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Desenvolvimento de Heurísticas para o Dimensionamento de Redes Óticas Transparentes

Development of Heuristics for Transparent Optical Networks Dimensioning

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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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Palavras-chave

CAPEX, heurísticas, redes óticas de transporte transparentes, camda lógica, camada física, algoritmos, escalonamento, encaminhamento, agregação, sobrevivência, método analítico, 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 global 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 suficientemente genérica para suportar diversos algoritmos. No âmbito desta tese foram desenvolvidos algoritmos de escalonamento dos pedidos baseados na quantidade de tráfego de cada pedido e ainda 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 apesar de se considerar a possibilidade de haver pedidos bloqueados. 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 as heurísticas desenvolvidas tendo por base os valores obtidos através de um modelo analítico e um modelo baseado em programação linear inteira desenvolvida numa dissertação anterior. Finalmente, são partilhadas e discutidas algumas conclusões e direções para o desenvolvimento de trabalho futuro.

Keywords

CAPEX, nodes, links, physical and logical topologies, transparent, heuristics, survivability, integer linear programming, analytical approach, routing, aggregation

Abstract

In this dissertation a study is conducted on the design and optimization of optical transparent networks. The key elements of networks are nodes and links, having that said, depending on the way they are connected and of the transport mode considered their physical and logical topologies can vary. In order to perform a thorough analysis it was chosen a specific arrangement of nodes and links and three different scenarios of ejected traffic in the network to obtain a wider and more significant spectrum of results. In order to optimize network design processes, some heuristic traffic organizing, forwarding and aggregation algorithms were developed and validated in this dissertation, based on the transparent transport mode without survivability case. The objective was to produce architectures, where a minimum amount of resources is utilized, thus minimizing the CAPEX of the network while also trying to guarantee the total traffic routing. A detailed and comparative study, considering the CAPEX, is also performed with values obtained through the Analytical approach, the Integer Linear Programming models from a previous dissertation and the heuristics proposed here. Finally, some conclusions and possible future work are discussed.

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List of acronyms

CAPEX	Capital Expenditure
IP	Internet Protocol
IPS	Input Parameters System
M2M	Machine-to-Machine
OADM	Optical Add/Drop Multiplexer
ODU	Optical Data Unit
O-E-O	Optical-Electronic-Optical
OPEX	Operational Expenditure
OTN	Optical Transport Network
QoS	Quality of Service
SDH	Synchronous digital hierarchy
SONET	Synchronous optical networking
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 their functions grown as well, in such a manner, that nowadays they may also include traffic integrity and survivability aspects, network management and performance monitoring, between others [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 [1]. Nowadays, telecommunication networks allow real-time worldwide communications.

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, 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. In those there is a dynamic allocation of transmission bandwidth, allowing many users to share the same transmission line and thus reducing the wastage of available transmission bandwidth resources [3], in contrast to old circuit switched networks where the same was pre allocated. These revolutionary packet-based digital networks proved to have superior performance regarding various aspects such as connection time, reliability, economy, flexibility and much more [4].

The current leading communication protocol used to transmit signals over optical fiber links is defined by ITU-T, as Optical Transport Network (OTN), its composed of a set of Optical Network Elements connected by optical fiber links, able to provide functionalities of transport, multiplexing, routing, management, supervision and survivability of optical channels carrying client signals, according to the requirements given in Recommendation G.872[5]. It integrates transport for all digital payloads with superior performance relatively to previous optical WDM transport solutions, Synchronous optical networking (SONET) and Synchronous digital hierarchy (SDH).

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 [6]. Access networks usually connect directly to end users, providing interfaces that operate at bit-rates suitable to support various different applications and typically covering a small geographical area, spanning the last tens of kilometers to the end user [7]. 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. [8]

Devices and connection demands to the Internet have been growing unbelievably fast mainly due to ,among other aspects, the expansion of optical fiber to customers homes, the recurrent variety of new broadband services, and business virtual private networks with remote access to huge databases, which also translates in a growth in Internet-based applications [2]. Each year, various new devices in different form factors with increased capabilities and intelligence are introduced and adopted in the market. Also the growing number of Machine-to-Machine (M2M) applications, such as smart meters, video surveillance, healthcare monitoring, transportation, and package or asset tracking, are contributing in a major way to that previously mentioned growth of devices and connections. One of the main contributing factors to growing traffic is consumer video use, with cloud storage or online social networks traffic being of major importance. All of this results in a major increase of Internet Protocol (IP) traffic as we can see below in Figure 5.3.

[9]

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. Currently carriers

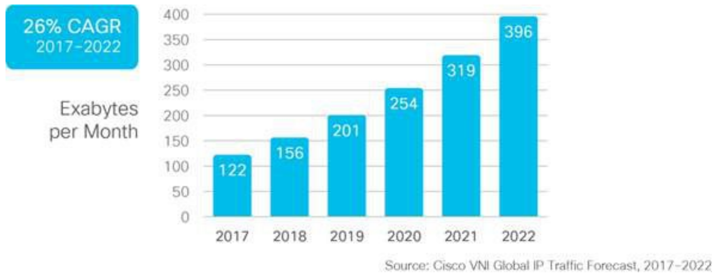


Figure 1.1: Cisco forecasts per month of IP traffic from 2017 until 2022.

are demanding WDM optical networking technologies that provide both low capital expenses and low operational expenses [2] 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). The cost factor is therefore a major issue in the telecommunication industry and tend to have strong influence in all engineering decisions. Therefore, any network investment must be evaluated from an economic perspective.

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 telecommunication industry and tend to have a strong influence in all engineering and administrative decisions, once it directly affects competitiveness of system vendors and network operators [8]. 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. 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 academic environments. Therefore, arose the interest and opportunity to develop the 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 and implemented in that same platform, offering near optimal solutions in shortest periods of time when compared with other methods, for instance the ILP models, due to the less complexity. 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, our 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. Create a generic framework for optical transport networks dimensioning.

2. Implement the framework recurring to the NetXPTO-NetPlanner simulator creating a generic platform.

3. Develop heuristic algorithms for transparent networks without survivability dimensioning and implement those in the previous platform.

4. Define one reference network and various different traffic scenarios for test performing purposes.

5. Calculate the analytical solutions for the various scenarios.

6. Elaborate a comparative study, regarding the subject of capital expenditure, with the results obtained through analytical and ILP models, this last from a previous dissertation.

1.3 Dissertation outline

This dissertation is organized in 7 chapters. Chapter 2 serves the purpose of a state-of-art review of optical transport networks dimensioning. Addi In chapter 3 a general description of the elaborated framework is provided as well as of the individual entities that it is comprised of,

1.4 Major Achievements

There are two main goals that this dissertation pretends to achieve. The first is to a generic platform over the NetXPTO-NetPlanner simulator over which heuristic algorithms can be developed, implemented and tested. Those algorithms must be capable of dimensioning transparent optical networks based on the entering traffic of the network, physical topology adjacency matrix, amongst other aspects. And the other objective is to obtain estimations for the capital expenditures of the dimensioned networks for both analytical, ILP and heuristic methods for a vast number of different scenarios.

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 and to define both a reference and a realistic network that will be used for the various types of dimensioning processes.

In the modern telecommunications era networks a vast and highly multidisciplinary field of study as it shall be seen further in 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 Capital Expenditure (CAPEX) of the network.

In the transparent transport mode, which will be the transport mode addressed, signals remain in the optical domain from its source to 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 [13]. 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[14]. 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 [13].

Regarding the network economic aspects, the dimensioning of a telecommunication network involves identifying the required resources and their respective quantities [15]. As both setting up and operating large telecommunications infrastructures require large amounts of money any network investment must be carefully evaluated [16]. These costs can be divided into two major branches: the CAPEX and the Operational Expenditure (OPEX). The first will be analyzed more closely in this dissertation and can be sub-divided into the cost of buying and installing the equipment's and setting up the infrastructures and the second represents an expense a network company incurs through its normal operations, which include rent, equipment, inventory costs, insurance, and funds allocated for research and development [8][17].

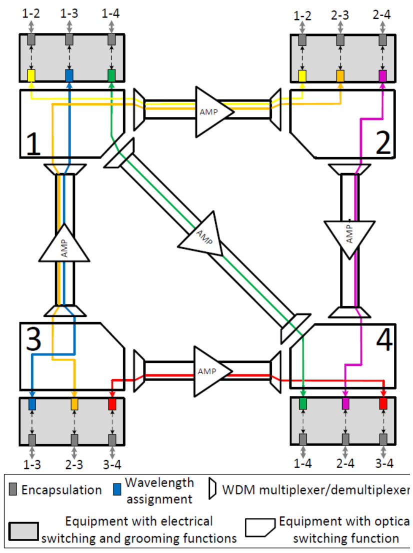


Figure 2.1: Example of an all-optical network with 4 nodes [13].

Above in figure 2.1 an example of 4 nodes all-optical network is shown where a single-hop grooming technique is used and O-E-O conversions only happen at end nodes.

2.1 Network Architecture

Telecommunication transport networks are essentially made of links and nodes, each of them comprising many other components. Links and nodes are interconnected through compatible interfaces in order to form, in a first instance, the physical topology. Therefore, a network topology can be described as the arrangement of nodes and links, and are usually represented as a graph, as it shall be seen further along in section 2.3.

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 [18]. Links can be composed by one or more transmission systems where each one comprises one pair of unidirectional optical fibers ensuring a bidirectional connection between nodes.[13] The optical fiber is the medium where the optical signal is transmitted and is capable of transporting data on wavelengths [19]. 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.[2] The distance between each amplification stage is typically called span.

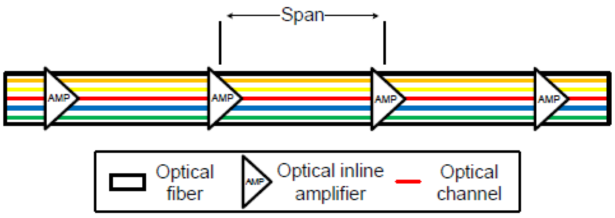


Figure 2.2: Schematic of a link: optical fiber and inline optical amplifiers.[13]

2.1.2 Nodes

Nodes are multirack systems that usually perform three major functions in optical networks being them as it follows: grooming lower data rate traffic into a higher bit rate wavelength channels, multiplexing various wavelengths into a WDM signal and routing that same signal to its destination through the correspondent interfaces [20]. All of these tasks will require a substantial amount of hardware making the nodes one of the most expensive components of the network [8]. Moreover, as the transiting traffic can potentially remain in the optical domain, 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. These 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, wavelength assignment and WDM multiplexing. Regarding the shelves they provide a common infrastructure to the modules and the rack to support and provide power to the shelves [13]. 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. Finally shelves are attached into racks, which consist in frames for mounting multiple shelves and providing power to the entire system.[20]

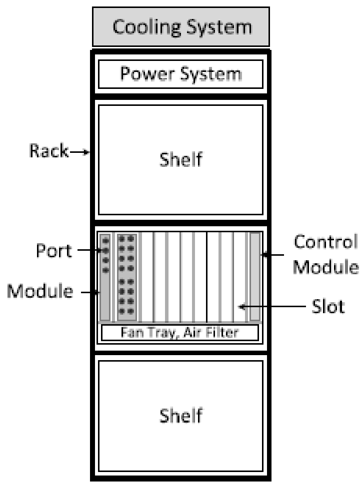


Figure 2.3: Schematic of a node structure[20].

2.2 Network Topologies

2.2.1 Physical Topology

The pattern that represents and characterizes the layout of an optical network, i.e., the disposition of nodes and the physical 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 [16].

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, but in this dissertation the focus will be on the transparent transport mode [21]. Likewise the physical topology previously referred it can also represented as a graph or through adjacency matrices.

2.3 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.

2.3.1 Physical Topology

As it is possible to see in figure 2.4 for this specific case the reference network consists in 6 nodes interconnected by 16 unidirectional links that combined constitute 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.

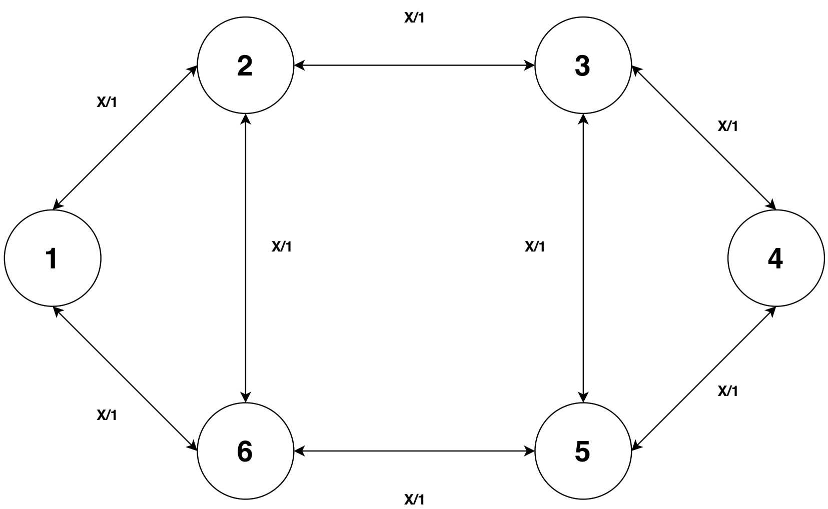


Figure 2.4: Reference network physical topology graph representation.

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 2.1: Reference network physical topology adjacency matrix.

Above in figures 2.4 and 2.1 the physical topology of the same 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 2.2: Table of reference network values.

2.3.2 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.

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

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

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

Through these ODU's we can calculate the total network traffic for the low traffic scenario:
$T_1^0 = 120\text{x}1.25 = 150$ Gbits/s $\qquad T_1^1 = 100\text{x}2.5 = 250$ Gbits/s $\qquad T_1^2 = 32\text{x}10 = 320$ Gbits/s

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

$T_1 = 150 + 250 + 320 + 480 + 800 = 2000$ Gbits/s $\qquad T = 1000/2 =$ **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 ODU's we can calculate the total network traffic for the medium traffic scenario:

$T_1^0 = 600\text{x}1.25 = 750$ Gbits/s $\quad T_1^1 = 500\text{x}2.5 = 1205$ Gbits/s $\quad T_1^2 = 160\text{x}10 = 1600$ Gbits/s

$T_1^3 = 60\text{x}40 = 2400$ Gbits/s $\quad T_1^4 = 40\text{x}100 = 4000$ Gbits/s

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

High Traffic Scenario

In this case it was chosen to have a total unidirectional traffic of 12 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 ODU's we can calculate the total network traffic for the high traffic scenario:
$T_1^0 = 1200\text{x}1.25 = 1500$ Gbits/s $\quad T_1^1 = 1000\text{x}2.5 = 2500$ Gbits/s

$T_1^2 = 320\text{x}10 = 3200$ Gbits/s $\quad T_1^3 = 120\text{x}40 = 4800$ Gbits/s

$T_1^4 = 80\text{x}100 = 8000$ Gbits/s $\quad T_1 = 20000$ Gbits/s

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

2.4 Realistic Network

The nodes are geographically distributed as shown in figure 2.5. As it can be seen this network is composed of 12 nodes and 17 bidirectional links.

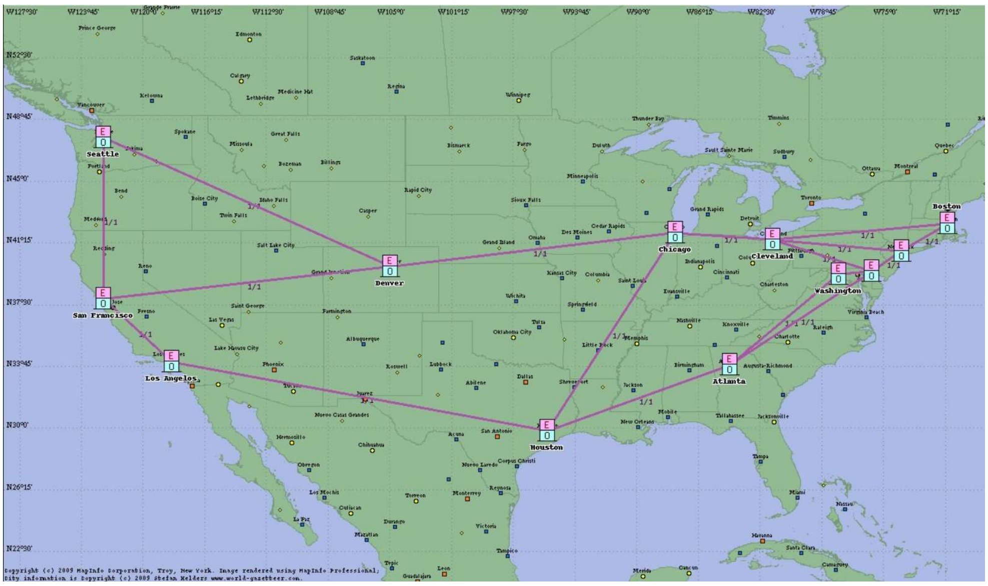


Figure 2.5: The Very-High Performance Backbone Network Service[22].

In order to re validate the developed heuristic algorithms it was decided to apply them into a real and more complex network, either in terms of size and capacity. 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 by 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 [23]. As before the transparent transport mode without survivability will be in focus.

2.4.1 Physical Topology

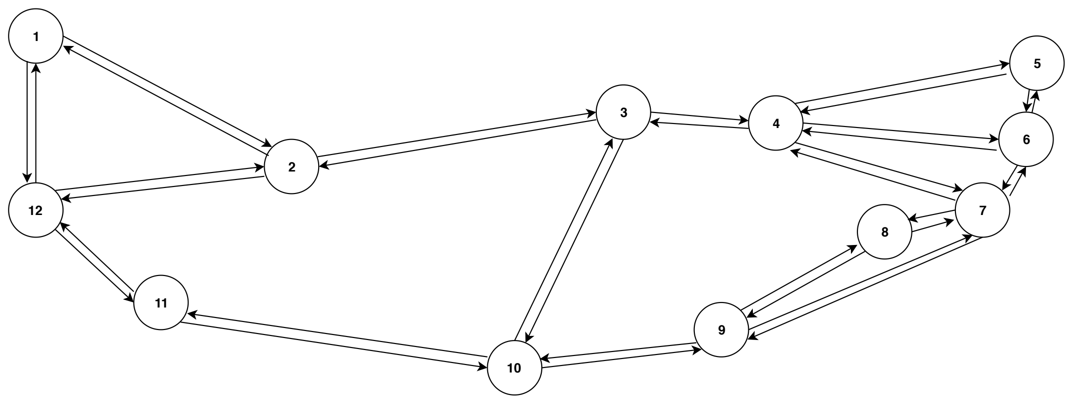


Figure 2.6: Physical topology graph representation.

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 2.3: Physical topology adjacency matrix.

Above in figures 2.6 and 2.3 the physical topology of the realistic network is specified as a graph and in an adjacency matrix, respectively.

In table 2.4 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
<δ>	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 2.4: Table of reference network values.

2.4.2 Traffic Matrices

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

2.5 Capital Expenditure Model

As networks are in a first instance 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 calculated by the 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.

2.5.1 Links Cost

First lets focus on the cost of the links part, C_L, in monetary units (e.g. euros, or dollars), which can be calculated through equation 2.2. In optical transport networks, links are point-to-point connections that interconnect two network nodes.[8] Furthermore, 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 equipment (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 once it is commom pratice in telecommunications for operators to lease fiber-optic cables instead of installing them [8]. In this dissertation each existent link is considered to possess just one transmission system. The typical architecture of an optical transmission system is represented below in figure 2.7.

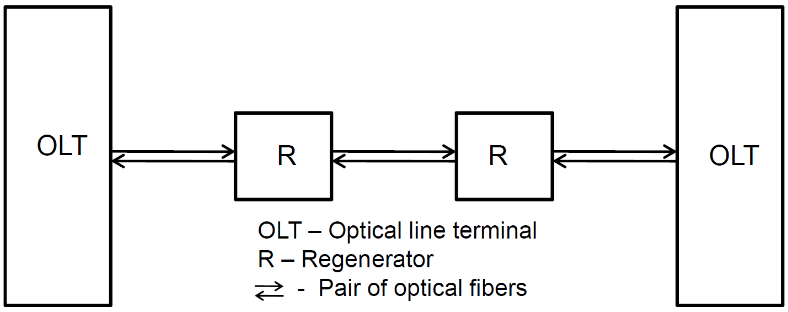


Figure 2.7: Generic optical transmission system [16].

In order to calculate the cost of the links, let's use equation 2.2.

$$C_L = \left(2L\gamma_0^{OLT}\right) + \left(2L\gamma_1^{OLT}\tau < w >\right) + \left(2N^R c^R\right) \tag{2.2}$$

where

- $\gamma_0^{OLT} \rightarrow$ OLT cost in euros
- $L \rightarrow$ Number of bidirectional links
- $\gamma_1^{OLT} \rightarrow$ Transponder cost in euros
- $< w > \rightarrow$ Average number of optical channels

- $\tau \rightarrow$ Line bit rate
- $N^R \rightarrow$ Total number of optical amplifiers
- $c^R \rightarrow$ Unidirectional Optical amplifiers cost in euros

Although mean values are used in equations 2.2, 2.5 and 2.6, it is important to notice that there are no mathematical approximations involved.

Through equation 2.3 it is possible to reach the number of optical amplifiers, N^R, as

$$N^R = \sum_{l=1}^{L} \left(\left\lceil \frac{len_l}{span} \right\rceil - 1 \right) \tag{2.3}$$

where len_l is the length of link l and *span* is the distance between amplifiers (here assumed 100 km) [16].

Again assuming that τ is 100 Gbits/s the only remaining unknown parameter is the number of optical amplifiers and the average number of optical channels [16]. This is where the various methodologies will diverge, once the average number of optical channels will depend directly of $< h >$, the average number of hops per demand, and of D which is the number of unidirectional demands processed by the network. While the analytical method uses approximated values for this parameters the ILPs and heuristics have access to all the information and as such will utilize the optimal values found by the algorithms.

2.5.2 Nodes Cost

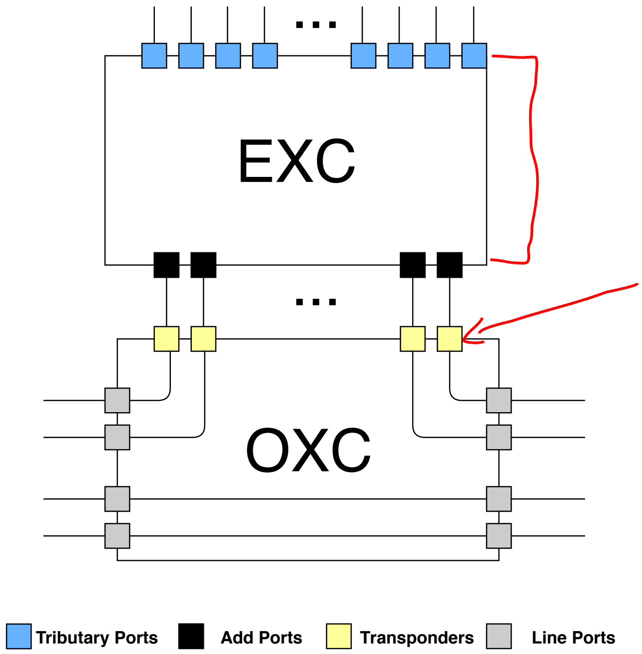
Regarding the nodes part of the costs, in transparent network nodes it is necessary to consider both the optical and the electrical parts, as it can be seen below in figure 2.8. The channels that just go through the node are switched in the optical domain and the channels that are local to the node are processed in the electrical domain, with the switching being performed in the wavelength-domain [16]. So, as the nodes have an electrical part and an optical part 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} → Optical node cost in monetary units (e.g. euros, or dollars)



add. ports

Figure 2.8: 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 [16]. Since in this case we have the interest in knowing the specific quantities of each of the port types that compose either the electrical and optical parts of the nodes, the use of mean values

$$C_{exc} = N \times (\gamma_{e0} + (\gamma_{e1}\tau < P_{exc} >)) + \gamma_{e1}P_{TRIB} \tag{2.5}$$

where:

- N → Number of nodes
- γ_{e0} → EXC cost in euros
- γ_{e1} → EXC port cost in euros
- τ → Line bit rate

- $< P_{exc} >$ → Average number of ports of the electrical switch
- P_{TRIB} → Total number of tributary ports

In relation to the optical part, C_{oxc}, to know the optical cost of the nodes that is given by equation 2.6

$$C_{oxc} = N \times (\gamma_{o0} + (\gamma_{o1} < P_{oxc} >)) \tag{2.6}$$

where:

- N → Number of nodes
- γ_{o0} → OXC cost in euros
- γ_{o1} → OXC port cost in euros
- $< P_{oxc} >$ → Average number of ports of the optical switch

So the electrical switch is composed of tributary and add ports. On the other hand, the number of ports of the the optical switch, is equal to the sum of the line ports with the add ports [18]. Once more, we have to take into account that the calculated value for the variables $< P_{exc} >$ and $< P_{oxc} >$ will depend not only on the mode of transport used but also of the approach taken and the variable P_{TRIB} will depend on the traffic scenario. Finally, in order to make these calculations it will also be needed to take into account the cost of the equipment used which can be consulted in table 2.5.

Equipment	Symbol	Cost
OLT without transponders	γ_0^{OLT}	15 000 €
Transponder	γ_1^{OLT}	5 000 €/Gbit/s
Unidirectional Optical Amplifier	c^R	2 000 €
EXC	γ_{e0}	10 000 €
OXC	γ_{o0}	20 000 €
EXC Add Ports ???	γ_{e1}	100 000 €/port
EXC Tributary Ports	γ_{e2}	1000 €/Gbit/s
OXC Port	γ_{o1}	2 500 €/port

Table 2.5: Table of costs used to calculate CAPEX using analytical models [8].

2.6 Capital Expenditure Estimation

2.6.1 Analytical Model

Through equations 2.7 and 2.8 it becomes possible to calculate the remaining unknown variables. The average number of optical channels [18], $< w >$, as

$$< w >= \left(\frac{\lceil D \times < h > \rceil}{L_u} \right) (1+ < k >) \tag{2.7}$$

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

$$D = \left(\frac{1}{2} \right) (1 + \xi) \left(\frac{T_1}{\tau} \right) \tag{2.8}$$

where ξ is the grooming coefficient, T_1 is the total unidirectional traffic and τ is the line bit rate [18].

Taking into account the particularities of the transparent transport mode it will be need to assume the following values:

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

It will be assumed that the grooming coefficient has value 1.25 that the survivability coefficient is zero because it non survivability is considered.

Finally looking at the equation 2.5 we can see that we already have practically all the values with the exception of three variables. The tributary ports, P_{TRIB}, that can be calculated through the ODU's matrices referred to in section 2.3.2, 2.3.2 and 2.3.2, and the average number of ports of the electrical switch,$< P_{exc} >$, that can be calculated as

$$< P_{exc} >=< d > \tag{2.9}$$

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

$$< P_{oxc} >=< d > [1 + (1+ < k >) < h >] \tag{2.10}$$

where $< d >$ is the average number of demands, $< k >$ is the survivability coefficient and $< h >$ is the average number of hops.

2.6.2 ILP Model

2.6.3 Heuristic Model

Chapter 3

Generic Heuristics Framework

In this chapter is intended to perform a description of the generic framework developed ~~and implemented on NetPlanner NetXPTO simulator along this dissertation~~. 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 the rectangle shapes represent the main entities of the framework.

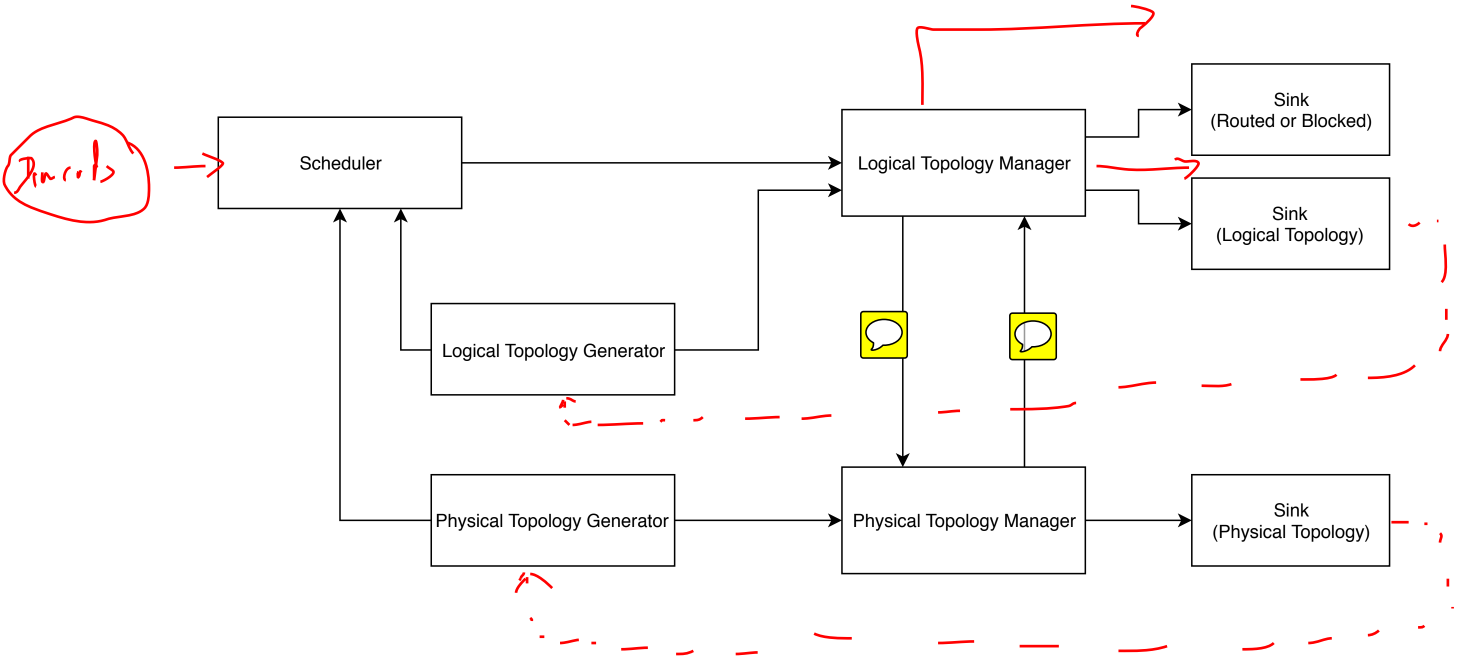


Figure 3.1: Top level diagram of the developed framework.

3.1 Scheduler

When global optimization techniques such as integer linear programming are utilized 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 an heuristic approach. 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 criteria. That same order becomes the order by which demands will be routed or blocked. Demands can be sorted in many different ways when recurring to different strategies, which usually also have different impacts on the cost of the network, the loading in the network and the blocking probability. Those strategies may rely individually on the quantity of traffic of each individual 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 but in general none of them reclaims the best results for every practical scenario.

3.2 Logical Topology Generator

Based on the physical topology adjacency matrix of the network and the transport mode utilized (opaque, transparent or translucent) ~~data structures can be created to represent a new upper layer of the network,~~ the logical layer, which will mostly be comprised of lightpaths, in which the information is carried. This data structures will represent the initial state of the logical layer of the network, and they can either be created void, if the network has no previous information, or an intermediate state can be loaded from a file. This data is subsequently passed to the logical topology manager block, where the routing and grooming heuristics algorithms that depend directly of the logical topology are implemented, and will be continually updated as demands are processed.

3.3 Physical Topology Generator

Here are created data structures to portray the initial physical layer state of the network. It consists in a set of physical links, which interconnect pairs 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. The number of existent transmission systems per link isn't static and as such can be defined by the developer according to each case necessity. 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.

3.4 Logical Topology Manager

In this block the initial logical layer, originating from the logical topology generator block, is stored and continuously updated as demands are processed. The routing and grooming 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 will contain information of the existent paths, lightpaths, etc. While processing a demand if there is no available path for it then a new shortest path should be selected, based on a defined strategy, and a request sent to the physical layer in order to that path to be established. Depending on the physical topology manager response either a path is created to route the demand or in the case it is not possible to do so the demand remains blocked. Only a demand request serves as input for this block but on the other hand the outputs can differ as they can represent a request to establish a path, sent to the physical layer manager of the network, or simply the information about whether or not a demand was routed.

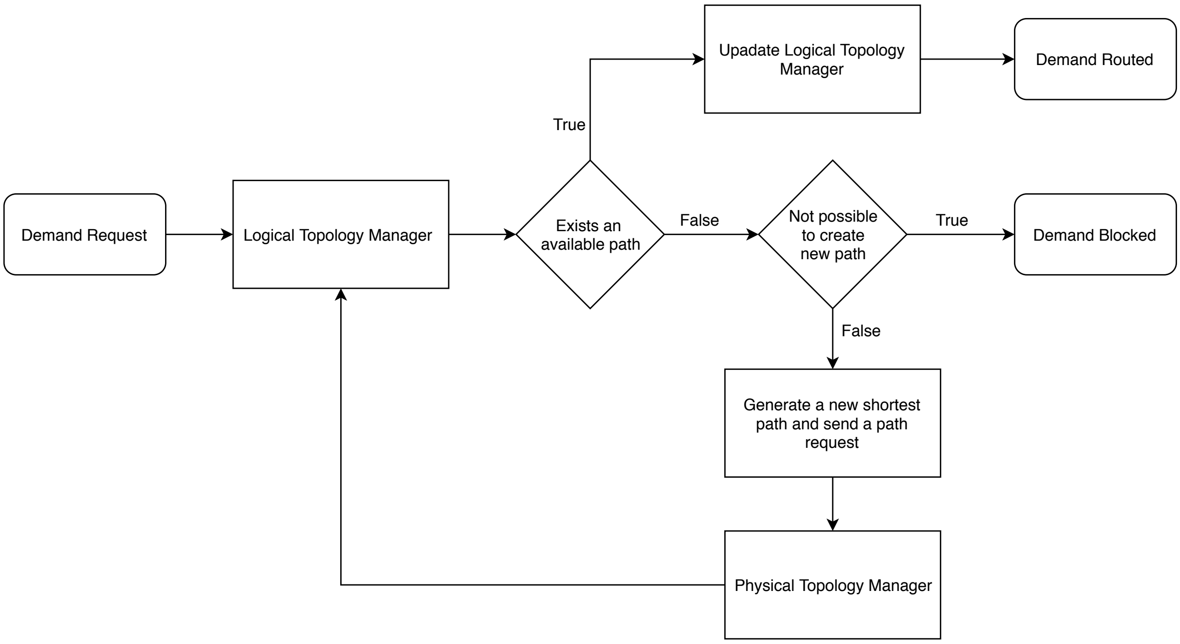


Figure 3.2: Flowchart representing the interaction between the logical and physical topology manager entities while processing a demand request.

3.5 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 a path. When a path is selected for a demand in the logical layer and a request is made for it and sent here, that path must be broken into sub-connections, if necessary, and each of the sub-connections assigned with a wavelength if possible, thus, the wavelength assignment strategy should be applied here. This need arises from the wavelength continuity property of optical-bypass-enabled networks and as such 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 sub-connections, 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.

3.6 Sink

Here the final states of the network are stored. Three blocks are in need, a first for the demands processed and two others for the logical and physical layer states of the network. The information about every traffic demand processed can be stored here, where each demand is properly identified by an unique index. Additionally, information regarding the demand status (routed or blocked) must be present, and in the case it has been successfully routed the path taken must also be identified by its respective index. The final values of the data structures that comprise the logical and the physical layers of the network are also to be stored and can be consulted. Combining all this information it is possible to trace the routing scheme of all the processed demands and elaborate an economic study regarding the capital expenditures of the network.

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. 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 are 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. More global information about each block input parameters/signals, state variables and output signals is present in sections 4.4 and 4.5 and finally on section 4.6 a generic description is given on how to interpret the final report generated by the system after running each simulation.

4.1 Input Parameters System

The execution of this simulator is based in a group of 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 same 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.

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	"opaque" or "transparent" This thesis focus only on 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 wavelenght used expressed in nanometers.
wavelenghtSpacing	0.8	Interval between used wavelenghts. (nm)
opticalChannelCapacity	80	Physical capacity of each optical channel expressed in number of ODU0 demands.
routingCriterionLogicalTopology	Hops	Shortest path type.
routingCriterionPhysicalTopology	Hops	Shortest path type.
blockingCriterionLogicalTopology	1	Number of attempted logical paths before blocking a demand.
blockingCriterionPhysicalTopology	3	Number of attempted conversions before discarding a logical path.

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.

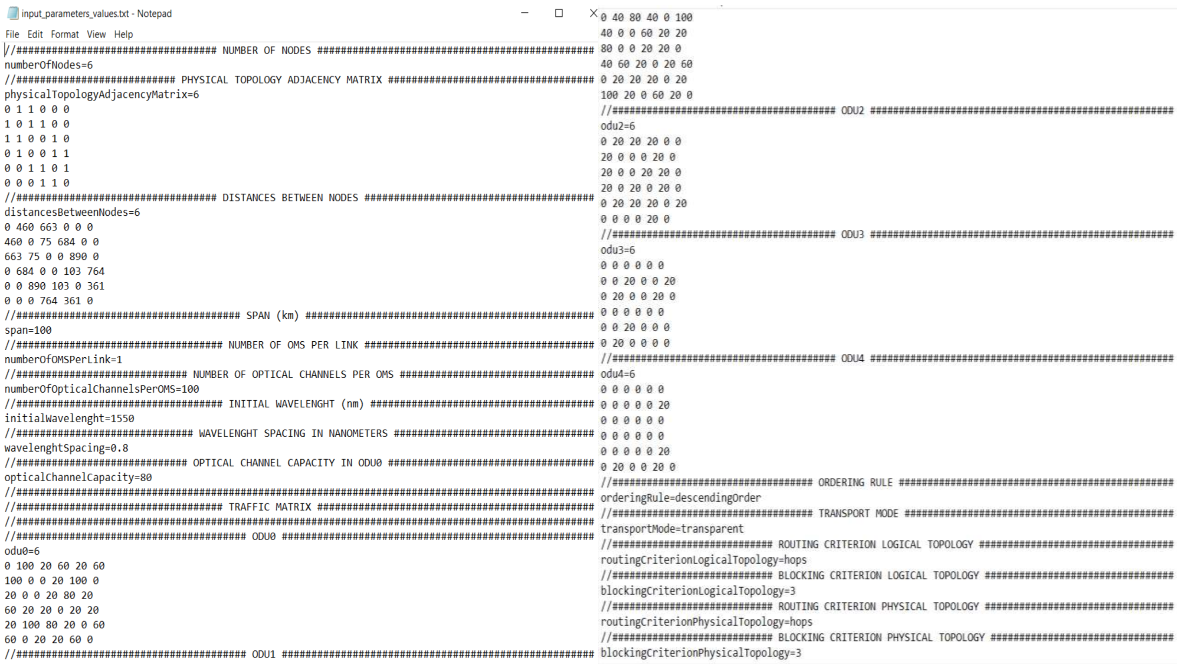
2. In the case of input paramenter of the matrix type, ODU traffic matrices and physical and logical topologies, newValue will assume the value of existing elements per line or column and the matrix value must be specified below this line.

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 is shown below in figure 4.1.



```
input_parameters_values.txt - Notepad
File Edit Format View Help
//################################## NUMBER OF NODES ##############################################
numberOfNodes=6
//########################### PHYSICAL TOPOLOGY ADJACENCY MATRIX ##################################
physicalTopologyAdjacencyMatrix=6
0 1 1 0 0 0
1 0 1 1 0 0
1 1 0 0 1 0
0 1 0 0 1 1
0 0 1 1 0 1
0 0 0 1 1 0
//################################## DISTANCES BETWEEN NODES ######################################
distancesBetweenNodes=6
0 460 663 0 0 0
460 0 75 684 0 0
663 75 0 0 890 0
0 684 0 0 103 764
0 0 890 103 0 361
0 0 0 764 361 0
//###################################### SPAN (km) ################################################
span=100
//################################## NUMBER OF OMS PER LINK #######################################
numberOfOMSPerLink=1
//############################## NUMBER OF OPTICAL CHANNELS PER OMS ###############################
numberOfOpticalChannelsPerOMS=100
//################################## INITIAL WAVELENGHT (nm) ######################################
initialWavelenght=1550
//############################## WAVELENGHT SPACING IN NANOMETERS #################################
wavelenghtSpacing=0.8
//############################## OPTICAL CHANNEL CAPACITY IN ODU0 #################################
opticalChannelCapacity=80
//#################################################################################################
//################################## TRAFFIC MATRIX ###############################################
//#################################################################################################
//######################################## ODU0 ###################################################
odu0=6
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
//######################################## ODU1 ###################################################
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
//######################################## ODU2 ###################################################
odu2=6
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
//######################################## ODU3 ###################################################
odu3=6
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
//######################################## ODU4 ###################################################
odu4=6
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
//################################### ORDERING RULE ###############################################
orderingRule=descendingOrder
//################################### TRANSPORT MODE ##############################################
transportMode=transparent
//############################ ROUTING CRITERION LOGICAL TOPOLOGY #################################
routingCriterionLogicalTopology=hops
//############################ BLOCKING CRITERION LOGICAL TOPOLOGY ################################
blockingCriterionLogicalTopology=3
//############################ ROUTING CRITERION PHYSICAL TOPOLOGY ################################
routingCriterionPhysicalTopology=hops
//############################ BLOCKING CRITERION PHYSICAL TOPOLOGY ###############################
blockingCriterionPhysicalTopology=3
```

Figure 4.1: **input_parameters_values.txt** file example.

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

Each node may be optical directly connected to each other, or only optical connected to adjacent nodes or optical connected to suitable nodes. These possibilities are demonstrated below on table 4.6, where 0/1 represents the existence of a logical connection between a pair of nodes.

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 matrix of N nodes.

Here value N represents the number of nodes present in the network. This variety of possible shorter optical paths along the route imposed by logical topology lead to a situation of three possible transport modes: opaque, transparent and translucent [21]. 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
0 or greater	1...N	1...N	0...80	0 or greater	[lp_1, lp_2, ...]

Table 4.3: Structure of a "Path" variable.

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
0 or greater	1...N	1...N	0..80	0 or greater	[och_1, och_2,...]

Table 4.4: Structure of a "Lightpath" variable.

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 [24]. Each lightpath is identified by a unique index and its capacity is also expressed in quantities of ODU0 demands. The number and an index of the optical channels that comprise each lightpath is 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
0 or greater	1...N	1...N	0...80	[to define]	0 or greater	[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 [18]. 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 matrix of N nodes.

Here value 1 simply indicates the existence of a physical link between a pair of nodes 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
0...L-1	1...N	1...N	OC	[w_1, w_2, ...]	[0/1 ... 0/1]

Table 4.7: Structure of a "Link" variable.

where

- OC is the number of existent optical channels in a link.
- L is the total number of existent unidirectional links in the network.
- w_1 is represents the wavelength value with the index number 1 associated.
- 0/1 indicates if the corresponding wavelength value is available or not to be used, 1 and 0 respectively.

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.

4.3.4 Path Request

Request Index	Demand Index	ODU Type	Source Node	Intermediate Nodes	Destination Node
0 or greater			1...N	1...N	1...N

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

A "Path Request" type signal is sent 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 are required. In this specific case, transparent transport mode, only direct logical connections will be taken into account, because, as previously mentioned, the information has to travel only 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.

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
0 or greater			true/false	0 or greater

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.

where, W is the actual value of the wavelength assigned to a lightpath.

This type 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 is possible to be created 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/false	0 or greater

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 Blocks input parameters and signals

Block	**Input Parameters**	**Input Signals**
Scheduler_	numberOfNodes, odu0, odu1, odu2, odu3, odu4, orderingRule	None
LogicalTopologyGenerator_	transportMode, physicalTopologyAdjacencyMatrix	None
PhysicalTopologyGenerator_	physicalTopologyAdjacencyMatrix, numberOfOMSPerLink, numberOfOpticalChannelsPerOMS, initialWavelenght, wavelenghtSpacing, opticalChannelCapacity	None
LogicalTopologyManager_	routingCriterionLogicalTopology, blockingCriterionLogicalTopology	Scheduler_Out, LogicalTopologyGenerator_Out, PhysicalTopologyManager_PathRequestRouted
PhysicalTopologyManager_	routingCriterionPhysicalTopology, blockingCriterionPhysicalTopology	PhysicalTopologyGenerator_Out, LogicalTopologyManager_PathRequest
SinkRoutedOrBlocked_	None	ProcessedDemand
SinkLogicalTopology_	None	FinalLogicalTopology
SinkPhysicalTopology	Node	FinalPhysicalTopology

Table 4.13: Blocks input parameters and signals.

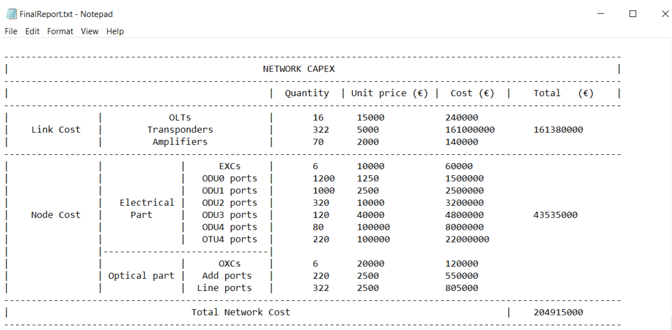
4.5 Blocks state variables and output signals

Block	State Variables	Output Signals
Scheduler_	odu0, odu1, odu2, odu3, odu4, demandIndex, numberOfDemands	Scheduler_Out
LogicalTopologyGenerator_	generate	LogicalTopologyGenerator_Out
PhysicalTopologyGenerator_	generate	PhysicalTopologyGenerator_Out
LogicalTopologyManager_	paths, lightPaths, opticalChannels, logicalTopologyAdjancencyMatrix	LogicalTopologyManager_PathRequest, ProcessedDemand
PhysicalTopologyManager_	opticalMultiplexingSystems, physicalTopologyAdjacencyMatrix	PhysicalTopologyManager_PathRequestRouted, FinalPhysicalTopology
SinkRoutedOrBlocked_	None	None
SinkLogicalTopology_	None	None
SinkPhysicalTopology_	None	None

Table 4.14: Blocks state variables and output signals.

4.6 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.


FinalReport.txt - Notepad
File Edit Format View Help

NETWORK CAPEX

			Quantity	Unit price (€)	Cost (€)	Total (€)
Link Cost	OLTs		16	15000	240000	
	Transponders		322	5000	161000000	161380000
	Amplifiers		70	2000	140000	
Node Cost	Electrical Part	EXCs	6	10000	60000	
		ODU0 ports	1200	1250	1500000	
		ODU1 ports	1000	2500	2500000	
		ODU2 ports	320	10000	3200000	
		ODU3 ports	120	40000	4800000	43535000
		ODU4 ports	80	100000	8000000	
		OTU4 ports	220	100000	22000000	
	Optical part	OXCs	6	20000	120000	
		Add ports	220	2500	550000	
		Line ports	322	2500	805000	
Total Network Cost						204915000

Figure 4.2: FinalReport.txt file example.

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 [25]. 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 [25]. Also they are able to produce a solution individually or to be used to provide a good baseline when supplemented with optimization algorithms [26]. There are many commonly used heuristics such as genetic algorithms, artificial neural networks and support vector machines [25]. 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, in this chapter some heuristic algorithms are proposed with a final major objective of minimizing the total CAPEX of a network. The developed algorithms in this dissertation were meant for traffic ordering, routing, aggregation and wavelength assignment purposes. Furthermore, they were all developed in C++ language with the aid of Visual Studio IDE.

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 the rectangle shape processes where can occur the simple assignment of a value to a variable, constant or parameter.

5.1 Scheduling

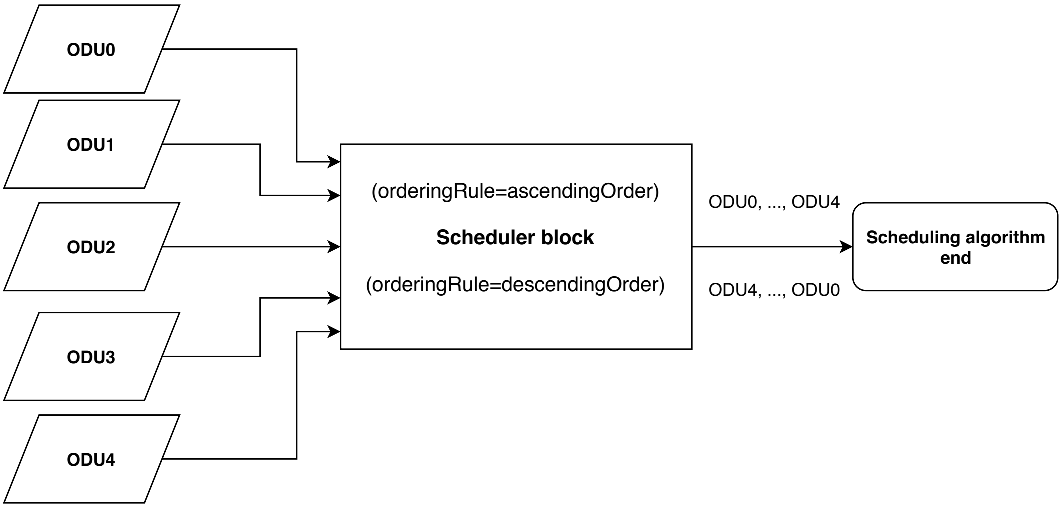


Figure 5.1: Scheduler algorithm illustration considering both ordering rules.

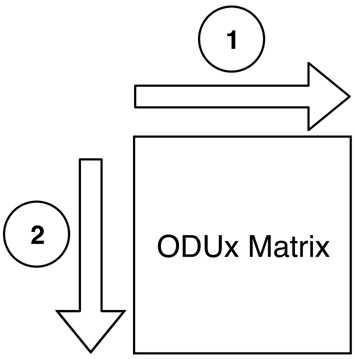


Figure 5.2: Scheduler algorithm illustration of how a ODUx traffic matrix is run through.

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 once 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 demands matrices are searched through can be seen in figure 5.2, from left to right the demands originating node 1 are the firsts to be processed and so on to the last node of the network. These choices may potentially affect the efficiency of the grooming process. The signal exiting from this block will be of the "Demand Request" type and will contain information of each demand's index, source and destination nodes, ODU type and survivability method chosen, if any. This signal is then sent to the logical topology manager. It is assumed that although multiple demands can be added at once to the network, each demand is processed individually before moving on to the next.

5.2 Logical Topology

As only the transparent transport mode is considered then the logical and physical topologies will differ from each other once the first one will be a full mesh network [21]. Below in figure 5.3 there is a graphical representation of the logical topology for the reference network considered in this dissertation.

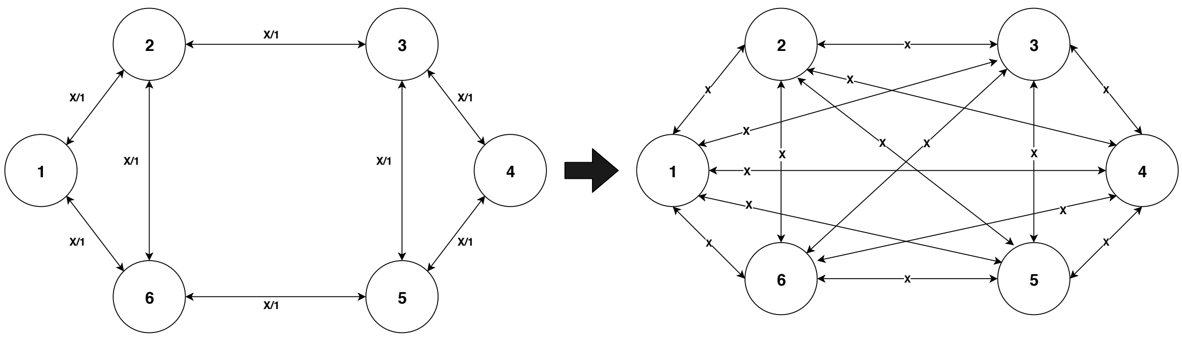


Figure 5.3: Logical topology algorithm: conversion from physical topology (left side) to the logical topology (right side) for transparent trasnport mode.

5.3 Routing

Routing is the process of assigning a unique path through the network for a demand request between source and destination nodes [2]. The number of paths generated can vary according to the user preference and so can the chosen key factor of Dijkstra's algorithm. Some examples to be considered are the number of links in the path, i.e., the number of hops, the distance of each path or the probability of the links being available. In this last case the metric is unrelated to distance and as such the term 'shortest paths' may in some cases be a misnomer [2]. The first step to take into account when a demand request 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.

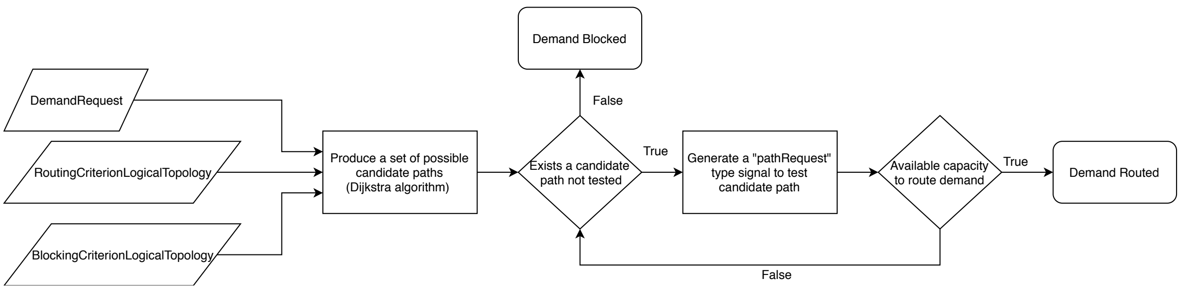


Figure 5.4: Routing algorithm code flow.

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 algorithm, in order to find the K-shortest paths between a source and a destination node [2]. 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 5.4. So 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, generating 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 is used a dynamic-path routing strategy[2], once it provides adaptability to network conditions. Here 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 Wavelength Assignment

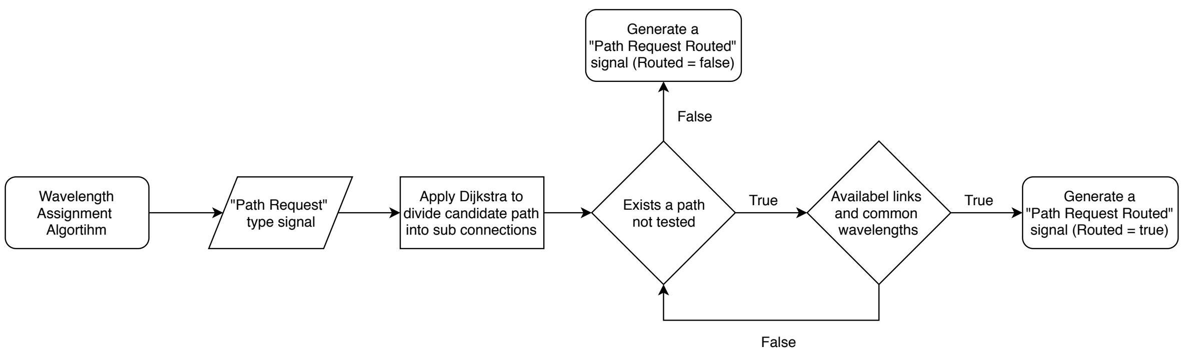


Figure 5.5: Wavelength Assignment algorithm code flow.

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 is the simplest of all these wavelength assignment schemes mentioned. Here every wavelength has an index associated 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 [27].

5.5 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, i.e., routing, regeneration and wavelength assignment can be performed on the bundle in order to better fill a wavelength[2]. In this transport mode demands may only ride together if the pair of source and destination nodes is the same.

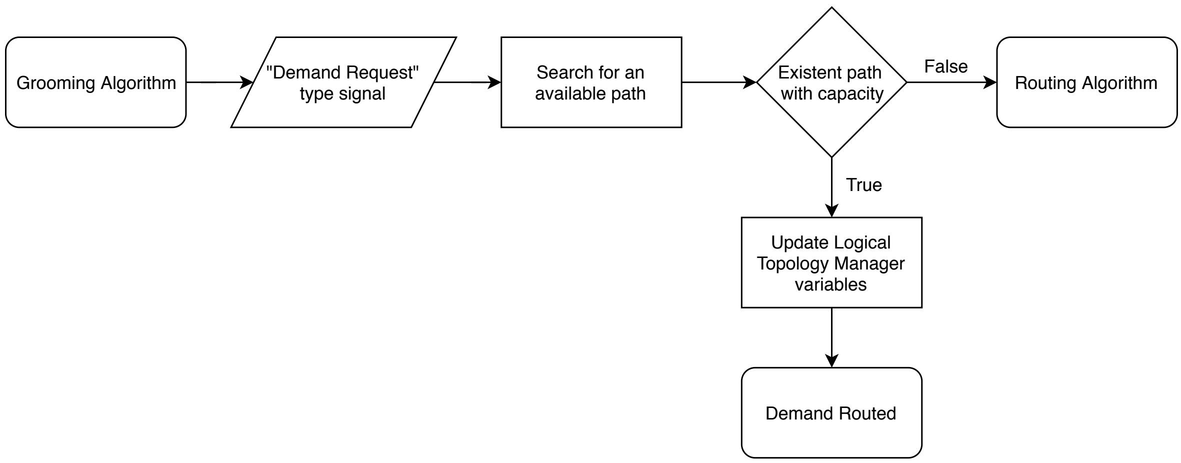


Figure 5.6: Grooming Algorithm code flow.

In a simulation the grooming stage occurs in the logical topology manager block, 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.

Chapter 6

Results

6.1 Reference Network

6.1.1 Analytical

Low traffic

In this case the survivability coefficient is zero since it is being considered a scenario without survivability.

In this scenario it has to be taken into account the traffic assumed in subsection 2.3.2.

Using equation 2.8:

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

Replacing in equation 2.7:

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

Through equation 2.3:

$N^R = 16$

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

$C_L = (2 * 8 * 15\ 000) + (2 * 8 * 5\ 000 * 100 * 2.156) + (2 * 16 * 2000) =$ **17 552 000 €**

In relation to the cost of the nodes firstly the average number of demands is calculated through equation **??**:

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

Replacing in equation 2.9 and 2.10:

$< P_{exc} > = 3.75$

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

Finally, replacing all in equation 2.5 and 2.6 the Node Cost is:

$C_N = (6 * (10000 + (1000 * 100 * 3.75)) + (1000 * 1.25 * 120) + (1000 * 2.5 * 100) + (1000 * 10 * 32) + (100$
$+ (6 * (20000 + (2500 * 9.4988)))$

C_N = 4 310 000 + 262 482 = **4 572 482 €**

$CAPEX$ = 17 552 000 + 4 572 482 $\quad CAPEX$ = **22 124 482 €**

Medium traffic

In this scenario it has to be taken into account the traffic assumed in subsection 2.3.2.

Using equation 2.8:

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

Replacing in equation 2.7:

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

Through equation 2.3:

$N^R = 16$

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

$C_L = (2 * 8 * 15\ 000) + (2 * 8 * 5\ 000 * 100 * 10.8125) + (2 * 16 * 2000) =$ **86 804 000 €**

In relation to the cost of the nodes firstly the average number of demands is calculated through equation **??**:

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

Replacing in equation 2.9 and 2.10:

$< P_{exc} > = 18.75$

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

Finally, replacing all in equation 2.5 and 2.6 the Node Cost is:

$C_N = (6 * (10000 + (1000 * 100 * 18.75)) + (1000 * 1.25 * 600) + (1000 * 2.5 * 500) + (1000 * 10 * 160) + (1$
$+ (6 * (20000 + (2500 * 47.4938)))$

$C_N = 21\ 310\ 000 + 832\ 407 =$ **22 142 407 €**

$CAPEX = 86\ 804\ 000 + 22\ 142\ 407$ $\qquad$ $CAPEX =$ **108 946 407 €**

High traffic

6.1.2 ILP

Low traffic

Medium traffic

High traffic

6.1.3 Heuristics

Low 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 2.3.2.

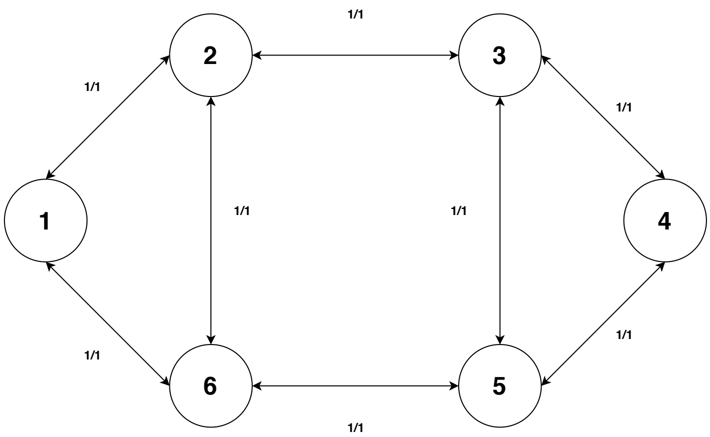


Figure 6.1: Physical topology after dimensioning for low scenario traffic.

Below in table 6.1 there is information regarding the global constitution of all network links, the number of optical channels and amplifiers present in each link is 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 6.1: Table with information regarding links for low traffic scenario.

In table 6.2 is presented information regarding all the network nodes. The number

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

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

Table 6.3: Detailed description of node 1 for low traffic scenario.

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 6.4: 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 6.5: Detailed description of node 3 for low traffic scenario.

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

Table 6.6: 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 6.7: 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 6.8: Detailed description of node 6 for low traffic scenario.

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

<table>
<tr><th colspan="7">Network CAPEX</th></tr>
<tr><th colspan="3"></th><th>Quantity</th><th>Unit Price</th><th>Cost</th><th>Total</th></tr>
<tr><td rowspan="3">Link Cost</td><td colspan="2">OLTs</td><td>16</td><td>15 000 €</td><td>240 000 €</td><td rowspan="3">20 304 000 €</td></tr>
<tr><td colspan="2">Transponders</td><td>40</td><td>5000 €/Gbit/s</td><td>20 000 000 €</td></tr>
<tr><td colspan="2">Amplifiers</td><td>32</td><td>2000 €</td><td>64 000 €</td></tr>
<tr><td rowspan="10">Node Cost</td><td rowspan="7">Electrical</td><td>EXCs</td><td>6</td><td>10 000 €</td><td>60 000 €</td><td rowspan="10">6 420 000 €</td></tr>
<tr><td>ODU0 Ports</td><td>120</td><td>1000 €/Gbit/s</td><td>150 000 €</td></tr>
<tr><td>ODU1 Ports</td><td>100</td><td>1000 €/Gbit/s</td><td>250 000 €</td></tr>
<tr><td>ODU2 Ports</td><td>32</td><td>1000 €/Gbit/s</td><td>320 000 €</td></tr>
<tr><td>ODU3 Ports</td><td>12</td><td>1000 €/Gbit/s</td><td>480 000 €</td></tr>
<tr><td>ODU4 Ports</td><td>8</td><td>1000 €/Gbit/s</td><td>800 000 €</td></tr>
<tr><td>Add Ports</td><td>40</td><td>1000 €/Gbit/s</td><td>4 000 000 €</td></tr>
<tr><td rowspan="3">Optical</td><td>OXCs</td><td>6</td><td>20 000 €</td><td>120 000 €</td></tr>
<tr><td>Line Ports</td><td>56</td><td>2 500 €</td><td>140 000 €</td></tr>
<tr><td>Add Ports</td><td>40</td><td>2 500 €</td><td>100 000 €</td></tr>
<tr><td colspan="6">Total Network Cost</td><td>26 724 000 €</td></tr>
</table>

Table 6.10: Detailed description of CAPEX for low traffic scenario.

Medium traffic

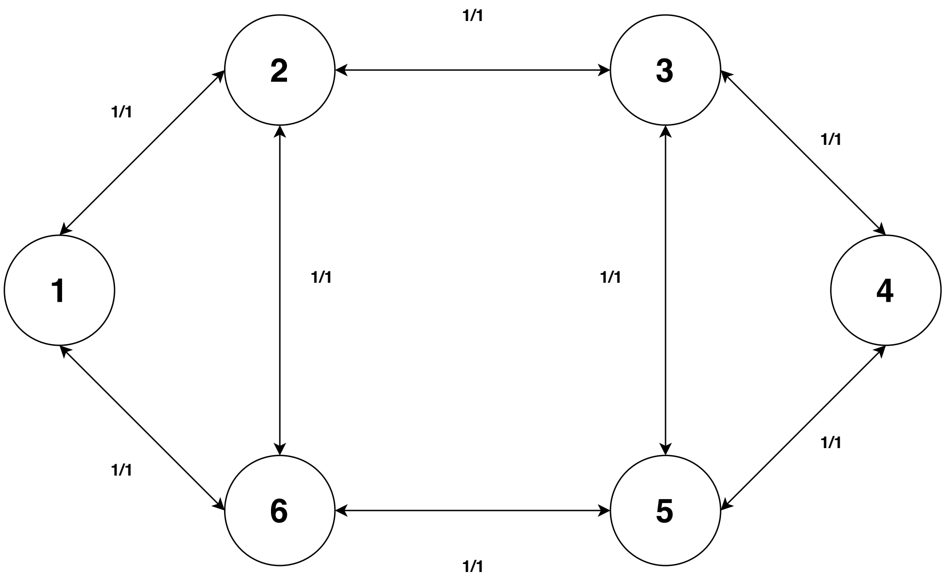


Figure 6.2: Physical topology after dimensioning for low scenario traffic.

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 6.11: Links information for medium traffic scenario.

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 6.12: Node information for medium traffic scenario.

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

Table 6.13: 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 6.14: 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 6.15: 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 6.16: 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 6.17: 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 6.18: Detailed description of node 6 for medium traffic scenario.

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

Network CAPEX						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	58 304 000 €
	Transponders		116	5000 €/Gbit/s	58 000 000 €	
	Amplifiers		32	2000 €	64 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	22 425 000 €
		ODU0 Ports	600	1000 €/Gbit/s	750 000 €	
		ODU1 Ports	500	1000 €/Gbit/s	1 250 000 €	
		ODU2 Ports	160	1000 €/Gbit/s	1 600 000 €	
		ODU3 Ports	60	1000 €/Gbit/s	2 400 000 €	
		ODU4 Ports	40	1000 €/Gbit/s	4 000 000 €	
		Add Ports	116	1000 €/Gbit/s	11 600 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	142	2 500 €	355 000 €	
		Add Ports	116	2 500 €	290 000 €	
Total Network Cost						80 729 000 €

Table 6.20: Detailed description of CAPEX for medium traffic scenario.

High traffic

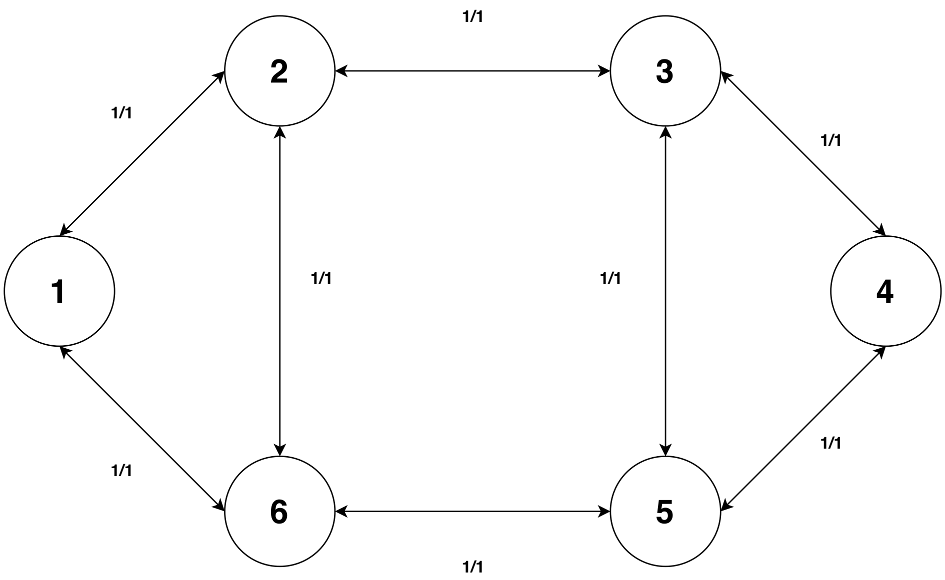


Figure 6.3: Physical topology after dimensioning for high scenario traffic.

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 6.21: Links information for high traffic scenario.

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 6.22: Node information for high traffic scenario.

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 6.23: 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 6.24: 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 6.25: 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 6.26: 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 6.27: 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 6.28: Detailed description of node 6 for high traffic scenario.

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

Network CAPEX						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	110 304 000 €
	Transponders		220	5000 €/Gbit/s	111 000 000 €	
	Amplifiers		32	2000 €	64 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	43 395 000 €
		ODU0 Ports	1200	1000 €/Gbit/s	1 500 000 €	
		ODU1 Ports	1000	1000 €/Gbit/s	2 500 000 €	
		ODU2 Ports	320	1000 €/Gbit/s	3 200 000 €	
		ODU3 Ports	120	1000 €/Gbit/s	4 800 000 €	
		ODU4 Ports	80	1000 €/Gbit/s	8 000 000 €	
		Add Ports	220	1000 €/Gbit/s	22 000 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	266	2 500 €	665 000 €	
		Add Ports	220	2 500 €	550 000 €	
Total Network Cost						153 699 000 €

Table 6.30: Detailed description of CAPEX for high traffic scenario.

6.1.4 Comparative Analysis

6.2 Realistic Network

6.2.1 Analytical

6.2.2 ILP

6.2.3 Heuristics

6.2.4 Comparative Analysis

Chapter 7

Conclusions and future directions

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