quad ODU1 = \begin{bmatrix} 0 & 20 & 40 & 20 & 0 & 50 \\ 20 & 0 & 0 & 30 & 10 & 10 \\ 40 & 0 & 0 & 10 & 10 & 0 \\ 20 & 30 & 10 & 0 & 10 & 30 \\ 0 & 10 & 10 & 10 & 0 & 10 \\ 50 & 10 & 0 & 30 & 10 & 0 \end{bmatrix}$$

$$ODU2 = \begin{bmatrix} 0 & 10 & 10 & 10 & 0 & 0 \\ 10 & 0 & 0 & 0 & 10 & 0 \\ 10 & 0 & 0 & 10 & 10 & 0 \\ 10 & 0 & 10 & 0 & 10 & 0 \\ 0 & 10 & 10 & 10 & 0 & 10 \\ 0 & 0 & 0 & 0 & 10 & 0 \end{bmatrix} \quad ODU3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 10 \\ 0 & 10 & 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ODU4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \\ 0 & 10 & 0 & 0 & 10 & 0 \end{bmatrix}$$

Through these matrices it becomes possible to calculate the total network traffic for the medium traffic scenario:

$T_1^0 = 600x1.25 = 750$ Gbits/s $T_1^1 = 500x2.5 = 1205$ Gbits/s $T_1^2 = 160x10 = 1600$ Gbits/s

$T_1^3 = 60x40 = 2400$ Gbits/s $T_1^4 = 40x100 = 4000$ Gbits/s

$T_1 = 750 + 1250 + 1600 + 2400 + 4000 = 10000$ Gbits/s $T = 10000/2 =$ **5 Tbits/s**

High Traffic Scenario

In this case it was chosen to have a total unidirectional traffic of 20 Tbit/s. That amount of traffic was distributed through the different ODU type matrices as it can be seen below.

$$ODU0 = \begin{bmatrix} 0 & 100 & 20 & 60 & 20 & 60 \\ 100 & 0 & 0 & 20 & 100 & 0 \\ 20 & 0 & 0 & 20 & 80 & 20 \\ 60 & 20 & 20 & 0 & 20 & 20 \\ 20 & 100 & 80 & 20 & 0 & 60 \\ 60 & 0 & 20 & 20 & 60 & 0 \end{bmatrix} \quad ODU1 = \begin{bmatrix} 0 & 40 & 80 & 40 & 0 & 100 \\ 40 & 0 & 0 & 60 & 20 & 20 \\ 80 & 0 & 0 & 20 & 20 & 0 \\ 40 & 60 & 20 & 0 & 20 & 60 \\ 0 & 20 & 20 & 20 & 0 & 20 \\ 100 & 20 & 0 & 60 & 20 & 0 \end{bmatrix}$$

$$ODU2 = \begin{bmatrix} 0 & 20 & 20 & 20 & 0 & 0 \\ 20 & 0 & 0 & 0 & 20 & 0 \\ 20 & 0 & 0 & 20 & 20 & 0 \\ 20 & 0 & 20 & 0 & 20 & 0 \\ 0 & 20 & 20 & 20 & 0 & 20 \\ 0 & 0 & 0 & 0 & 20 & 0 \end{bmatrix} \quad ODU3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 20 & 0 & 0 & 20 \\ 0 & 20 & 0 & 0 & 20 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 20 & 0 & 0 & 0 \\ 0 & 20 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ODU4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20 \\ 0 & 20 & 0 & 0 & 20 & 0 \end{bmatrix}$$

Through these matrices it becomes possible to calculate the total network traffic for the high traffic scenario:

$T_1^0 = 1200x1.25 = 1500$ Gbits/s $T_1^1 = 1000x2.5 = 2500$ Gbits/s

T_1^2 = 320x10 = 3200 Gbits/s $\quad$ T_1^3 = 120x40 = 4800 Gbits/s

T_1^4 = 80x100 = 8000 Gbits/s $\quad$ T_1 = 20000 Gbits/s

T = 20000/2 = **10 Tbits/s**

2.5 Realistic Network

The nodes are geographically distributed as shown in figure 2.7. As it can be seen this network is composed of 12 nodes and 17 bidirectional links.

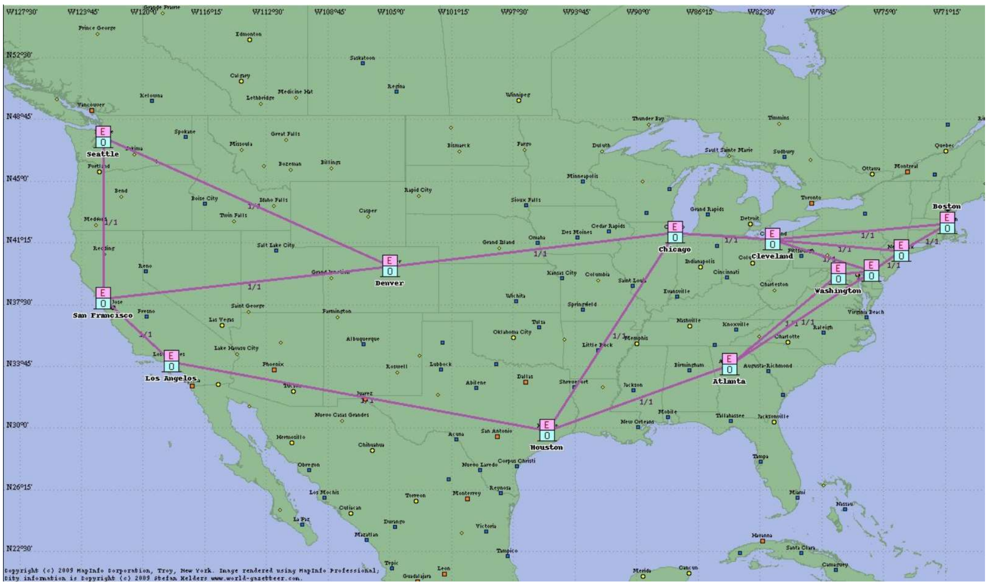

Figure 2.7: The Very-High Performance Backbone Network Service [20].

In order to validate the developed heuristic algorithms it was decided to apply them into a real and more complex network. The chosen network was the vBNS (very high-speed Backbone Network Service), which is a National Science Foundation sponsored high-performance network service implemented in the United States of America by the MCI Telecommunications Corporation. It supports scientific applications between NSF-supported supercomputer centers, directly connected research institutions and research institutions that are served by other networks [21]. As before the only the transparent transport mode without survivability will be approached.

2.5.1 Physical Topology

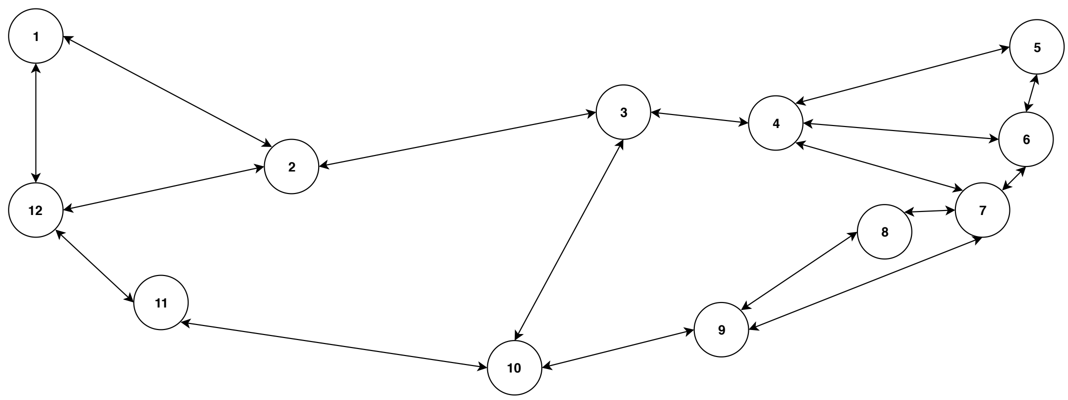

Figure 2.8: Physical topology graph representation.

Node	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	0	1	0	0	0	0	0	0	0	0	0	1
2	1	0	1	0	0	0	0	0	0	0	0	1
3	0	1	0	1	0	0	0	0	0	1	0	0
4	0	0	1	0	1	1	1	0	0	0	0	0
5	0	0	0	1	0	1	0	0	0	0	0	0
6	0	0	0	1	1	0	1	0	0	0	0	0
7	0	0	0	1	0	1	0	1	1	0	0	0
8	0	0	0	0	0	0	1	0	1	0	0	0
9	0	0	0	0	0	0	1	1	0	1	0	0
10	0	0	1	0	0	0	0	0	1	0	1	0
11	0	0	0	0	0	0	0	0	0	1	0	1
12	1	1	0	0	0	0	0	0	0	0	1	0

Table 2.5: Physical topology adjacency matrix.

Above in figure 2.8 and table 2.5 the physical topology of the realistic network is specified as a graph and in an adjacency matrix, respectively.

In table 2.6 we have the global variables that characterize the Very-High Performance Backbone Network Service.

Constant	Description	Value
N	Number of nodes	12
L	Number of bidirectional links	17
$<\delta>$	Node degree	2.83
<len>	Mean link length (km)	965
<h>	Mean number of hops for working paths	2.40
<h'>	Mean number of hops for backup paths	3.90

Table 2.6: Table of vBNS network values.

2.5.2 Traffic Matrices

Below, are presented the traffic matrices used in order to test this network. The matrices for this traffic scenario were generated randomly. The total amount of bidirectional traffic in the network considering this set of demands stays around 7.5 Tbit/s. It should be noted that the total number of columns and rows is equal to the number of nodes and the main diagonal of the matrices is composed of zeros, since it does not make sense for a node to send traffic to itself. Additionally, the missing matrices for ODU0 and ODU4 represent the absence of demand requests of this type.

ODU1	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	2	4	4	3	1	3	4	0	0	0
2	0	0	50	5	50	5	5	50	5	0	5	50
3	2	50	0	5	5	5	5	5	5	5	5	50
4	4	5	5	0	4	6	0	0	0	1	30	2
5	4	50	5	4	0	1	6	3	3	6	9	3
6	3	5	5	6	1	0	1	6	4	6	3	2
7	1	5	5	0	6	1	0	2	3	9	2	2
8	3	50	5	0	3	6	2	0	3	6	3	1
9	4	5	5	0	3	4	3	3	0	40	3	2
10	0	0	5	1	6	6	9	6	40	0	9	3
11	0	5	5	30	9	3	2	3	3	9	0	1
12	0	50	50	2	3	2	2	1	2	3	1	0

Table 2.7: ODU1 traffic matrix for the realistic network.

Through table 2.7 is possible to obtain the quantity of unidirectional ODU1 traffic in the network:

$T_1^1 = 394\text{x}2.5 = 985$ Gbits/s

ODU2	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	0	0	0	1	2	1	1
2	0	0	2	2	1	1	2	1	2	2	1	1
3	0	2	0	1	2	2	4	1	0	0	0	2
4	0	2	1	0	2	4	2	1	2	2	0	2
5	0	1	2	2	0	2	2	0	0	0	1	4
6	0	1	2	4	2	0	2	4	2	1	2	1
7	0	2	4	2	2	2	0	4	1	0	0	0
8	0	1	1	1	0	4	4	0	1	2	2	2
9	1	2	0	2	0	2	1	1	0	4	2	2
10	2	2	0	2	0	1	0	2	4	0	1	4
11	1	1	0	0	1	2	0	2	2	1	0	2
12	1	1	2	2	4	1	0	2	2	4	2	0

Table 2.8: ODU2 traffic matrix for the realistic network.

Through table 2.8 is possible to obtain the quantity of unidirectional ODU2 traffic in the network:
T_1^2 = 190x10 = 1 900 Gbits/s

ODU3	1	2	3	4	5	6	7	8	9	10	11	12
1	0	5	1	2	2	0	2	2	5	5	5	0
2	5	0	1	10	1	10	2	2	2	2	2	2
3	1	1	0	1	2	20	2	2	2	0	2	0
4	2	10	1	0	2	1	1	2	2	1	4	1
5	2	1	2	2	0	0	0	2	1	1	4	0
6	0	10	20	1	0	0	2	1	4	4	1	2
7	2	2	2	1	0	2	0	2	4	2	2	2
8	2	2	2	2	2	1	2	0	2	1	4	2
9	5	2	2	2	1	4	4	2	0	1	2	4
10	5	2	0	1	1	4	2	1	1	0	1	1
11	5	2	2	4	4	1	2	4	2	1	0	5
12	0	2	0	1	0	2	2	2	4	1	5	0

Table 2.9: ODU3 traffic matrix for the realistic network.

Through table 2.9 is possible to obtain the quantity of unidirectional ODU3 traffic in the network:
T_1^3 = 314x40 = 12 560 Gbits/s

$T_1 = 0 + 985 + 1\ 900 + 12\ 560 + 0 \sim 15$ Tbits/s
$T = 1000/2 =$ **7.5 Tbits/s**

Once again, as referred in the previous section the variable T_1^x represents the unidirectional traffic of the ODUx, for example, T_1^0 represents the unidirectional traffic of the ODU0 and T_1^1 represents the unidirectional traffic of the ODU1. The variable T_1 represents the total of unidirectional traffic that is injected into the network. Finally, the variable T represents the total of bidirectional traffic.

2.6 Chapter summary

An optical network is mainly composed of fiber-optic cables that carry channels of light, combined with the equipment deployed along the fiber to process it [2]. The two main concepts in optical network designing are the physical and logical topologies of the network, on which directly depend their capabilities. The layout of the network, i.e., the physical locations of the node sites and connections between them define the physical topology, on the other hand, the logical topology represents an upper layer that defines how the elements of the network may be optically connected between each other, and as such, different logical topologies are related to how the optical signal can propagate in the network [19]. In this dissertation only the transparent transport mode is addressed, where every node is directly connected to all others, meaning that the signal propagates from its source node to the respective destination node always in the optical domain, without suffering O-E-O conversions and so a single-hop grooming scheme is applied. This so called optical-bypass can cause significant savings on the electrical components of a node. The calculation of the CAPEX values of a network can be performed recurring to various methods, in this chapter was analyzed an analytical, an ILP and a heuristic model and applied to the study of both a reference and a realistic network.

Chapter 3

Generic Heuristics Framework

In this chapter, is intended to perform a detailed description of the generic framework here created, in order to test the different heuristic algorithms developed along this dissertation. This chapter begins by providing a global description of the created framework in section 3.1 and by presenting a flowchart explaining how it works. In the remaining sections, a detailed description is provided on every individual main entity of the framework. In section 3.2 is addressed the scheduler block, in section 3.3 the logical topology generator, in section 3.4 the physical topology generator, in subsection 3.5 the logical topology manager and finally, in section 3.6 the physical topology manager.

3.1 General Description

The key role of frameworks, in general, is to permit developers to address only project relative needs rather than the low level phases of working systems, resulting in reduced times for development tasks. Speaking more specifically about the framework here created, it consists in a conceptual structure composed of a set of different layered entities which provide generic functionality while also being able to be selectively changed, thus enabling the possibility of future improvement by introducing new and more complex features and considerations of real worldwide networks. This framework was intended to serve as a support for the complex problem of dimensioning optical transparent networks. In figure 3.1 a top level diagram of the developed platform, in which the heuristic algorithms were later implemented, is provided. In this flowchart, as well as for the remaining in this chapter, the rectangle shapes represent the main entities of the framework, the diamond shapes symbolize decision points and the rounded rectangle shapes symbolize the system entry parameters.

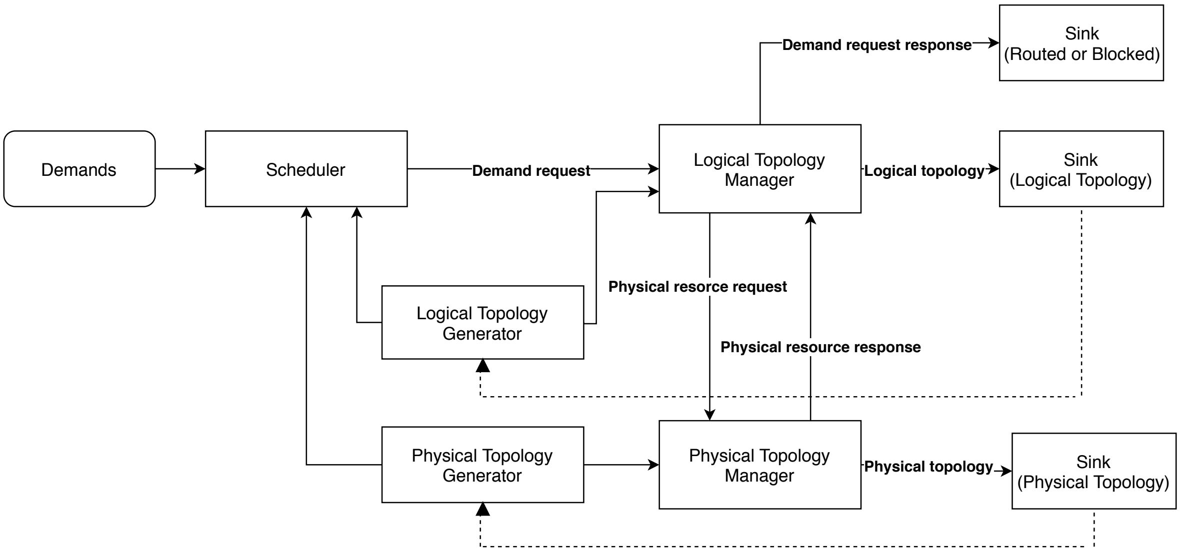

Figure 3.1: Top level diagram of the developed framework. The solid lines represent vital connections between blocks as well as the flow of information, on the other hand, the dashed lines represent possible but non obligatory connections, since the framework runs correctly with or without them. They provide the possibility of starting a simulation by creating a void physical and/or logical topology or to load a previous state.

When there is one or multiple traffic demands to be processed initially they must be sorted in a scheduler block, according to a predefined rule. Thereafter, the demands are sent one by one into a logical topology manager block where either an already existent capacity is used to route the demand or a request is made to create the capacity. That request is sent to a physical topology manager, where the information about the network physical links capacity is stored, and depending on the existence of remaining capacity, between other aspects, a response is given back to the logical topology manager regarding the possibility or not to route the demand. Finally, the useful information contained on the logical and physical manager blocks, as well as the information regarding the status of each processed demand, can be stored in sink blocks also presented in the diagram above.

3.2 Scheduler

When using global optimization techniques such as integer linear programming, the order of the demands becomes not relevant, once every possible scenario is tested, however, this is not the case since in this dissertation we are considering heuristic approaches. Having that said, before the traffic demands can be processed a scheduler block is needed, which will be responsible for the creation of an ordered queue based on specific predefined criteria. That same order becomes the order by which demands will be processed, and so ultimately routed or blocked. Demands can be sorted in many different ways when recurring to different strategies, which may potentially affect the efficiency of the routing and grooming processes. Therefore, different methods usually also have different impacts on the cost of the network, the loading in the network and the blocking probability.

3.3 Logical Topology Generator

Based on the physical topology adjacency matrix of the network and the transport mode utilized a new upper layer can be created, the logical topology. Each node may be optical directly connected to each other, only optical connected to adjacent nodes or optical connected to suitable nodes. Between directly interconnected nodes a lightpath can be established, in which the information is carried. This variety of possible optical paths along the route imposed by logical topology lead to a situation of three possible transport modes: opaque, transparent or translucent [19]. In this block the initial logical topology must be created and sent to a logical topology manager block where the routing and grooming heuristic algorithms, that depend directly of the logical topology, are implemented and will be continually updated as demands are processed. Once again, the dashed lines presented in figure 3.1 symbolize the ability of a logical topology generator block to create the logical topology either void, when no previous information is provided, or by loading a previous network state, where there were already demand requests being supported and as such some lightpaths had already been established.

3.4 Physical Topology Generator

Here, is created the initial physical layer of the network. It consists mainly in a set of physical links, which may interconnect a pair of nodes and can be expressed as being uni or bidirectional, in such a way, that each of the transmission systems that support the links are comprised of a unique fiber or a pair of fibers transmitting in opposite directions, respectively. Once more, the dashed lines presented in figure 3.1 symbolize the ability of a physical topology generator block to also create the physical topology either void, when no previous information is provided to it, or by loading a previous network state where there were already demand requests being supported and as such some physical capacity had already been reserved.

3.5 Logical Topology Manager

In this block the initial logical layer, originating from a logical topology generator block, is stored and continuously updated as demands are processed. The grooming and part of the routing algorithms should be implemented here and they can assume many different strategies.

The current logical layer state of the network is accessible from this block and can contain information of the existent paths and the respective lightpaths that comprise them, between others. While processing a demand if there is no available path available for it then a new should be selected, based on a defined routing strategy, and a request sent to the physical topology manager in order to verify the possibility of establishing that path. Depending on the physical topology manager response either a path is created and the demand routed or, in the case it is not possible to do so, the demand remains blocked. Only a demand request serves as input for this entity but on the other hand the outputs can differ as they can represent a request to establish a new path, sent to the physical topology manager of the network, or simply the information about whether or not a demand was routed, sent to a sink block.

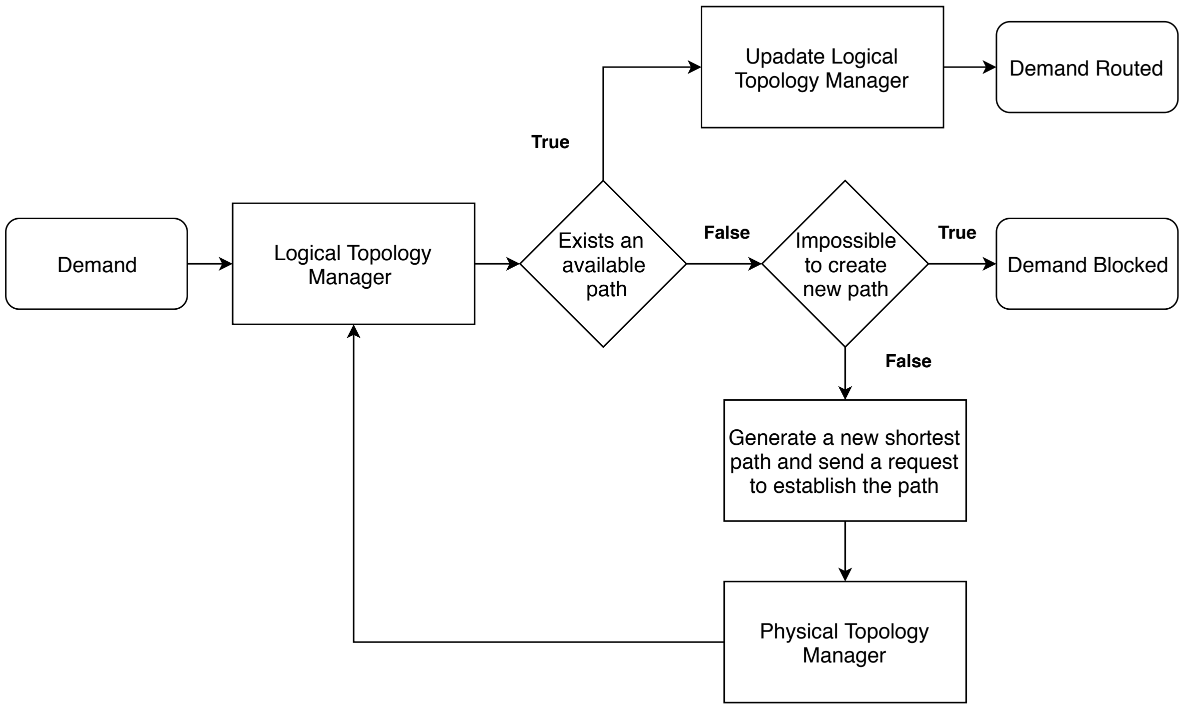

Figure 3.2: Flowchart representing the interaction between the logical and physical topology manager entities while processing a demand request.

3.6 Physical Topology Manager

The main function of this block is to administrate the physical layer of the network and inform the logical topology manager of the available physical capacities of all the links necessary to establish paths. When a path is selected for a demand in the logical layer, through a routing algorithm, a request is made for it and sent here. That path must be broken into sub-connections, i.e. lightpaths, if necessary, and each of the lightpaths assigned with a wavelength if possible. Thus, the wavelength assignment strategy should be applied here. The need of wavelength continuity arises for optical-bypass-enabled networks and as such, this property is tightly coupled to the routing process, as the selection of the route determines the links on which a free wavelength must be found [2]. However, there is the possibility of none feasible wavelength to be found for one or more of the lightpaths, resulting in the occurrence of the wavelength contention phenomenon. Due to the possible loss of network efficiency, caused by wavelength contention situations, this is a problem that must be carefully addressed.

3.7 Chapter summary

In this chapter are introduced some concepts regarding the created framework and the constituting entities are summarize in terms of features and possibilities provided. A flowchart is also provided where is represented the interaction between the two main entities of the framework (logical and physical topology managers), while processing a single traffic request. Although in this dissertation, is only addressed the problem of transparent networks, it is important to notice that the framework was developed to allow a more generic use, it provides the possibility of future improvements in order to contemplate other realistic network scenarios, for example other transport modes or the existence of protected traffic.

Chapter 4

NetXPTO Implementation

This chapter consists in an overview of the created platform, in which the developed heuristic algorithms were implemented. The starting point was the NetXPTO-Netplanner open source simulator, which is a real-time simulator that allows the creation of generic systems comprised of a set of blocks that interact with each other through signals. The NetXPTO-NetPlanner has been developed by several people using git as a version control system and its repository is located in the GitHub site https://github.com/netxpto/NetPlanner. This chapter is organized in six subsections where a general description is given on how the platform was implemented and on how it operates in practical terms. In section 4.1 is presented an explanation on which are the accepted entry parameters of the system and how they can be provided, on section 4.2 is addressed the functionality of the log file and how to access it and on section 4.3 the type of existent signals and which information they carry and share between blocks. On section 4.4 a generic description is given on how to interpret the final report generated by the system after running each simulation and finally more generic information about each block input parameters/signals, state variables and output signals is present in section 4.5.

4.1 Input Parameters System

The execution of a simulation is mainly based in three files. Initially, there is an **input_parameters_values.txt** file, which contains all the entry variables that the system needs in order to run correctly, however, if any of the variables is missing or incorrectly declared then the default value defined for that variable is considered, they can be consulted below in table 4.1. There is also an executable file named **transparent.exe** generated after compiling the project, which will load the entry variables values from the previously mentioned text file, run the simulation and later on print the final results in an other text file, **FinalReport.txt**.

The purpose of this section is to describe the Input Parameters System (IPS) which enables the reading of input parameters values from any text file.

4.1.1 Entry variables

The system input parameters are described below in table 4.1 and their respective default values are given.

Parameter	Default value	Description
numberOfNodes	0	Number of existing nodes in the network.
odu0	[0]	N by N matrix containing ODU0 demands.
odu1	[0]	N by N matrix containing ODU1 demands.
odu2	[0]	N by N matrix containing ODU2 demands.
odu3	[0]	N by N matrix containing ODU3 demands.
odu4	[0]	N by N matrix containing ODU4 demands.
orderingRule	descendingOrder	descendingOrder (ODU4...0) ascendingOrder (ODU0...4)
transportMode	transparent	This dissertation focus only on the transparent mode approach
physicalTopologyAdjacencyMatrix	[0]	N by N matrix containing existent physical connections between nodes.
numberOfTSPerLink	1	Number of transmission systems existing in each physical link.
numberOfOpticalChannelsPerLink	100	Number of optical channels per physical link.
initialWavelenght	1550	Initial value of the wavelength used expressed in nanometers.
wavelengthSpacing	0.8	Interval between used wavelengths. (nm)
opticalChannelCapacity	80	Physical capacity of each optical channel expressed in number of ODU0 demands.
distancesBetweenNodes	[0]	N by N matrix containing distances between node sites.
routingCriterionLogicalTopology	Hops	Shortest path type.
routingCriterionPhysicalTopology	Hops	Shortest path type.
blockingCriterionLogicalTopology	1	Number of shortest logical paths generated by the routing algorithm.
blockingCriterionPhysicalTopology	3	Number of shortest physical paths generated by the routing algorithm.

Table 4.1: System input parameters.

4.1.2 Format of the Input File

The input file to run this simulator must respect the following properties:

1. Input parameter values can be changed by adding a line in the following format: **paramName=newValue**, where paramName represents the name of the input parameter and newValue the value to be assigned.

2. In the case of an input paramenter of the matrix type, ODU traffic matrices and/or physical and logical topologies, newValue will assume the value of existing elements per line or column and the matrix value must be specified below this line.

3. If an input parameters is assigned the wrong type of value, method readSystemInputParameters() will throw an exception.

4. In the case and input parameter is not assigned with a specific value it will assume the default value.

5. The IPS supports comments in the form of the characters //. The comments will only be recognized if placed at the beginning of a line.

An example of the **input_parameters_values.txt** used to load values into the simulator, for a network with 6 nodes, is shown below.

```
//############################## NUMBER OF NODES ##########################################
numberOfNodes=6
//################### PHYSICAL TOPOLOGY ADJACENCY MATRIX ############################
physicalTopologyAdjacencyMatrix=6
0 1 0 0 0 1
1 0 1 0 0 1
0 1 0 1 1 0
0 0 1 0 1 0
0 0 1 1 0 1
1 1 0 0 1 0
//######################## DISTANCES BETWEEN NODES (km) ############################
distancesBetweenNodes=6
0 350 0 0 0 150
350 0 400 0 0 120
0 400 0 250 100 0
0 0 250 0 200 0
0 0 100 200 0 600
150 120 0 0 600 0
//############################### SPAN (km) ########################################
span=100
//############################## NUMBER OF TS PER LINK ##################################
```

```
numberOfTSPerLink=1
//#################### NUMBER OF OPTICAL CHANNELS PER LINK #######################
numberOfOpticalChannelsPerLink=100
//########################## INITIAL WAVELENGTH (nm) #############################
initialWavelenght=1550
//###################### WAVELENGHT SPACING IN NANOMETERS ########################
wavelenghtSpacing=0.8
//#################### OPTICAL CHANNEL CAPACITY IN ODU0 ##########################
opticalChannelCapacity=80
//##############################################################################
//########################## TRAFFIC MATRIX ######################################
//##############################################################################
//############################### ODU0 ###########################################
odu0=6
0 10 2 6 2 6
10 0 0 2 10 0
2 0 0 2 8 2
6 2 2 0 2 2
2 10 8 2 0 6
6 0 2 2 6 0
//##############################################################################
//############################# OTHER ODU MATRICES ###############################
//##############################################################################
//############################# ORDERING RULE ####################################
orderingRule=descendingOrder
//############################# TRANSPORT MODE ###################################
transportMode=transparent
//#################### ROUTING CRITERION LOGICAL TOPOLOGY ########################
routingCriterionLogicalTopology=hops
//################### BLOCKING CRITERION LOGICAL TOPOLOGY ########################
blockingCriterionLogicalTopology=1
//################### ROUTING CRITERION PHYSICAL TOPOLOGY ########################
routingCriterionPhysicalTopology=hops
//################### BLOCKING CRITERION PHYSICAL TOPOLOGY #######################
blockingCriterionPhysicalTopology=3
```

Listing 4.1: input_parameters_values.cpp code

4.1.3 Loading Input Parameters From A File

Execute the following command in the Command Line:

transparent.exe<input_file_path><output_directory>

where transparent.exe is the name of the executable generated after compiling the project, <input_file_path> is the path to the file containing the new input parameters;

<output_directory> is the directory where the output signals will be written into. The final report file, **FinalReport.txt**, will be written the directory of the project itself.

4.2 Log File

The Log File allows for a detailed analysis of a simulation. It will output a file named **log.txt** containing the timestamp of when a block is initialized, the number of samples in the buffer ready to be processed for each input signal, the signal buffer space for each output signal and the amount of time in seconds that took to run each block. This will occur in each and every cycle until the system terminates the simulation.

4.3 Type signals structure

4.3.1 Logical Topology

A Logical Topology type signal contains numerous data structures that comprise the logical layer of the network. Below those structures are represented.

Logical Topology Adjacency Matrix

The possible logical connections between a pair of nodes is demonstrated below on table 4.2, where 1 and 0 represent the existence or not of a connection, respectively.

Nodes	1	2	...	N
1	**0**	0/1	...	0/1
2	0/1	**0**	...	0/1
⋮	⋮	⋮	⋱	⋮
N	0/1	0/1	...	**0**

Table 4.2: Allowed logical topology for a network of N nodes.

Here, value N represents the number of nodes present in the network. During this dissertation, the focus was on the transparent mode, where each node connects to all others creating direct logical links between all nodes of the network. The next considered variables are distributed in an hierarchical way as a path consists in one or more lightpaths which in its own turn are formed by one or more optical channels from distinct physical links.

Path

Path Index	Source Node	Destination Node	Capacity (ODU0s)	Number of Lightpaths	Lightpaths Index
Integer (>=0)	1...N	1...N	Integer (>0)	Integer (>=0)	[lp_1, lp_2, ...]

Table 4.3: Structure of a "Path" variable.

It represents a unique route identified by an index, containing one or more lightpaths and assigned to specific connection request, where for example lp_1 and lp_2 represent the lightpaths with index number 1 and 2, respectively. The capacity available of each path is given in terms of quantity of ODU0 demands.

Lightpath

Lightpath Index	Source Node	Destination Node	Capacity (ODU0s)	Number of Optical Channels	Optical Channels Index
Integer (>=0)	1...N	1...N	Integer (>0)	Integer (>=0)	[och_1, och_2,...]

Table 4.4: Structure of a "Lightpath" variable.

It represents a set of one or more optical channels that transport information, from source to the destination node, while forcing data to remain in the optical domain without any O-E-O conversion in between [22]. Each lightpath is identified by an unique index and its capacity is also expressed in quantities of ODU0 demands. The number and the indexes of the optical channels that comprise each lightpath are provided, where variables och_1 and och_2 represent the optical channels with index number 1 and 2, respectively.

Optical Channel

Optical Channel Index	Source Node	Destination Node	Capacity (ODU0s)	Wavelenght (nm)	Number of Demands	Demands Index
Integer (>=0)	1...N	1...N	Integer (>=0)	Real(>0)	Integer (>=0)	[d_1, ...]

Table 4.5: Structure of an "Optical Channel" variable.

Each optical channel is identified by an unique index. The wavelength used in each channel is expressed in terms of nanometers (nm) and the number of demands carried through as well their index is recorded. Here d_1 represents the demand with index number 1.

4.3.2 Physical Topology

The allowed physical topology is defined by the duct and sites in the field [7]. It is assumed that each duct supports up to 2 unidirectional fiber links that together will behave like a bidirectional connection between a pair of nodes. Also each site supports up to 1 node. Below are represented the data structures that comprise signals of this type.

Physical Topology Adjecency Matrix

Nodes	1	2	...	N
1	**0**	0/1	...	0/1
2	0/1	**0**	...	0/1
⋮	⋮	⋮	⋱	⋮
N	0/1	0/1	...	**0**

Table 4.6: Allowed physical topology for a network of N nodes.

Here, the value 1 simply indicates the existence of a physical link between a pair of nodes and 0 symbolizes the absence of it.

Link

Based on the physical topology adjacency matrix variable another data structure is created for each of the existent physical links.

Link Index	Source Node	Destination Node	Number of Wavelengths	Wavelengths	Available Wavelengths	Amplifiers
0...L-1	1...N	1...N	OC	[w_1, w_2, ...]	[0/1 ... 0/1]	Integer (>=0)

Table 4.7: Structure of a "Link" variable.

where:

- OC → Number of existent optical channels in a link
- L → Number of unidirectional links in the network
- w_1 → Wavelength value with the index number 1 associated

Once again, 1 and 0 indicates if the corresponding wavelength value is available or already being used, respectively. Other aspects as the quantity of wavelengths available per fiber, as well as its values, should also be discriminated. Regarding the capacity of each optical channel/wavelength, it can be expressed in different formats, for example, in terms of Gbit/s or in terms of the ODU0 demands, the lower unit of traffic considered. Finally, the number of needed amplifiers will depend of the length of the link and the assumed span value.

4.3.3 Demand Request

Demand Index	**Source Node**	**Destination Node**	**ODU Type**	**Survivability Method**
0...D-1	1...N	1...N	0...4	none protection_1_plus_1 restoration

Table 4.8: Constitution of a 'Demand Request' type signal.

A "Demand Request" type signal stands for a unique traffic request, where D represents the total number of demand requests entering the network. It is possible to know the number of total unidirectional demands once we are dealing with static traffic and so all the traffic requests are known. In the situation where all requests for traffic are not known, the traffic is said to be dynamic. Regarding the survivability method, in this dissertation the work developed only considered the existence of none.

4.3.4 Path Request

Request Index	Demand Index	ODU Type	Source Node	Intermediate Nodes	Destination Node
Integer (>=0)	0...D-1	0...4	1...N	1...N	1...N

Table 4.9: Constitution of a "Path Request" type signal.

A "Path Request" type signal is sent with an unique identifying index, from the logical topology manager block to the physical topology manager block asking for a path to be created between the source and destination nodes of a demand. In order establish that path, one or more lightpaths may be required, in the case there are intermediate nodes. In this specific case, transparent transport mode, only direct logical connections are taken into account, once, as previously mentioned, the information has to travel in the optical domain from source to destination, and so all paths created will be formed by only one direct lightpath. This means that in this specific scenario there will be no intermediate nodes, and when this happens the assumed value for this variable will be -1.

4.3.5 Path Request Routed

A "Path Request Routed" type signal contains the response from the physical topology manager block to a "Path Request" signal, indicating whether or not it is possible to establish a path requested for a demand. It is formed by the following data structures specified in tables 4.10 and 4.11.

Path Information

Request Index	Demand Index	ODU Type	Routed	Number of Lightpaths
Integer (>=0)	D-1	0...4	True or False	Integer greater or equal to 0

Table 4.10: Structure of a "Path Information" variable.

Lightpaths Table

Source Node	Destination Node	Number of Intermidiate Nodes	Intermediate Nodes	Wavelenght
1...N	1...N	0...N-2	[1...N ... 1...N]	W
...	...	...	...	...

Table 4.11: Structure of a "Lightpaths Table" variable.

Here, W represents the actual value of the wavelength assigned to a lightpath. This type of signal possesses a "Request Index" variable that identifies these signals as a response to the "Path Request" signal with the same index. It is also formed by one boolean variable, "Routed", which will return true in the case a demand is routed correctly through the network, validating the remaining information fields of the signal, or false in the case it is not, which means no path was possible to be established in order to route the demand and so the other fields of this signal will be void or filled with invalid information.

4.3.6 Demand Request Routed

Demand Index	Routed	Path Index
0...D-1	True or False	Integer (>=0)

Table 4.12: Structure of a "Demand Request Routed" type signal.

This signal contains information regarding a demand, properly identified through the "Demand Index" variable, that has already been processed and so it contains a variable "Routed" which informs the user about whether the demand was routed or blocked. In the case the demand was correctly routed, this boolean variable assumes a true value and the path used is identified through "Path Index" variable.

4.4 Final Report

After running a simulation a text file named **FinalReport.txt** is generated, in the same directory of the project, containing the final results. Detailed information regarding the network nodes and links constitution, a routing scheme of the demands processed and the final CAPEX values obtained for the network are presented in this file. In section 6.1.3 is provided the information contained in this files for each different tested scenario.

```
--------------------------------------------------------------------------------
|                        Information regarding links                           |
--------------------------------------------------------------------------------
|     Unidirectional link     |      Optical channels      |     Amplifiers     |
--------------------------------------------------------------------------------
         Node 1 <-> 2                      3                        3
         Node 1 <-> 6                      2                        1
         Node 2 <-> 3                      6                        3
         Node 2 <-> 6                      4                        1
         Node 3 <-> 4                      3                        2
         Node 3 <-> 5                      3                        0
         Node 4 <-> 5                      2                        1
         Node 5 <-> 6                      5                        5
--------------------------------------------------------------------------------

--------------------------------------------------------------------------------
|                            Information regarding nodes                        |
--------------------------------------------------------------------------------
|                       |        Electrical part         |     Optical part     |
--------------------------------------------------------------------------------
| Node | Nodal degree | Tributary ports |Transponders| Add ports | Line ports |
--------------------------------------------------------------------------------
   1          2              56                 5            5          5
   2          3              46                 7            7          13
   3          3              36                 6            6          12
   4          2              40                 5            5          5
   5          3              48                 8            8          10
   6          3              44                 9            9          11
--------------------------------------------------------------------------------
```

Listing 4.2: Partial example of a FinalReport.txt file.

4.5 Practical Implementation

This section serves the purpose of displaying how the framework created in chapter 3 was built in more practical terms. Starting by table 4.13 where the input variables and signals of all the implemented blocks are presented.

Block	Input Parameters	Input Signals
Scheduler_	numberOfNodes, odu0, odu1, odu2, odu3, odu4, orderingRule	None
LogicalTopologyGenerator_	transportMode, physicalTopologyAdjacencyMatrix	None
PhysicalTopologyGenerator_	physicalTopologyAdjacencyMatrix, numberOfTSPerLink, numberOfOpticalChannelsPerLink, initialWavelenght, wavelenghtSpacing, opticalChannelCapacity, distancesBetweenNodes	None
LogicalTopologyManager_	routingCriterionLogicalTopology, blockingCriterionLogicalTopology	Scheduler_DemandRequest, InitialLogicalTopology, PhysicalTopologyManager_PathRequestRouted
PhysicalTopologyManager_	routingCriterionPhysicalTopology, blockingCriterionPhysicalTopology	InitialPhysicalTopology, LogicalTopologyManager_PathRequest
SinkRoutedOrBlocked_	None	ProcessedDemand
SinkLogicalTopology_	None	FinalLogicalTopology
SinkPhysicalTopology_	Node	FinalPhysicalTopology

Table 4.13: Blocks input parameters and signals.

Below in table 4.14 are specified the state variables and signals of all the implemented blocks.

Block	State Variables	Output Signals
Scheduler_	odu0, odu1, odu2, odu3, odu4, demandIndex, numberOfDemands	Scheduler_DemandRequest
LogicalTopologyGenerator_	generate	InitialLogicalTopology
PhysicalTopologyGenerator_	generate	InitialPhysicalTopology
LogicalTopologyManager_	paths, lightPaths, opticalChannels, logicalTopologyAdjancencyMatrix	LogicalTopologyManager_PathRequest, ProcessedDemand, FinalLogicalTopology
PhysicalTopologyManager_	Link, Physical Topology Adjacency Matrix	PhysicalTopologyManager_PathRequestRouted, FinalPhysicalTopology
SinkRoutedOrBlocked_	None	None
SinkLogicalTopology_	None	None
SinkPhysicalTopology_	None	None

Table 4.14: Blocks state variables and output signals.

Finally, in figure 4.1 is presented a detailed scheme regarding the practical implementation of the framework discussed in chapter 3. The blocks that comprise the system are represent by rectangular shapes and identified according to their respective name, the signals are represented by flow lines that connect the blocks and are properly identified both by their name and the type of signal. Finally, the entry parameters are represented by parallelogram shapes and again are also identified by the respective names, present in table 4.1.

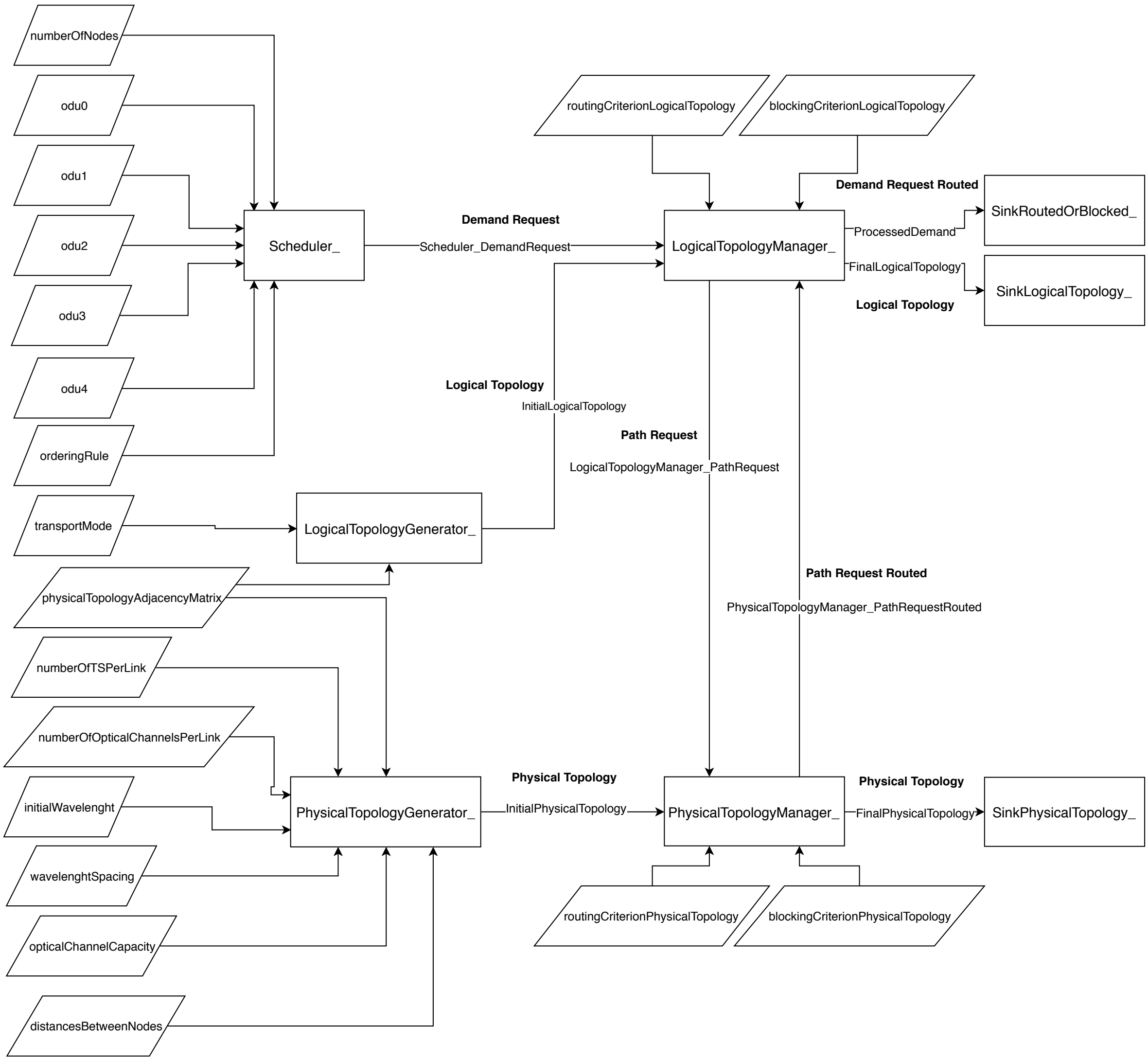

Figure 4.1: Final scheme of the implemented platform.

4.6 Chapter summary

The framework described in the previous chapter 3 was implemented over the NetXPTO-Netplanner simulator. In this chapter is intended to provide a general guideline to simplify its generic use for other users. Starting by a simple explanation of the simulator entry parameters, their meaning and the format in which they are accepted by the system. The various data structures that comprise the different existent signal types are approached and finally is addressed the final report generated by the simulator in the end of each simulation, on which the heuristic results presented in chapter 6 are based.

Chapter 5

Heuristic algorithms

Heuristic algorithms are approaches designed for solving a given problem in a faster and more efficient fashion than traditional methods by trading optimality, accuracy, precision, or completeness for speed [23]. Are often used to solve problems where there is no known efficient way to find a solution quickly and accurately once they have low time complexity [23]. Also they are able to produce a solution individually or to be used to provide a good baseline when supplemented with optimization algorithms [24]. There are many commonly used heuristics such as genetic algorithms, artificial neural networks and support vector machines [23]. When networks are too large, the dimensioning problem becomes too complex and so the ILP models can be very slow to obtain the solution, whereas heuristic solutions lead to good performances in practical network scenarios when presented a sufficiently feasible solution, instead of an optimal solution. Therefore, this chapter is organized in five subsections where some heuristic algorithms are proposed with a final major objective of minimizing the total CAPEX of a network. In subsection 5.1 some sorting methods are approached, in subsection 5.2 is addressed the conversion from the physical to the logical topology of a network and the respective implications, in subsection 5.3 various routing strategies are debated and an explanation is given over the chosen method and in subsection 5.4 the grooming strategy utilized is explained. Finally, in subsection 5.5 the possible wavelength assignment methods are discussed as well as some of the implications. The created algorithms in this dissertation were all developed in C++ language with the aid of Visual Studio IDE and some of the pseudo code developed for these algorithms is also shown below into various flowcharts which use rounded rectangle shapes to symbolize the beginning or the end of the program, parallelogram shapes to indicate a point where there is an input to the program, diamond shapes symbolizing decision points and rectangle shapes representing a whole variety of processes, such as, a simple assignment of a value to a variable, constant or parameter.

5.1 Scheduling

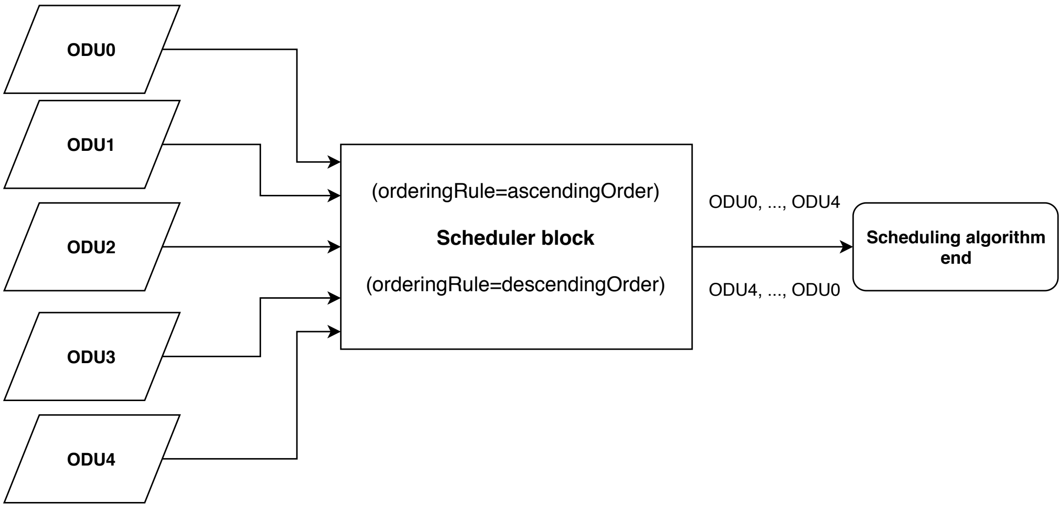

Figure 5.1: Scheduler algorithm illustration considering both ordering rules.

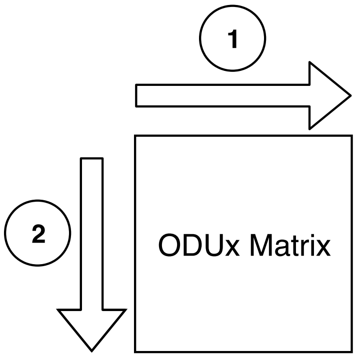

Figure 5.2: Illustration of the order by which an ODUx traffic matrix is searched through.

There are many different possible strategies that can be used for traffic ordering purposes. Most may rely individually on the quantity of traffic of each request, the traffic granularity, the length of the shortest logical or physical paths either in terms of distance or hops, the need of protection paths, the quality of the path set in terms of desirable path options or a smart combination of some of this aspects [2]. Other ordering strategies are also possible and in general none of them reclaims the best results for every practical scenario. In this specific scenario, as it is shown above in figure 5.1 by choosing an ascending ordering rule the first demands to be processed will be of the ODU0 type, followed by ODU1, ODU2, ODU3 and finally ODU4. If on the other hand, it is chosen the descending ordering rule then demands will be processed in the backwards order. The chosen criteria for test performing purposes was the descending ordering rule since demands that require bigger bandwidths become harder to accommodate and thus should be the first ones to be processed in order to guarantee the assignment of the optimal paths. Additionally, the way that each of the ODU demand matrices are searched through can be seen in figure 5.2, from left to right the demands originating in node one are the firsts to be processed and so on to the last node of the network. It is assumed that although multiple demands can be added at once till the network, each demand is processed individually before moving on to the next.

5.2 Logical Topology

As in this dissertation only the transparent transport mode is considered, then the logical and physical topologies will differ from each other since the first one will be a full mesh network [19]. Below in figure 5.3 there is a graphical representation of the logical topology for the reference network considered in this dissertation.

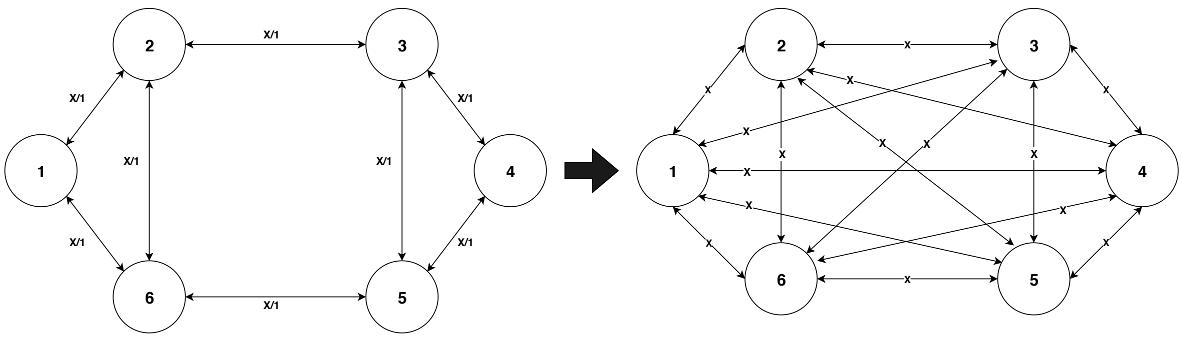

Figure 5.3: Logical topology algorithm: conversion from physical topology (left side) to the logical topology (right side) for transparent transport mode.

5.3 Routing

Routing is the process of assigning a unique path through the network for a demand request between the source and destination nodes [2]. The first step to take into account when a demand is received by the network is to search in the logical topology manager block for a prior existent path between the same source/destination combination with remaining available capacity to route this demand. If there is any path with the characteristics described above then the same is re utilized to forward the demand, having no need to communicate with the physical topology manager block. In this case only the remaining capacity of the path needs to be updated. If on the other hand, there is no desirable path then a new one must be created to answer this demand request and if there is no possible way of establishing a new path then the demand request is blocked by the network. Below in sections 5.3.1 and 5.3.2 the steps taken to create and test a path for a demand are analysed in more detail.

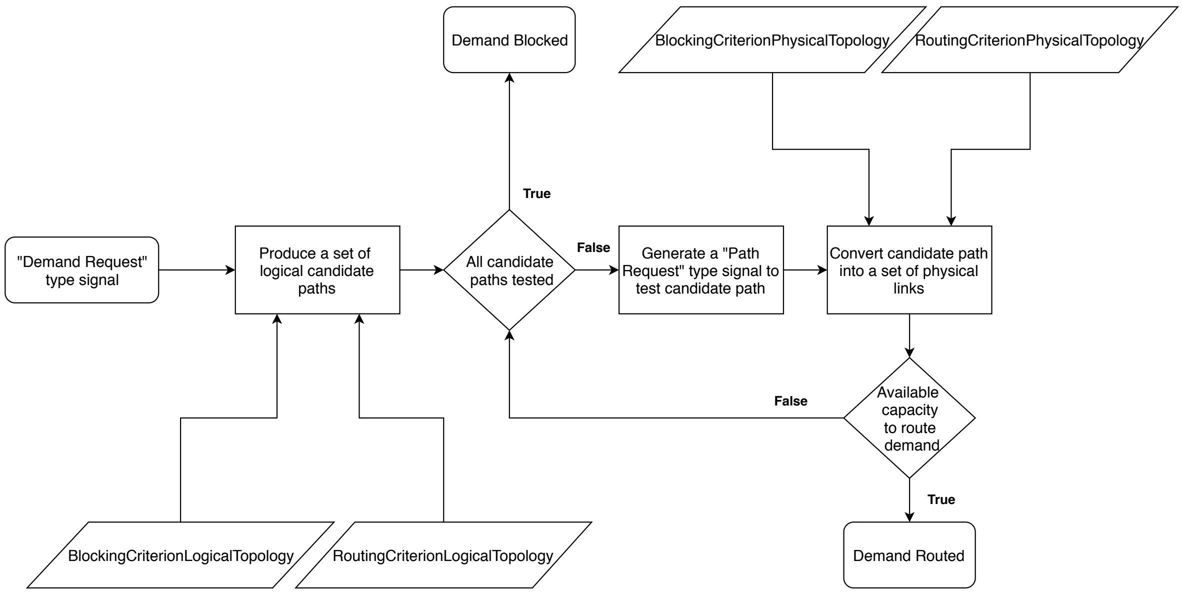

Figure 5.4: Routing algorithm code flow.

5.3.1 Producing a set of candidate paths

The routing strategy applied incorporates the use of a K-shortest path algorithm, based on Dijkstra's algorithm, in order to find the K-shortest paths between a source and a destination node [2]. The number of paths generated both on the physical and logical layers will depend directly on the user preference. In transparent networks, where optical bypass is enabled, the need for optical regeneration favors in a way the use of distance as a metric to select the shortest paths. However, in this systems there is another major constraint to be considered which is the need for wavelength continuity, which means that a signal travelling from a source to a destination node must remain in the same wavelength as it optically bypasses intermediate nodes [2]. Thus, arises another problem, finding a common available wavelength in all the constituting links of a path. The difficulty and complexity of achieving this escalates significantly as the number of links in the path increases as it shall be analysed further in section 5.5. As such, it was decided to use the number of hops as the metric to find the shortest paths in the studies conducted. Other concerns, such as, considering a bottleneck-avoidance strategy in the routing stage to generate shortest paths with good link diversity could have been taken into account if not for simplicity reasons.

5.3.2 Selecting a candidate path

In this step it was used a dynamic-path routing strategy to the detriment of other strategies such as fixed or alternative-path routing, once it provides adaptability to network conditions [2]. There is no prior determination of the paths to be used for a demand request between a given source and destination nodes. That calculation is performed when a demand request is received and it depends only of the current logical and physical topology states of the network. In the case a given logical or physical links have insufficient capacity to carry the new demand they should be momentarily withdrawn from the network topology so that in further iterations new demand requests that require the same capacity (same ODU type) don't consider those links while generating the set of candidate paths. After the topology has been trimmed based on the current network state the K-shortest paths algorithm can be applied [2].

5.4 Grooming

As the majority of the traffic going through the network usually requires a minor bit-rate than of a full wavelength, i.e., line-rate traffic, a necessity arose for a process capable of diminishing the percentage of wasted wavelength capacity, making networks more efficient [2]. This process is named grooming, which is a simple way of grouping sub-rate traffic in order to better utilize networks capacity. In transparent networks the type of grooming performed is called end-to-end multiplexing, where traffic demands are packed into wavelengths and processed as a single unit from source to destination [2]. In this transport mode demands may only ride together if the pair of source and destination nodes is the same.

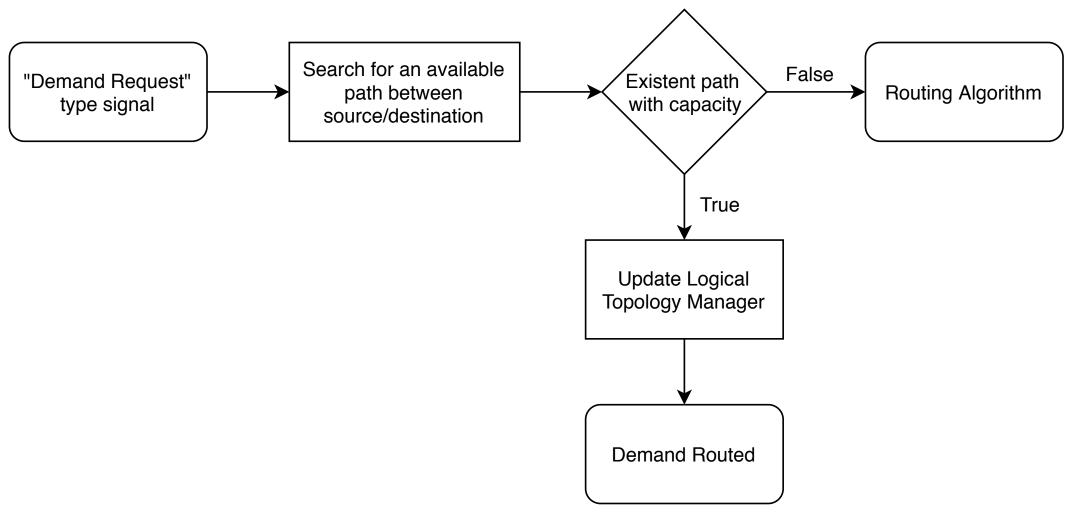

Figure 5.5: Grooming algorithm code flow.

In the framework discussed in chapter 3 the grooming stage occurs in the logical topology manager, where a demand being processed looks for an available path between the same pair of source and destination nodes, previously established and still with sufficient remaining capacity. If such a path exists than it will be re-utilized in order to route this demand and its capacity is refreshed but if not than the routing algorithm must be applied.

5.5 Wavelength Assignment

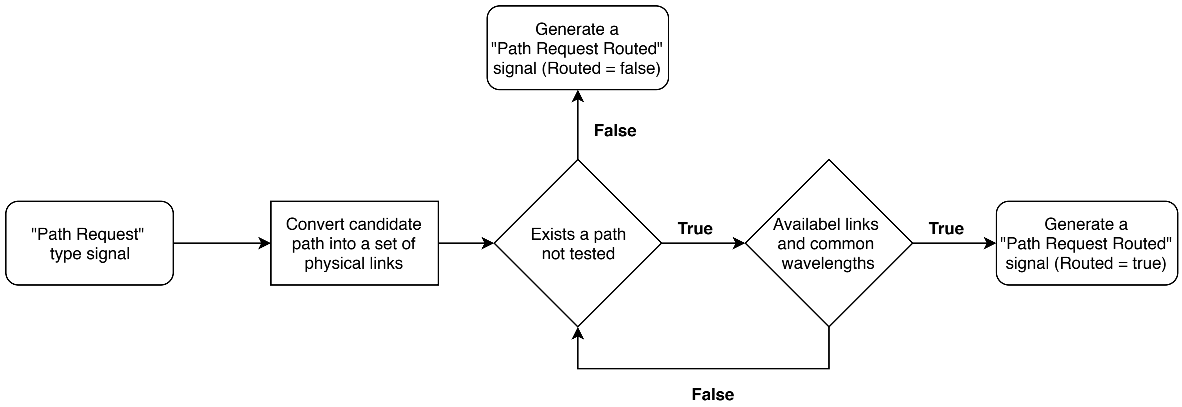

Figure 5.6: Wavelength Assignment algorithm code flow.

This is one crucial step in transparent networks planning once they require wavelength continuity in all nodes from source to the destination, meaning that signals entering a source node are kept in the optical domain at every intermediate nodes of the path until reaching its destination [2]. O-E-O conversions are only performed in end nodes, therefore, the wavelengths that are in use in a particular link may have influence on the wavelengths that can be assigned to other links. This step follows the routing process. Thus, wavelength assignment is a major issue in optical-bypass networks once a poor routing strategy can lead to a situation of wavelength contention provoking the loss of network efficiency as demands are blocked instead of being routed. Another relevant aspect is how to choose the wavelength to assign to a certain connection from the set of all wavelengths supported on a fiber. The strategy adopted in this dissertation is commonly know as First-Fit[2], but other methods could also be applied, such as:

- Most-Used.
- Relative Capacity Loss.
- Qualitative Comparison.

First-Fit was chosen for being the simplest of all these wavelength assignment schemes mentioned. Every wavelength has an associated index and the one with the lowest index is selected from the set of the available wavelengths. This strategy does not require global knowledge about the network and as the computational overhead is small and the complexity low the performance in terms of wavelength contention is among the best [25].

5.6 Chapter summary

Many heuristic algorithms were implemented and tested along this dissertation. Starting by the scheduling algorithm, a very simplistic and straightforward strategy was implemented based only on the traffic quantity of each individual demand request. Although it has some advantages, like the minimum computational effort and time efficiency, it won't provide the best solutions for every practical scenario. In terms of routing, a dynamic-path routing strategy incorporating a K-shortest path algorithm was chosen once it provides adaptability to network conditions, which allows the avoidance of heavily loaded links, thus, lowering the blocking probability of the network. As the only the transparent transport mode was addressed the choice of the grooming strategy was bounded to an end-to-end single hop scheme. Finally, regarding the wavelength assignment process a first-fit strategy was adopted for its simplicity, low computational complexity and proper performance.

Chapter 6

Results

The focus of this current chapter is to propose and describe the results obtained, regarding the network CAPEX, for both the analytical and the heuristic models here proposed and the ILP model used from a previous dissertation. Additionally, a comparative study of the algorithms performance in terms of speed was also elaborated. The chapter is mainly divided into two subsections, subsection 6.1 contains the results correspondent to the study of reference network, considering the traffic scenarios designed in section 2.4, and in subsection 6.2 related to the realistic network. Although in section 6.1 the results are present for all considered models (analytical, ILP and heuristic), in the particular case of the heuristic model are drawn some specific conclusions regarding the cost per Gbit/s between other aspects. In the end of each section a comparative analysis is provided between the results obtained through the different previously mentioned models. Once again, it is important to alert that only the transparent transport mode without survivability is considered.

6.1 Reference Network

In this section are presented the results related to the CAPEX values of the reference network for the low, medium and high traffic scenarios regarding the different considered methods, namely the analytical, the ILP and the heuristic models. At the end, a comparison is made between the values obtained with each method for each traffic scenario and some conclusions are elaborated.

6.1.1 Analytical

For this specific model all the necessary formulas to obtain the CAPEX value are presented in section 2.3.3. Moreover, for every scenario the survivability coefficient is considered to be zero since there is no survivability and the grooming coefficient assumes the value 1.25.

Low traffic

In this scenario it has to be taken into account the traffic assumed in subsection 2.4.3.

Using equation 2.14:

$D = \frac{1}{2} \times (1 + 1.25) \times (\frac{2000}{100})$ $D = 22.5$

Replacing in equation 2.13:

$< w > = (\frac{22.5 \times 1.533}{16}) \times (1 + 0)$ $< w > = 2.156$

Through equation 2.12:

$N^R = 16$

Finally, substituting all these values in equation 2.11 the Link Cost obtained is:

$C_L = (2 \times 8 \times 15000) + (2 \times 8 \times 5000 \times 2.156) + (2 \times 16 \times 2000) =$ **476 480 €**

In relation to the cost of the nodes firstly the average number of demands is calculated as it follows:

$< d > = \frac{22.5}{6}$ $< d > = 3.75$

Replacing in equations 2.17 and 2.18:

$< P_{exc} > = 3.75$

$< P_{oxc} > = 3.75 \times [1 + (1 + 0) \times 1.533]$ $< P_{oxc} > = 9.4988$

Finally, replacing all these values in equations 2.15 and 2.16 the Node Cost is:

$C_N = (6 \times (10000 + (100 \times 100 \times 3.75)) + (100 \times 1.25 \times 120) + (100 \times 2.5 \times 100) + (100 \times 10 \times 32) + (100 \times 40 \times 12) + (100 \times 100 \times 8)) + (6 \times (20000 + (2500 \times 9.4988)))$

$C_N = 485\ 000 + 262\ 482 =$ **747 482 €**

$CAPEX = 476\ 480 + 747\ 482 \qquad CAPEX = \mathbf{1\ 223\ 962}$ **€**

Medium traffic

In this scenario it has to be taken into account the traffic assumed in subsection 2.4.3.

Using equation 2.14:

$D = \frac{1}{2} \times (1 + 1.25) \times (\frac{10000}{100}) \qquad D = 112.5$

Replacing in equation 2.13:

$< w > = (\frac{112.5 \times 1.533}{16}) \times (1 + 0) \qquad < w > = 10.8125$

Through equation 2.12:

$N^R = 16$

Finally, substituting all these values in equation 2.11 the Link Cost obtained is:

$C_L = (2 \times 8 \times 15000) + (2 \times 8 \times 5000 \times 10.8125) + (2 \times 16 \times 2000) = \mathbf{1\ 169\ 000}$ **€**

In relation to the cost of the nodes firstly the average number of demands is calculated as it follows:

$< d > = \frac{112.5}{6} \qquad < d > = 18.75$

Replacing in equations 2.17 and 2.18:

$< P_{exc} > = 18.75$

$< P_{oxc} > = 18.75 \times [1 + (1 + 0) \times 1.533] \qquad < P_{oxc} > = 47.4938$

Finally, replacing all these values in equations 2.15 and 2.16 the Node Cost is:

$C_N = (6 \times (10000 + (100 \times 100 \times 18.75)) + (100 \times 1.25 \times 600) + (100 \times 2.5 \times 500) + (100 \times 10 \times 160) + (100 \times 40 \times 60) + (100 \times 100 \times 40)) + (6 \times (20000 + (2500 \times 47.4938)))$

$C_N = 2\ 185\ 000 + 832\ 407 = \mathbf{3\ 017\ 407\ €}$

$CAPEX = 1\ 169\ 000 + 3\ 017\ 407$ $\qquad CAPEX = \mathbf{4\ 186\ 407\ €}$

High traffic

In this scenario it has to be taken into account the traffic assumed in subsection 2.4.3.

Using equation 2.14:

$D = \frac{1}{2} \times (1 + 1.25) \times (\frac{20000}{100})$ $\qquad D = 225$

Replacing in equation 2.13:

$< w > = (\frac{225 \times 1.533}{16}) \times (1 + 0)$ $\qquad < w > = 21.5625$

Through equation 2.12:

$N^R = 16$

Finally, substituting all these values in equation 2.11 the Link Cost obtained is:

$C_L = (2 \times 8 \times 15000) + (2 \times 8 \times 5000 \times 21.5625) + (2 \times 16 \times 2000) = \mathbf{2\ 029\ 000\ €}$

In relation to the cost of the nodes firstly the average number of demands is calculated as it follows:

$< d > = \frac{225}{6}$ $\qquad < d > = 37.5$

Replacing in equations 2.17 and 2.18:

$< P_{exc} > = 37.5$

$< P_{oxc} > = 37.5 \times [1 + (1 + 0) \times 1.533]$ $\qquad < P_{oxc} > = 94.9875$

Finally, replacing all these values in equations 2.15 and 2.16 the Node Cost is:

$C_N = (6 \times (10000 + (100 \times 100 \times 37.5)) + (100 \times 1.25 \times 600) + (100 \times 2.5 \times 500) + (100 \times 10 \times 160) + (100 \times 40 \times 60) + (100 \times 100 \times 40)) + (6 \times (20000 + (2500 \times 94.9875)))$

$C_N = 4\ 310\ 000 + 1\ 544\ 800 =$ **5 854 800 €**

$CAPEX = 2\ 029\ 000 + 5\ 854\ 800$ $CAPEX =$ **7 883 800 €**

Below, in table 6.1 are summarize the analytical parameters calculated for each traffic scenario.

	Low	**Medium**	**High**
$< w >$	2.156	10.8125	21.5625
N	16	16	16
$< d >$	3.75	18.75	37.5
P_{exc}	3.75	18.75	37.5
P_{oxc}	9.4988	47.4938	94.9875
C_L	476 480 €	1 169 000 €	2 0 29 000 €
C_N	747 482 €	3 017 407 €	5 854 000 €
C_C	1 223 962 €	4 186 407 €	7 883 000 €

Table 6.1: Table containing the analytical estimations for the CAPEX in each traffic scenario.

6.1.2 ILP

This section contains the obtained CAPEX values for the different traffic scenarios recurring to an ILP model from a previous dissertation [7]. The type of components, as well its quantity and unity price are also presented. Finally, the cost of the links and also of the nodes is calculated in order to obtain the total cost of the network.

Low traffic

Network CAPEX						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	584 000 €
	Optical Channels		56	5000 €	280 000 €	
	Amplifiers		32	2000 €	64 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	1 020 000 €
		ODU0 Ports	120	100 €/Gbit/s	15 000 €	
		ODU1 Ports	100	100 €/Gbit/s	25 000 €	
		ODU2 Ports	32	100 €/Gbit/s	32 000 €	
		ODU3 Ports	12	100 €/Gbit/s	48 000 €	
		ODU4 Ports	8	100 €/Gbit/s	80 000 €	
		LR Transponders	40	100 €/Gbit/s	400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		OXC Ports	96	2 500 €	240 000 €	
Total Network Cost						1 604 000 €

Table 6.2: Detailed description of CAPEX for low traffic scenario using ILPs.

Medium traffic

Network CAPEX						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	1 004 000 €
	Optical Channels		140	5000 €	700 000 €	
	Amplifiers		32	2000 €	64 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	2 955 000 €
		ODU0 Ports	600	100 €/Gbit/s	75 000 €	
		ODU1 Ports	500	100 €/Gbit/s	125 000 €	
		ODU2 Ports	160	100 €/Gbit/s	160 000 €	
		ODU3 Ports	60	100 €/Gbit/s	240 000 €	
		ODU4 Ports	40	100 €/Gbit/s	400 000 €	
		LR Transponders	114	100 €/Gbit/s	1 140 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		OXC Ports	254	2 500 €	635 000 €	
Total Network Cost						3 959 000 €

Table 6.3: Detailed description of CAPEX for medium traffic scenario using ILPs.

High traffic

Network CAPEX						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	1 604 000 €
	Optical Channels		260	5000 €	1 300 000 €	
	Amplifiers		32	2000 €	64 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	5 505 000 €
		ODU0 Ports	1200	100 €/Gbit/s	150 000 €	
		ODU1 Ports	1000	100 €/Gbit/s	250 000 €	
		ODU2 Ports	320	100 €/Gbit/s	320 000 €	
		ODU3 Ports	120	100 €/Gbit/s	480 000 €	
		ODU4 Ports	80	100 €/Gbit/s	800 000 €	
		LR Transponders	214	100 €/Gbit/s	2 140 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		OXC Ports	474	2 500 €	1 185 000 €	
Total Network Cost						7 109 000 €

Table 6.4: Detailed description of CAPEX for high traffic scenario using ILPs.

6.1.3 Heuristics

In this section the simulations are performed recurring to the default parameters provided in table 4.1 for all entry variables of the system excluding the network number of nodes, the traffic and distance matrices and also the physical topology adjacency matrix whose values are provided in section 2.4.

Low traffic

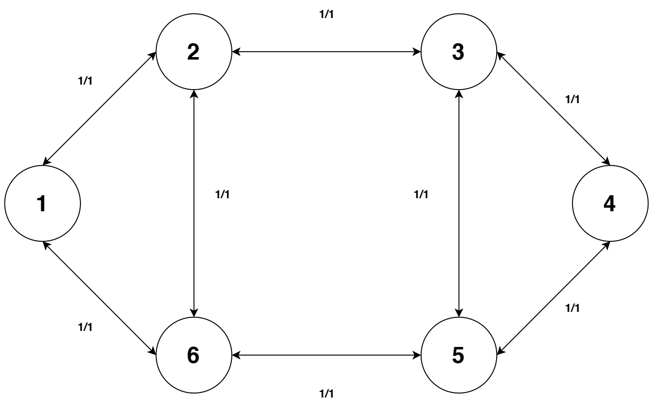

Figure 6.1: Physical topology after the dimensioning process for low scenario traffic.

In a first instance the resulting physical topology of the reference network is presented above in figure 6.1 and the traffic model utilized for this specific scenario is referred in section 2.4.3. It becomes noticeable that all physical links are in use for this scenario.

Below in table 6.5 information regarding the global constitution of all network links is provided, the number of optical channels and the amplifiers present in each link is calculated through equations 2.2 and 2.3, respectively.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <->Node 2	3	3
Node 1 <->Node 6	2	1
Node 2 <->Node 3	6	3
Node 2 <->Node 6	4	1
Node 3 <->Node 4	3	2
Node 3 <->Node 5	3	0
Node 4 <->Node 5	2	1
Node 5 <->Node 6	5	5

Table 6.5: Table with information regarding links for low traffic scenario.

In table 6.6 is presented detailed information regarding all the network nodes, the number of tributary ports is calculated through equation 2.6, the number of add ports through 2.9 and the number of long-reach transponders through equation 2.7.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	58	5	5	5
2	3	46	7	7	13
3	3	36	6	6	12
4	2	40	5	5	5
5	3	48	8	8	10
6	3	44	9	9	11

Table 6.6: Table with information regarding nodes for low traffic scenario.

Below, are presented some more tables properly identified that contain specific information regarding each of the nodes that comprise the reference network, after the dimensioning process. It becomes possible to analyze how many tributary ports each node contain and the respective bit-rates, the number of add and line ports connected and also the number of transponders used. In some cases the number of add ports and line ports in a node may differ, this happens if some of the traffic processed by the node is not originating from there, i.e. that node is not the source node for all the demands there processed. Having that said, when a node is equal to the source of a demand, it means that an add port and a line port are in use, otherwise, it means that through ports are used and in this case the number of ports is double the number of optical channels that go through the node.

Detailed description of node 1		
Electrical part	Number of total demands	Bit rate
58 tributary ports	26	ODU0
	26	ODU1
	6	ODU2
	Node <-Optical Channels->Node	Bit rate
5 LR Transponders	1 <- 1 ->2	100 Gbit/s
	1 <- 1 ->3	
	1 <- 1 ->4	
	1 <- 1 ->5	
	1 <- 1 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
5 Add Ports	1 <- 1 ->2	100 Gbit/s
	1 <- 1 ->3	
	1 <- 1 ->4	
	1 <- 1 ->5	
	1 <- 1 ->6	
5 Line Ports	1 <- 3 ->2	
	1 <- 2 ->6	

Table 6.7: Detailed description of node 1 for low traffic scenario.

In this particular case, for node 1 the number of add ports and line ports is the same, which means that all the traffic processed by the node is originating from there.

Detailed description of node 2		
Electrical part	Number of total demands	Bit rate
46 tributary ports	22 14 4 4 2	ODU0 ODU1 ODU2 ODU3 ODU4
	Node <-Optical Channels->Node	Bit rate
7 LR Transponders	2 <- 1 ->1 2 <- 1 ->3 2 <- 1 ->4 2 <- 1 ->5 2 <- 3 ->6	100 Gbit/s
Optical part	Node <-Optical Channels->Node	Bit rate
7 Add Ports	2 <- 1 ->1 2 <- 1 ->3 2 <- 1 ->4 2 <- 1 ->5 2 <- 3 ->6	100 Gbit/s
13 Line Ports	2 <- 3 ->1 2 <- 6 ->3 2 <- 4 ->6	

Table 6.8: Detailed description of node 2 for low traffic scenario.

Detailed description of node 3		
Electrical part	Number of total demands	Bit rate
36 tributary ports	14	ODU0
	12	ODU1
	6	ODU2
	4	ODU3
	Node <-Optical Channels->Node	Bit rate
6 LR Transponders	3 <- 1 ->1	100 Gbit/s
	3 <- 1 ->2	
	3 <- 1 ->4	
	3 <- 2 ->5	
	3 <- 3 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
6 Add Ports	3 <- 1 ->1	100 Gbit/s
	3 <- 1 ->2	
	3 <- 1 ->4	
	3 <- 2 ->5	
	3 <- 3 ->6	
12 Line Ports	3 <- 6 ->2	
	3 <- 3 ->4	
	3 <- 3 ->5	

Table 6.9: Detailed description of node 3 for low traffic scenario.

Detailed description of node 4		
Electrical part	Number of total demands	Bit rate
	14	ODU0
40 tributary ports	20	ODU1
	6	ODU2
	Node <-Optical Channels->Node	Bit rate
	4 <- 1 ->1	
	4 <- 1 ->2	
5 LR Transponders	4 <- 1 ->3	100 Gbit/s
	4 <- 2 ->5	
	4 <- 3 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
	4 <- 1 ->1	
	4 <- 1 ->2	
5 Add Ports	4 <- 1 ->3	
	4 <- 2 ->5	100 Gbit/s
	4 <- 3 ->6	
5 Line Ports	4 <- 3 ->3	
	4 <- 2 ->5	

Table 6.10: Detailed description of node 4 for low traffic scenario.

Detailed description of node 5		
Electrical part	Number of total demands	Bit rate
48 tributary ports	28 8 8 2 2	ODU0 ODU1 ODU2 ODU3 ODU4
	Node <-Optical Channels->Node	Bit rate
8 LR Transponders	5 <- 1 ->1 5 <- 1 ->2 5 <- 2 ->3 5 <- 1 ->4 5 <- 3 ->6	100 Gbit/s
Optical part	Node <-Optical Channels->Node	Bit rate
8 Add Ports	5 <- 1 ->1 5 <- 1 ->2 5 <- 2 ->3 5 <- 1 ->4 5 <- 3 ->6	100 Gbit/s
10 Line Ports	5 <- 3 ->3 5 <- 2 ->4 5 <- 5 ->6	

Table 6.11: Detailed description of node 5 for low traffic scenario.

Detailed description of node 6		
Electrical part	Number of total demands	Bit rate
44 tributary ports	16	ODU0
	20	ODU1
	2	ODU2
	2	ODU3
	4	ODU4
	Node <-Optical Channels->Node	Bit rate
9 LR Transponders	6 <- 1 ->1	100 Gbit/s
	6 <- 3 ->2	
	6 <- 1 ->3	
	6 <- 1 ->4	
	6 <- 3 ->5	
Optical part	Node <-Optical Channels->Node	Bit rate
9 Add Ports	6 <- 1 ->1	100 Gbit/s
	6 <- 3 ->2	
	6 <- 1 ->3	
	6 <- 1 ->4	
	6 <- 3 ->5	
11 Line Ports	6 <- 2 ->1	
	6 <- 4 ->2	
	6 <- 5 ->5	

Table 6.12: Detailed description of node 6 for low traffic scenario.

In the following table 6.13, the routing information is in focus. Again, the paths are considered bidirectional and as such the paths between the same pair of nodes but in opposite directions are still the same.

Routing Scheme							
Source	Destination	Links	ODU0	ODU1	ODU2	ODU3	ODU4
1	2	{(1,2)}	10	4	2	0	0
1	3	{(1,2),(2,3)}	2	8	2	0	0
1	4	{(1,2),(2,3),(3,4)}	6	4	2	0	0
1	5	{(1,6),(6,5)}	2	0	0	0	0
1	6	{(1,6)}	6	10	0	0	0
2	3	{(2,3)}	0	0	0	2	0
2	4	{(2,3),(3,4)}	2	6	0	0	0
2	5	{(2,3),(3,5)}	10	2	2	0	0
2	6	{(2,6)}	0	2	0	2	2
3	4	{(3,4)}	2	2	2	0	0
3	5	{(3,5)}	8	2	2	2	0
3	6	{(3,2),(2,6)}	2	0	0	0	0
4	5	{(4,5)}	2	2	2	0	0
4	6	{(4,5),(5,6)}	2	6	0	0	0
5	6	{(5,6)}	6	2	2	0	2

Table 6.13: Detailed description of the routing process for low traffic scenario.

Finally, in table 6.14 is presented the final CAPEX results obtained for the low traffic scenario, obtained through the heuristic model.

Network CAPEX						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	584 000 €
	Optical Channels		56	5000 €	280 000 €	
	Amplifiers		32	2000 €	64 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	1 020 000 €
		ODU0 Ports	120	100 €/Gbit/s	15 000 €	
		ODU1 Ports	100	100 €/Gbit/s	25 000 €	
		ODU2 Ports	32	100 €/Gbit/s	32 000 €	
		ODU3 Ports	12	100 €/Gbit/s	48 000 €	
		ODU4 Ports	8	100 €/Gbit/s	80 000 €	
		LR Transponders	40	100 €/Gbit/s	400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		OXC Ports	96	2 500 €	240 000 €	
Total Network Cost						1 604 000 €

Table 6.14: Detailed description of CAPEX for low traffic scenario.

Medium traffic

In a first instance the resulting physical topology of the reference network is presented below in figure 6.2. The traffic model utilized for this specific scenario is referred in section 2.4.3.

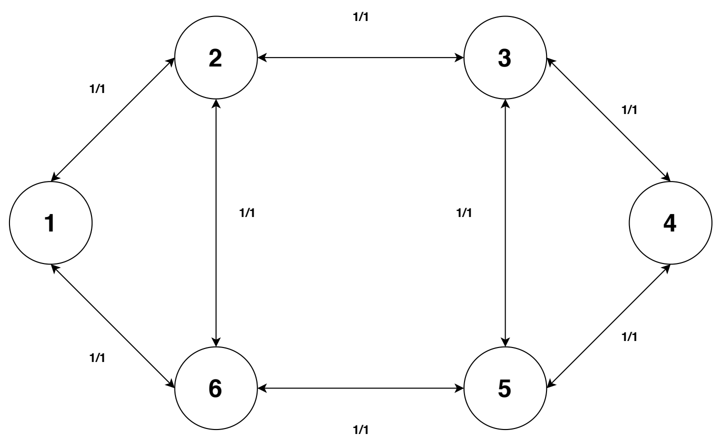

Figure 6.2: Physical topology after dimensioning for medium scenario traffic.

It is noticeable that all physical links are in use for this scenario. Below in table 6.15 information regarding the global constitution of all network links is provided, the number of optical channels and the amplifiers present in each link is calculated through equations 2.2 and 2.3, respectively.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <->Node 2	8	3
Node 1 <->Node 6	3	1
Node 2 <->Node 3	14	3
Node 2 <->Node 6	16	1
Node 3 <->Node 4	5	2
Node 3 <->Node 5	8	0
Node 4 <->Node 5	3	1
Node 5 <->Node 6	14	5

Table 6.15: Links information for medium traffic scenario.

In table 6.16 is presented detailed information regarding all the network nodes, the number of tributary ports is calculated through equation 2.6, the number of add ports through 2.9 and the number of long-reach transponders through equation 2.7.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	290	11	11	11
2	3	230	26	26	38
3	3	180	17	17	27
4	2	200	8	8	8
5	3	240	23	23	25
6	3	220	31	31	33

Table 6.16: Node information for medium traffic scenario.

Below, are presented some more tables properly identified that contain specific information regarding each of the nodes that comprise the reference network, after the dimensioning process.

Detailed description of node 1		
Electrical part	Number of total demands	Bit rate
290 tributary ports	130 130 30	ODU0 ODU1 ODU2
	Node <-Optical Channels->Node	Bit rate
11 LR Transponders	1 <- 3 ->2 1 <- 3 ->3 1 <- 2 ->4 1 <- 1 ->5 1 <- 2 ->6	100 Gbit/s
Optical part	Node <-Optical Channels->Node	Bit rate
11 Add Ports	1 <- 3 ->2 1 <- 3 ->3 1 <- 2 ->4 1 <- 1 ->5 1 <- 2 ->6	100 Gbit/s
11 Line Ports	1 <- 8 ->2 1 <- 3 ->6	

Table 6.17: Detailed description of node 1 for medium traffic scenario.

Detailed description of node 2		
Electrical part	Number of total demands	Bit rate
230 tributary ports	110	ODU0
	70	ODU1
	20	ODU2
	20	ODU3
	10	ODU4
	Node <-Optical Channels->Node	Bit rate
26 LR Transponders	2 <- 3 ->1	100 Gbit/s
	2 <- 5 ->3	
	2 <- 1 ->4	
	2 <- 2 ->5	
	2 <- 15 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
26 Add Ports	2 <- 3 ->1	100 Gbit/s
	2 <- 5 ->3	
	2 <- 1 ->4	
	2 <- 2 ->5	
	2 <- 15 ->6	
38 Line Ports	2 <- 8 ->1	
	2 <- 14 ->3	
	2 <- 16 ->6	

Table 6.18: Detailed description of node 2 for medium traffic scenario.

Detailed description of node 3		
Electrical part	Number of total demands	Bit rate
180 tributary ports	70	ODU0
	60	ODU1
	30	ODU2
	20	ODU3
	Node <-Optical Channels->Node	Bit rate
17 LR Transponders	3 <- 3 ->1	100 Gbit/s
	3 <- 5 ->2	
	3 <- 2 ->4	
	3 <- 6 ->5	
	3 <- 1 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
17 Add Ports	3 <- 3 ->1	100 Gbit/s
	3 <- 5 ->2	
	3 <- 2 ->4	
	3 <- 6 ->5	
	3 <- 1 ->6	
27 Line Ports	3 <- 14 ->2	
	3 <- 5 ->4	
	3 <- 8 ->5	

Table 6.19: Detailed description of node 3 for medium traffic scenario.

Detailed description of node 4		
Electrical part	Number of total demands	Bit rate
200 tributary ports	70	ODU0
	100	ODU1
	30	ODU2
	Node <-Optical Channels->Node	Bit rate
8 LR Transponders	4 <- 2 ->1	100 Gbit/s
	4 <- 1 ->2	
	4 <- 2 ->3	
	4 <- 2 ->5	
	4 <- 1 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
8 Add Ports	4 <- 2 ->1	100 Gbit/s
	4 <- 1 ->2	
	4 <- 2 ->3	
	4 <- 2 ->5	
	4 <- 1 ->6	
8 Line Ports	4 <- 5 ->3	
	4 <- 3 ->5	

Table 6.20: Detailed description of node 4 for medium traffic scenario.

Detailed description of node 5		
Electrical part	Number of total demands	Bit rate
240 tributary ports	140	ODU0
	40	ODU1
	40	ODU2
	10	ODU3
	10	ODU4
	Node <-Optical Channels->Node	Bit rate
23 LR Transponders	5 <- 1 ->1	100 Gbit/s
	5 <- 2 ->2	
	5 <- 6 ->3	
	5 <- 2 ->4	
	5 <- 12 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
23 Add Ports	5 <- 1 ->1	100 Gbit/s
	5 <- 2 ->2	
	5 <- 6 ->3	
	5 <- 2 ->4	
	5 <- 12 ->6	
25 Line Ports	5 <- 8 ->3	
	5 <- 3 ->4	
	5 <- 14 ->6	

Table 6.21: Detailed description of node 5 for medium traffic scenario.

Detailed description of node 6		
Electrical part	Number of total demands	Bit rate
220 tributary ports	80	ODU0
	100	ODU1
	10	ODU2
	10	ODU3
	20	ODU4
	Node <-Optical Channels->Node	Bit rate
31 LR Transponders	6 <- 2 ->1	100 Gbit/s
	6 <- 15 ->2	
	6 <- 1 ->3	
	6 <- 1 ->4	
	6 <- 12 ->5	
Optical part	Node <-Optical Channels->Node	Bit rate
31 Add Ports	6 <- 2 ->1	100 Gbit/s
	6 <- 15 ->2	
	6 <- 1 ->3	
	6 <- 1 ->4	
	6 <- 12 ->5	
33 Line Ports	6 <- 3 ->1	
	6 <- 16 ->2	
	6 <- 14 ->5	

Table 6.22: Detailed description of node 6 for medium traffic scenario.

In the following table 6.13, the routing information is in focus.

Routing Scheme							
Source	Destination	Links	ODU0	ODU1	ODU2	ODU3	ODU4
1	2	{(1,2)}	50	20	10	0	0
1	3	{(1,2),(2,3)}	10	40	10	0	0
1	4	{(1,2),(2,3),(3,4)}	30	20	10	0	0
1	5	{(1,6),(6,5)}	10	0	0	0	0
1	6	{(1,6)}	30	50	0	0	0
2	3	{(2,3)}	0	0	0	10	0
2	4	{(2,3),(3,4)}	10	30	0	0	0
2	5	{(2,3),(3,5)}	50	10	10	0	0
2	6	{(2,6)}	0	10	0	10	10
3	4	{(3,4)}	10	10	10	0	0
3	5	{(3,5)}	40	10	10	10	0
3	6	{(3,2),(2,6)}	10	0	0	0	0
4	5	{(4,5)}	10	10	10	0	0
4	6	{(4,5),(5,6)}	10	30	0	0	0
5	6	{(5,6)}	30	10	10	0	10

Table 6.23: Detailed description of the routing process for medium traffic scenario.

Finally, in table 6.14 is presented the final CAPEX results obtained for the low traffic scenario, obtained through the heuristic model.

Network CAPEX						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	1 014 000 €
	Optical Channels		142	5000 €	710 000 €	
	Amplifiers		32	2000 €	64 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	2 985 000 €
		ODU0 Ports	600	100 €/Gbit/s	75 000 €	
		ODU1 Ports	500	100 €/Gbit/s	125 000 €	
		ODU2 Ports	160	100 €/Gbit/s	160 000 €	
		ODU3 Ports	60	100 €/Gbit/s	240 000 €	
		ODU4 Ports	40	100 €/Gbit/s	400 000 €	
		LR Transponders	116	100 €/Gbit/s	1 160 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		OXC Ports	258	2 500 €	645 000 €	
Total Network Cost						3 999 000 €

Table 6.24: Detailed description of CAPEX for medium traffic scenario.

High traffic

In a first instance the resulting physical topology of the reference network is presented below in figure 6.3. The traffic model utilized for this specific scenario is mentioned in the section 2.4.3.

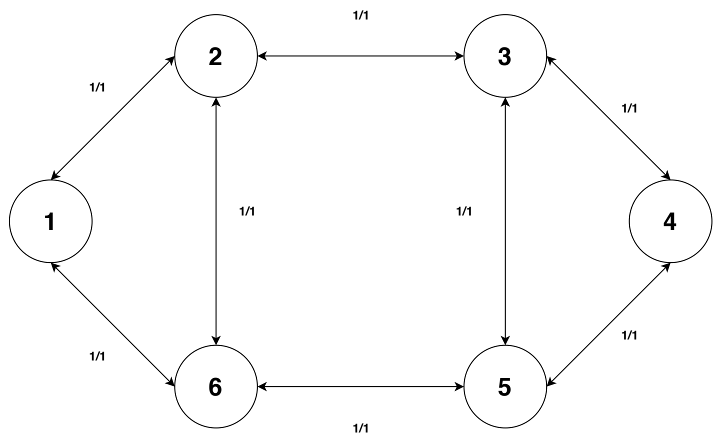

Figure 6.3: Physical topology after dimensioning process for high scenario traffic.

It is noticeable that all physical links are in use for this scenario. Below in table 6.25 information regarding the global constitution of all network links is provided, the number of optical channels and the amplifiers present in each link is calculated through equations 2.2 and 2.3, respectively.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <->Node 2	14	3
Node 1 <->Node 6	5	1
Node 2 <->Node 3	26	3
Node 2 <->Node 6	31	1
Node 3 <->Node 4	9	2
Node 3 <->Node 5	16	0
Node 4 <->Node 5	5	1
Node 5 <->Node 6	27	5

Table 6.25: Links information for high traffic scenario.

In table 6.26 is presented detailed information regarding all the network nodes, the number of tributary ports is calculated through equation 2.6, the number of add ports through 2.9 and the number of long-reach transponders through equation 2.7.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	580	19	19	19
2	3	460	51	51	71
3	3	360	31	31	51
4	2	400	14	14	14
5	3	480	44	44	48
6	3	440	61	61	63

Table 6.26: Node information for high traffic scenario.

Below, are presented some more tables properly identified that contain specific information regarding each of the nodes that comprise the reference network, after the dimensioning process.

Detailed description of node 1		
Electrical part	Number of total demands	Bit rate
580 tributary ports	260	ODU0
	260	ODU1
	60	ODU2
	Node <-Optical Channels->Node	Bit rate
19 LR Transponders	1 <- 5 ->2	100 Gbit/s
	1 <- 5 ->3	
	1 <- 4 ->4	
	1 <- 1 ->5	
	1 <- 4 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
19 Add Ports	1 <- 5 ->2	100 Gbit/s
	1 <- 5 ->3	
	1 <- 4 ->4	
	1 <- 1 ->5	
	1 <- 4 ->6	
19 Line Ports	1 <- 14 ->2	
	1 <- 5 ->6	

Table 6.27: Detailed description of node 1 for high traffic scenario.

Detailed description of node 2		
Electrical part	Number of total demands	Bit rate
460 tributary ports	220	ODU0
	140	ODU1
	40	ODU2
	40	ODU3
	20	ODU4
	Node <-Optical Channels->Node	Bit rate
51 LR Transponders	2 <- 5 ->1	100 Gbit/s
	2 <- 10 ->3	
	2 <- 2 ->4	
	2 <- 4 ->5	
	2 <- 30 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
51 Add Ports	2 <- 5 ->1	100 Gbit/s
	2 <- 10 ->3	
	2 <- 2 ->4	
	2 <- 4 ->5	
	2 <- 30 ->6	
71 Line Ports	2 <- 14 ->1	
	2 <- 26 ->3	
	2 <- 31 ->6	

Table 6.28: Detailed description of node 2 for high traffic scenario.

Detailed description of node 3		
Electrical part	Number of total demands	Bit rate
360 tributary ports	140	ODU0
	120	ODU1
	60	ODU2
	40	ODU3
	Node <-Optical Channels->Node	Bit rate
31 LR Transponders	3 <- 5 ->1	100 Gbit/s
	3 <- 10 ->2	
	3 <- 3 ->4	
	3 <- 12 ->5	
	3 <- 1 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
31 Add Ports	3 <- 5 ->1	100 Gbit/s
	3 <- 10 ->2	
	3 <- 3 ->4	
	3 <- 12 ->5	
	3 <- 1 ->6	
51 Line Ports	3 <- 26 ->2	
	3 <- 9 ->4	
	3 <- 16 ->5	

Table 6.29: Detailed description of node 3 for high traffic scenario.

Detailed description of node 4		
Electrical part	Number of total demands	Bit rate
400 tributary ports	140	ODU0
	200	ODU1
	60	ODU2
	Node <-Optical Channels->Node	Bit rate
14 LR Transponders	4 <- 4 ->1	100 Gbit/s
	4 <- 2 ->2	
	4 <- 3 ->3	
	4 <- 3 ->5	
	4 <- 2 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
14 Add Ports	4 <- 4 ->1	100 Gbit/s
	4 <- 2 ->2	
	4 <- 3 ->3	
	4 <- 3 ->5	
	4 <- 2 ->6	
14 Line Ports	4 <- 9 ->2	
	4 <- 5 ->4	

Table 6.30: Detailed description of node 4 for high traffic scenario.

Detailed description of node 5		
Electrical part	Number of total demands	Bit rate
480 tributary ports	280	ODU0
	80	ODU1
	80	ODU2
	20	ODU3
	20	ODU4
	Node <-Optical Channels->Node	Bit rate
44 LR Transponders	5 <- 1 ->1	100 Gbit/s
	5 <- 4 ->2	
	5 <- 12 ->3	
	5 <- 3 ->4	
	5 <- 24 ->6	
Optical part	Node <-Optical Channels->Node	Bit rate
44 Add Ports	5 <- 1 ->1	100 Gbit/s
	5 <- 4 ->2	
	5 <- 12 ->3	
	5 <- 3 ->4	
	5 <- 24 ->6	
48 Line Ports	5 <- 16 ->3	
	5 <- 5 ->4	
	5 <- 27 ->6	

Table 6.31: Detailed description of node 5 for high traffic scenario.

Detailed description of node 6		
Electrical part	Number of total demands	Bit rate
440 tributary ports	160	ODU0
	200	ODU1
	20	ODU2
	20	ODU3
	40	ODU4
	Node <-Optical Channels->Node	Bit rate
61 LR Transponders	6 <- 4 ->1	100 Gbit/s
	6 <- 30 ->2	
	6 <- 1 ->3	
	6 <- 2 ->4	
	6 <- 24 ->5	
Optical part	Node <-Optical Channels->Node	Bit rate
61 Add Ports	6 <- 4 ->1	100 Gbit/s
	6 <- 30 ->2	
	6 <- 1 ->3	
	6 <- 2 ->4	
	6 <- 24 ->5	
63 Line Ports	6 <- 5 ->1	
	6 <- 31 ->2	
	6 <- 27 ->5	

Table 6.32: Detailed description of node 6 for high traffic scenario.

In the following table 6.13, the routing information is in focus.

Routing Scheme							
Source	Destination	Links	ODU0	ODU1	ODU2	ODU3	ODU4
1	2	{(1,2)}	100	40	20	0	0
1	3	{(1,2),(2,3)}	20	80	20	0	0
1	4	{(1,2),(2,3),(3,4)}	60	40	20	0	0
1	5	{(1,6),(6,5)}	20	0	0	0	0
1	6	{(1,6)}	60	100	0	0	0
2	3	{(2,3)}	0	0	0	20	0
2	4	{(2,3),(3,4)}	20	60	0	0	0
2	5	{(2,3),(3,5)}	100	20	20	0	0
2	6	{(2,6)}	0	20	0	20	20
3	4	{(3,4)}	20	20	20	0	0
3	5	{(3,5)}	80	20	20	20	0
3	6	{(3,2),(2,6)}	20	0	0	0	0
4	5	{(4,5)}	20	20	20	0	0
4	6	{(4,5),(5,6)}	20	60	0	0	0
5	6	{(5,6)}	60	20	20	0	20

Table 6.33: Detailed description of the routing process for high traffic scenario.

Finally, in table 6.14 is presented the final CAPEX results obtained for the low traffic scenario, obtained through the heuristic model.

Network CAPEX						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	1 634 000 €
	Optical Channels		266	5000 €	1 330 000 €	
	Amplifiers		32	2000 €	64 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	5 595 000 €
		ODU0 Ports	1200	100 €/Gbit/s	150 000 €	
		ODU1 Ports	1000	100 €/Gbit/s	250 000 €	
		ODU2 Ports	320	100 €/Gbit/s	320 000 €	
		ODU3 Ports	120	100 €/Gbit/s	480 000 €	
		ODU4 Ports	80	100 €/Gbit/s	800 000 €	
		LR Transponders	220	100 €/Gbit/s	2 200 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		OXC Ports	486	2 500 €	1 215 000 €	
Total Network Cost						7 229 000 €

Table 6.34: Detailed description of CAPEX for high traffic scenario.

6.1.4 Comparative Analysis

Economics

For a better analysis of the results obtained in the previous sections, the following table 6.35, was created. It contains summarized information regarding the reference network CAPEX values obtained for all traffic scenarios using different dimensioning models, namely, the analytical, the ILP and the heuristic.

		Heuristic	Analytical	ILP
Low Traffic	Link Cost	584 000 €	476 480 € (-18,4%)	584 000 € (0%)
	Node Cost	1 020 000 €	747 482 € (-26,7%)	1 020 000 € (0%)
	CAPEX	1 604 000 €	1 223 962 € (-23,7%)	1 604 000 € (0%)
Medium Traffic	Link Cost	1 014 000 €	1 169 000 € (+15,3%)	1 004 000 € (-1%)
	Node Cost	2 985 000 €	3 017 407 € (+1,1%)	2 955 000 € (-1%)
	CAPEX	3 999 000 €	4 186 407 € (+4,7%)	3 959 000 € (-1%)
High Traffic	Link Cost	1 634 000 €	2 029 000 € (+24,2%)	1 604 000 € (-1,8%)
	Node Cost	5 595 000 €	5 854 800 € (+4,6%)	5 505 000 € (-1.6%)
	CAPEX	7 229 000 €	7 883 800 € (+9,1%)	7 109 000 € (-1,7%)

Table 6.35: Comparison between the CAPEX values obtained through different methods for all traffic scenarios.

As expected the heuristic CAPEX values tend to be equal or worse (higher) relatively to the ones found by the ILP model, although sufficiently close. Since heuristic algorithms in some cases may only be capable of reaching an approximation of the exact optimal solution, another scenario could simply not happen. The purpose of heuristic algorithms is to reach an optimal solution for a problem within a group of feasible solutions. That group may contain the optimal solution or only near optimal solutions, and the only way to confirm that is to compare the results obtained with the results provided by an ILP model. Speaking more specifically of the results presented in table 6.35, for low traffic scenarios as the problem is relatively easy to solve the heuristic algorithms performance can match the results obtained through the ILP model but as the the traffic grows, as well as the complexity of the dimensioning problem, the results obtained through heuristics tend to worsen. Relatively to the analytical values, some higher fluctuations were recorded because since the analytical model works with mean values the results may be lower or higher than the supposed optimal solutions obtained through the ILP model. This happens because for the analytic model the grooming coefficient value is initially defined and fixed for every scenario but in the case of the ILP or the heuristic model this does not happen, there the coefficients vary and in the low traffic scenario case due to the existence of little traffic this coefficients assume much higher values than the analytical one, thus explaining high error margin (23,7%) for the low traffic scenario. As the traffic grows the results obtained through this statistical method tend to become worse and worse relatively to the values obtained through the heuristic and the ILP model. It is common practice to use heuristic models in low complexity networks just for a matter of calibration, to see if the results given can reach closely the optimal values provided by the ILP model. As seen in table 6.35 it does, once for the low complexity case it can match the same CAPEX values and for the worst cases the margin of error is always lower than 2%. Having that said, the calibration is considered to be successful and so the the heuristic values become validated.

Execution Time

The following table 6.36 contains information regarding the execution time of each model. For the analytical model it is assumed to be instantaneous.

		Heuristic	ILP
Low Traffic	Elapsed time	1.5 s	20.1 s (+1240%)
Medium Traffic	Elapsed time	7.2 s	26.4 s (+267%)
High Traffic	Elapsed time	13.3 s	51.4 s (+286%)

Table 6.36: Comparison between the execution time of the heuristic and ILP methods for different traffic scenarios.

The existent drawback between the ILP and heuristic models consists in the trade-off between time and accuracy, since, although the ILP models always provide optimal solutions the time of execution of the mathematical model can extend to hours, days or even weeks, depending on the complexity of the problem in hands, while the heuristics provide solutions in many cases sufficiently close, depending on the quality of the applied algorithms, in a matter of minutes or even seconds. Having that said, as expected the ILP model was much slower to find a solution when compared to the heuristic model, for all cases. This is actually a pretty standard situation, since most of the heuristic algorithms developed during this dissertation have low levels of complexity, thus, severely limiting the possible range of solutions.

Brief Techno-Economical Analysis

After discussing the CAPEX results obtained for the reference network applying different models, thus, validating the heuristic results obtained from the previous section 6.1.3 it becomes possible to draw some specific conclusions about the results for this method. In order to facilitate the analysis the following table 6.37 is presented.

	Low Traffic	**Medium Traffic**	**High Traffic**
Bidirectional traffic (Gbit/s)	1000	5000	10 000
Number of Add ports	40	116	220
Number of Line ports	56	142	266
Number of Tributary ports	272	1360	2720
Number of Transceivers	56	142	266
Number of Transponders	40	116	220
Link Cost	584 000 €	1 014 000 €	1 634 000 €
Node Cost	1 020 000 €	2 985 000 €	5 595 000 €
Total CAPEX	1 604 000 €	3 999 000 €	7 229 000 €
CAPEX/Gbit/s	**1 604 €**	**800 €**	**723 €**

Table 6.37: Comparison of the different heuristic CAPEX values obtained for the different traffic scenarios.

Looking at table 6.37 some conclusions can be drawn relatively to the obtained values. In relation to the CAPEX cost per bit it is noticeable that for the low traffic scenario the cost is much higher when compared to the values obtained for the medium and high traffic scenarios. Thus, the higher the traffic the better the network will be capable of aggregating traffic more efficiently, therefore minimizing the percentage of bandwidth wasted. An other relevant aspect that also contributes to this lower cost per bit resides in the fact that while the traffic processed may enlarge in some cases the amount of equipment needed remains the same, for example, an optical amplifier that is not being used to its full extent can process more optical channels when the quantity of traffic increases without the need of another module, thus resulting in a lower CAPEX cost per bit. This same phenomenon may happen with other network components.

6.2 Realistic Network

6.2.1 Analytical

All the necessary formulas to obtain the CAPEX value for the vBNS network are presented in section 2.3.3. Additionally, the survivability coefficient is again considered to be zero since there is no survivability and the grooming coefficient assumes the value 1.25. In this scenario it has to be taken into account the traffic assumed in subsection 2.5.2. It is being considered a medium-high traffic scenario with a total bidirectional traffic of 7.5 Tbit/s.

Using equation 2.14:

$D = \frac{1}{2} \times (1 + 1.25) \times (\frac{15000}{100}) \qquad D = 168.75$

Replacing in equation 2.13:

$< w > = (\frac{168.75 \times 2.40}{34}) \times (1 + 0) \qquad < w > = 11.92$

Through equation 2.12:

$N^R = 306$

Finally, substituting all these values in equation 2.11 the Link Cost obtained is:

$C_L = (2 \times 17 \times 15000) + (2 \times 17 \times 5000 \times 11.92) + (2 \times 153 \times 2000) = \mathbf{3\ 148\ 400\ €}$

In relation to the cost of the nodes firstly the average number of demands is calculated as it follows:

$< d > = \frac{112.5}{6} \qquad < d > = 28.125$

Replacing in equations 2.17 and 2.18:

$< P_{exc} > = 28.125$

$< P_{oxc} > = 28.125 \times [1 + (1 + 0) \times 2.40] \qquad < P_{oxc} > = 95.625$

Finally, replacing all these values in equations 2.15 and 2.16 the Node Cost is:

$C_N = (12 \times (10000 + (100 \times 100 \times 28.125)) + (100 \times 2.5 \times 1042) + (100 \times 10 \times 190) + (100 \times 40 \times 298)) + (12 \times (20000 + (2500 \times 95.625)))$

$C_N = 5\ 133\ 000 + 3\ 108\ 750 = \mathbf{8\ 241\ 750\ €}$

$CAPEX = 3\ 148\ 400 + 8\ 241\ 750$ $\quad CAPEX = \mathbf{11\ 390\ 150\ €}$

6.2.2 Heuristics

Regarding the heuristic approach, different CAPEX values can be obtained according to the values of some chosen entry parameters of the system. Here only the different sorting rules of the traffic scheduling block are tested, in order to observe their impact on the CAPEX value of the network. Below on tables 6.38 and 6.39 are presented the detailed CAPEX results for the ascending and descending ordering rules, respectively.

Ascending ordering rule

Network CAPEX						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		34	15 000 €	510 000 €	3 992 000 €
	Optical Channels		560	5000 €	2 800 000 €	
	Amplifiers		306	2000 €	612 000 €	
Node Cost	Electrical	EXCs	12	10 000 €	120 000 €	6 402 500 €
		ODU0 Ports	0	100 €/Gbit/s	0 €	
		ODU1 Ports	1042	100 €/Gbit/s	260 500 €	
		ODU2 Ports	190	100 €/Gbit/s	190 000 €	
		ODU3 Ports	298	100 €/Gbit/s	1 192 000 €	
		ODU4 Ports	0	100 €/Gbit/s	0 €	
		LR Transponders	240	100 €/Gbit/s	2 400 000 €	
	Optical	OXCs	12	20 000 €	240 000 €	
		OXC Ports	800	2 500 €	2 000 000 €	
Total Network Cost						10 324 500 €

Table 6.38: Detailed description of the CAPEX value for the realistic network, considering an ascending ordering rule.

Descending ordering rule

<table>
<tr><td colspan="3">Network CAPEX</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3"></td><td>Quantity</td><td>Unit Price</td><td>Cost</td><td>Total</td></tr>
<tr><td rowspan="3">Link Cost</td><td colspan="2">OLTs</td><td>34</td><td>15 000 €</td><td>510 000 €</td><td rowspan="3">3 752 000 €</td></tr>
<tr><td colspan="2">Optical Channels</td><td>526</td><td>5000 €</td><td>2 630 000 €</td></tr>
<tr><td colspan="2">Amplifiers</td><td>306</td><td>2000 €</td><td>612 000 €</td></tr>
<tr><td rowspan="9">Node Cost</td><td rowspan="7">Electrical</td><td>EXCs</td><td>12</td><td>10 000 €</td><td>120 000 €</td><td rowspan="9">6 167 500 €</td></tr>
<tr><td>ODU0 Ports</td><td>0</td><td>100 €/Gbit/s</td><td>0 €</td></tr>
<tr><td>ODU1 Ports</td><td>1042</td><td>100 €/Gbit/s</td><td>260 500 €</td></tr>
<tr><td>ODU2 Ports</td><td>190</td><td>100 €/Gbit/s</td><td>190 000 €</td></tr>
<tr><td>ODU3 Ports</td><td>298</td><td>100 €/Gbit/s</td><td>1 192 000 €</td></tr>
<tr><td>ODU4 Ports</td><td>0</td><td>100 €/Gbit/s</td><td>0 €</td></tr>
<tr><td>LR Transponders</td><td>228</td><td>100 €/Gbit/s</td><td>2 280 000 €</td></tr>
<tr><td rowspan="2">Optical</td><td>OXCs</td><td>12</td><td>20 000 €</td><td>240 000 €</td></tr>
<tr><td>OXC Ports</td><td>754</td><td>2 500 €</td><td>1 885 000 €</td></tr>
<tr><td colspan="6">Total Network Cost</td><td>9 919 500 €</td></tr>
</table>

Table 6.39: Detailed description of the CAPEX value for the realistic network, considering a descending ordering rule.

6.2.3 Comparative Analysis

Economics

The following table 6.40 contains a summary of the CAPEX values obtained for the realistic network. As expected, for a complex real network such as the vBNS the performance of heuristic algorithms largely transcends the results provided by statistical methods. Choosing different ordering rules it was observed that both rules provided lower CAPEX values for the network when compared to the analytical method. A descending ordering rules appears to favor more efficient routing and grooming strategies on the network. Here the idea was to start by processing the bigger demand requests first, in this case the ODU4 demands, once they are harder to fit, thus providing a better grooming arrangement and the assignment of optimal paths. Relatively to the ILP model, it was not possible to reach a solution for this problem once the network is too complex, thus proving one of the downsides of this method for practical applications.

		Heuristic (descending order)	Heuristic (ascending order)	Analytical	ILP
Realistic network	Link Cost	3 752 000 €	3 992 000 € (+6,4%)	3 148 400 € (-16,1%)	Not possible to achieve
	Node Cost	6 167 500 €	6 402 500 € (+3,8%)	8 241 750 € (+33,6%)	
	CAPEX	9 919 500 €	10 324 500 €(+4,1%)	11 390 150 €(+14,8%)	

Table 6.40: Results comparison between heuristics and analytical models.

The existence of an inconsistency should also be noted, since in the analytical method although it presents a higher total CAPEX value, which was suppose to, the links part of the cost is substantially lower that the cost obtained through the heuristic methods. This situation may be explained by a poorly chosen value for the grooming coefficient.

Execution time

The following table 6.41 contains information regarding the execution time of each model. Once again, for the analytical model it is assumed to be an instantaneous process.

		Heuristic	ILP
Realistic network (vBNS)	Elapsed time	16 s	Timed out after 24 hours

Table 6.41: Comparison between the execution time of the heuristic and ILP methods for the realistic network.

When the complexity of the problem arises ILP models reveal to be poorly scalabe, and in this case for larger and more complex networks the heuristic models tend to have an even much superior performance in terms of execution time. As expected, for the realistic network selected, only the heuristic model was capable of providing a solution in a reasonable amount of time. The defined deadline was 24 hours and the ILP was not capable of meeting this agreement, thus, once again demonstrating that heuristic methods are crucial for network planning.

6.3 Chapter summary

Usually ILP models present better performances for solving simpler network dimensioning problems, however, they suffer from a poor scalability factor. As the problem becomes more complex and consequently the range of possible solutions enlarges, the execution time of these models arises exponentially. That is where the heuristic models come in hand, being capable to solve problems where there is no known efficient way to find a solution quickly and accurately since they have low time complexity. Having that said, the use of heuristic models in simple networks is usually related with the process of calibration, to verify the existent gap between the optimal solution provided by an ILP model and the one provided by the heuristics, which should as minimal as possible. This conclusions were supported by the results above mentioned, for the simple case of the reference network the heuristics were quicker to obtain a solution, and that same solution although near the optimal was partially higher for some cases. When it came to the study of a real and more complex network, unlike the ILP model the developed heuristics were capable of providing a solution and in a reasonable amount of time, thus, demonstration the poor scalability factor of the ILP models.

Chapter 7

Conclusions and future directions

The present chapter serves the purpose of reviewing and comparing the results obtained in the previous chapter for the analytical, the ILP and the heuristic models for the different networks and traffic scenarios designed, in order to elaborate some master conclusions. This chapter is divided in two main sections, in section 7.1 is made a review on the work developed along the dissertation and summarize the main conclusions obtained and in section 7.2 some suggestions for improvement and future research are provided.

7.1 Conclusions

This dissertation begins by introducing some of the main concepts on the optical networking area and a more specific explanation on transparent networks. In order to calculate the CAPEX of a network different models were used, more specifically, an analytical and a heuristic model here proposed and an ILP from a previous dissertation was used for comparison purposes. To perform a detailed study of this models two different networks were used, a more simplistic reference network, composed of 6 nodes and 8 bidirectional links, and one other real and more complex network comprised of 12 nodes and 17 bidirectional links. Additionally, various traffic scenarios were defined for each network in order to analyze their behavior. Throughout this dissertation it was developed and implemented a set of heuristic algorithms, for transparent optical networks dimensioning purposes. In order to implement those algorithms a generic framework had to be created and then implemented over the NetXPTO-NetPlanner simulator, an academic open source real-time simulator, which allows the creation of generic systems comprised of a set of blocks that interact with each other through signals. The created simulator is extremely adaptable since it contemplates a vast list of entry parameters, representing the specific characteristics of the network to be tested, that may be modified according to the user preferences. Although the simulator only contemplates the case of transparent networks without survivability this platform was designed to be sufficiently generic so that in the future it can be complemented with other features such as different transport modes (opaque and translucent) and different protection schemes, such as, 1+1 and dedicated paths. A final report is also generated after the completion of each simulation and the model of costs, provided in this dissertation, is applied in order to obtain the heuristics results presented in chapter 6. The objective was to perform two comparative studies regarding the CAPEX solutions provided and the time of execution metrics of the different models used. This study was initially performed for the reference network in order to evaluate the existent gap between the CAPEX values provided by the ILP model, considered to be the optimal solutions, and the ones given by the developed heuristics and the analytical model just for a matter of calibration. Looking now for the results obtained we concluded that the heuristics applied were well calibrated since the margin of error towards the ILP results was minimal, under 2% for the medium and high traffic scenarios, or even nonexistent for the low traffic scenario, which means that for simpler cases the heuristics performance can match the ILPs. Having that said, it was now possible to apply the heuristics to a real and more complex network, in this case the chosen network was the vBNS, where a medium-high traffic scenario was applied. Here only the heuristic algorithms were capable of providing dimensioning solution in a reasonable amount of time, about 16 seconds, while the ILP model was not capable of encountering the solution under a maximum defined timeout period of 24 hours, thus, once again showing that these algorithms may be a good solution for real and more complex problems considering that the ILP models for these cases take a long time to obtain results.

7.2 Future directions

During this dissertation some specific situations were analyzed and some open issues were discovered. Since there is always space for improvement especially when optimization is involved, some future work suggestions are provided below:

1. Allow the possibility of existing protected traffic, the present platform does not take into account either the existence of shared protection or dedicated link protection.

2. Implement the opaque and translucent transport modes, since this platform only considers the possibility of transparent networks.

3. Perform studies considering multiple transmission systems in each link, although the present platform allows this possibility, this case was not studied.

4. Regarding the scheduling algorithm, consider the use of other metrics, such as, the length of the shortest logical or physical paths in terms of distance, the need for protection paths, the quality of the path set in terms of desirable path options or a smart combination of some of this aspects.

5. Regarding the routing strategy, consider the use of other metrics, based for example on the lengths of the shortest paths and the need for protection or optical regeneration.

6. Giving continuity to the GIT repository, where all the documents and developed code regarding this dissertation and some other previous works in the same field of investigation, were released.

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