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# Desenvolvimento de Heurísticas para o Dimensionamento de Redes Óticas Transparentes

# Development of Heuristics for Transparent Optical Networks Dimensioning

DOCUMENTO
PROVISÓRIO

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**Eduardo José Domingues Fernandes**

# Desenvolvimento de Heurísticas para o Dimensionamento de Redes Óticas Transparentes

# Development of Heuristics for Transparent Optical Networks Dimensioning

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 Coriant Portugal. Tendo como instituição de acolhimento o Instituto de Telecomunicações - Pólo de Aveiro.

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**Palavras-chave** CAPEX, nós, ligações, topologias física e lógica, transparente, heurísticas, sobrevivência, programação linear inteira, métodos analíticos, encaminhamento, agregação

**Resumo** Nesta dissertação ~~foi elaborado um estudo~~ ~~sobre o~~ ~~design~~ ~~e a otimização~~ de redes de transporte transparentes. Os elementos chave de uma rede são os nós e as ligações, e dependendo da forma como se conectam entre si e do modo de transporte utilizado as suas topologias física e lógica poderão variar. De forma a elaborar uma análise rigorosa, foi escolhido um determinado arranjo de nós e ligações, e três diferentes cenários de tráfego injetado na rede por forma a obter um espectro mais globlal e significativo de resultados. De maneira a optimizar os processos de design em redes óticas alguns algoritmos foram desenvolvidos e validados, no decorrer desta dissertação relativos à organização, ao encaminhamento e à agregação de tráfego. Tudo isto para o modo de transporte transparente sem sobrevivência. O objetivo passaria por produzir arquitecturas, onde se fizesse o uso de um mínimo possível de recursos, o que faria com que o CAPEX da rede fosse também ele o menor possível, mas tentando sempre garantir o encaminhamento total do tráfego. Foi também elaborado um estudo detalhado e comparativo, tendo em foco o CAPEX, com os valores obtidos através dos métodos analíticos, dos modelos de programação linear inteira e finalmente com os valores obtidos pelas heurísticas desenvolvidas. Finalmente, são partilhadas e discutidas algumas conclusões e dicas para futuro trabalho.

**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 |
| **FTTH** | Fiber-to-the-home |
| **IP** | Internet Protocol |
| **IPS** | Input Parameters System |
| **M2M** | Machine-to-Machine |
| **O-E-O** | Optical-Electronic-Optical |
| **OADM** | Optical Add/Drop Multiplexer |
| **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 networks have become larger and more complex and so their functions grown as well in such a manner that nowadays they may also include traffic integrity and survivability aspects, network management, 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, somke or sound signals, in this particular case just confirming prearranged messages. In the new Telecommunications Era this master-to-servant relationships were eradicated, replacing the service of a messenger by mechanical telegraphs, followed by copper wires and electromagnetic waves and most lately by optical fibers, which revolutionized telecommunications. These advances dramatically reduced the time required to transport messages, accelerated business transactions, and so improved human relationships. [1] Nowadays, telecommunications 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 the fiber optic cables that carry channels of light, combined with equipment deployed along the fibers to process, in many different ways, that same light. 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. Even if transmission and switching are still the basic building blocks of any network, telecommunication networks fundamentals nowadays cover a much complex and broader scope nowadays mainly due to the arise of digital technologies which introduced packet switched networks where 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 is defined by ITU-T, as Optical Transport Network (OTN), its composed of a set of Optical Network Elements connected by optical fibre 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 and support for the next generation of dynamic services with operational efficiencies not expected from 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 network, being the last two almost entirely based on optical fiber systems although the penetration of optical fiber communications in the access segment is progressing at an astonishing rate in order to allow faster connections[6]. Access networks usually connect directly to end users, provide interfaces operating at bit-rates suitable to support various different applications such as Fiber-to-the-home (FTTH) but also for backhauling data communications as well as for mobile back- and fronthauling purposes and typically cover 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 the aggregated traffic between major cities, countries or continents. Finally, core networks who are also named transport or backbone networks cover a large geographical area. [8]

Devices and connection demands to the Internet have been growing unbelievably fast mainly due to ,amongst 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 4.4.

[9]

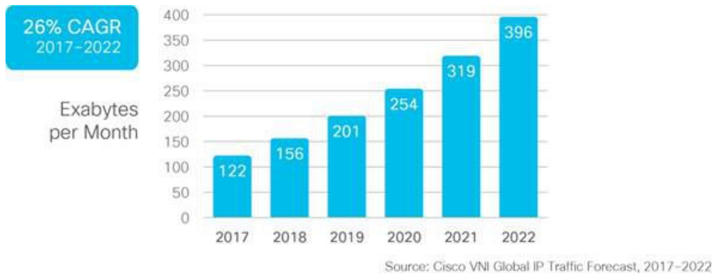



Figure 1.1: Cisco forecasts per month of IP traffic from 2017 until 2022.

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 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 is the result of the ability to place in the market telecommunication services at lower prices that end users can easily afford. 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 protect traffic in a network or how to bundle it into wavelenghts, must usually be performed and or assisted by software tools, the so-called network planning tools, because of the extreme difficulty to make a fast and scalable manual planning to a large and complex telecommunications network[2]. Those 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 arised the interest and oportunity to develop the planning tool created along this thesis, which was made for academic and educational research purposes only. The heuristics algorithms were developed from scratch, recurring to the NetXPTO simulator and offer 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 a great asset.

## 1.2 Objectives

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

1. Define one reference network and various different traffic scenarios for test performing purposes.
2. Develop Heuristic algorithms for transparent networks without survivability.
3. Calculate the analytical solutions for the same case studies.
4. Elaborate a comparative study, regarding the subject of capital expenditure, with the results obtained analytically, through ILP methods and the Heuristics developed.

## 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 design and dimensioning.

## 1.4 Major Achievements

There are two main goals that this dissertation pretends to achieve. The first is to create algorithms capable of dimensioning transparent optical networks based on the entering traffic of the network, physical topology adjacency matrix, amongst other aspects. This algorithms are made in language C++ and are based on NetXPTO which is a real time simulator capable of designing generic systems comprised of blocks. Those blocks interact between each other through signals. And the other objective is to obtain estimations for the capital expenditures of the dimensioned networks for both analytical, ILP and heuristic methods.

# Chapter 2

# Optical Transparent Networks

The scope of this chapter resides on an elaboration of a state-of-the-art review from an optical networking engineering point of view. The study of optical transport networks is a vast and highly multidisciplinary field in the modern telecommunication world as it shall be seen further along this dissertation. In the transparent transport mode, 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 lightpath (high-bandwidth end-to-end circuits, occupying a wavelength on each link of the path) [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 path used [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]. Here the so called electro-optic bottleneck is eliminated, once this method allows information transfer rates to reach close values to those allowed by optical devices, which are significantly beyond the rates achievable in an electronic 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].

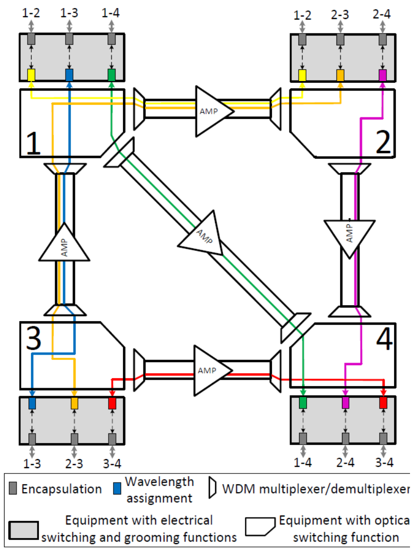



Figure 2.1: Transparent network with 4 nodes: here the mode of operation, with a single-hop grooming technique, is represented. O-E-O are only performed at end nodes[13].

## 2.1 Network Architecture

Telecommunication transport networks are essentially made of links and nodes, each of them comprising many other simpler 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 in section 2.3.

### 2.1.1 Links

Physical point-to-point connections between adjacent nodes ensuring the transmission of WDM signals between them. 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.[15] In networks capable of allowing the transiting traffic to remain in the optical domain 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.

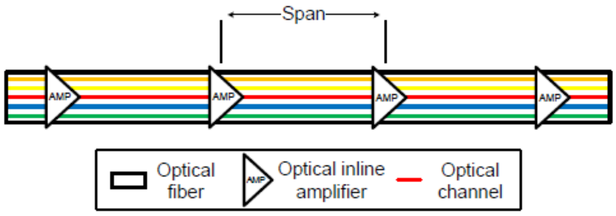



Figure 2.2: Schematic of a link: optical fiber and inline optical amplifiers.[13]

### 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[16]. All of these tasks will require a substantial amount of hardware making the nodes one of the most expensive components of optical networks.[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 the 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, independent modules attached to shelves to allow backplane communication, with 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, and also shelves to 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.[16] Lastly, nodes perform two major functions: (mapping, aggregation and switching) switching, grooming and wavelength assignment. This set of operations it typically designated of bandwith management and it can be performed in the electrical or optical domain.[17]

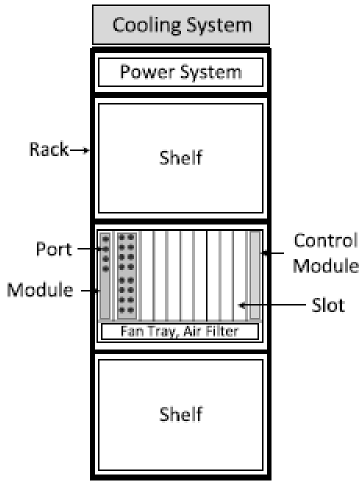



Figure 2.3: Schematic of a node structure[16].

## 2.2 Network Topologies

In a network nodes and links interconnect to each other through the respective interfaces forming the so called network topology. 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[17].

### 2.2.1 Physical Topology

The pattern that represents the real layout of an optical network, i.e., the disposition of nodes and the physical connections between them, which in the case of OTN networks are optical fiber links[18].

### 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 without survivability case[19].

## 2.3 Reference Network

Here will be described the 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 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 connections.

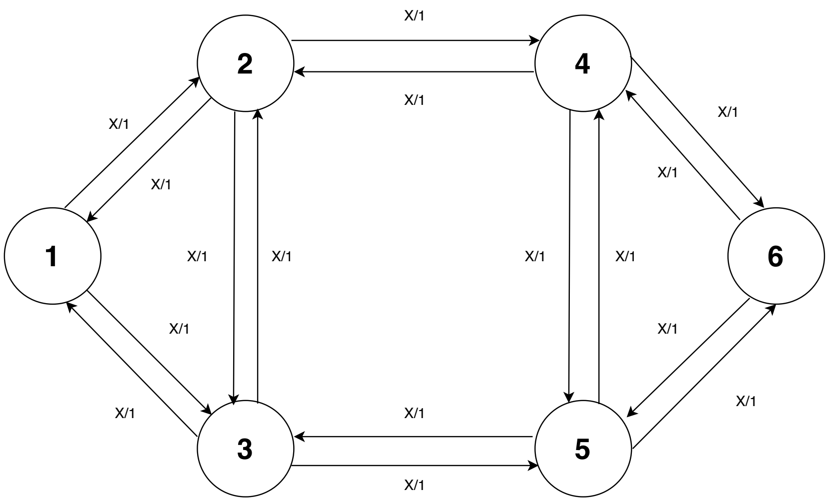



Figure 2.4: Reference network physical topology graph representation.

| **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.

Below we have a 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. Once more,

$$Dist = \begin{bmatrix} 0 & 460 & 663 & 0 & 0 & 0 \\ 460 & 0 & 75 & 684 & 0 & 0 \\ 663 & 75 & 0 & 0 & 890 & 0 \\ 0 & 684 & 0 & 0 & 103 & 764 \\ 0 & 0 & 890 & 103 & 0 & 361 \\ 0 & 0 & 0 & 764 & 361 & 0 \end{bmatrix}$$

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) | 500 |
| <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 test the results given by the simulator with the optimal solutions provided by ILP methods. Each of the scenarios are composed of 5 matrices of different ODU types, namely, ODU0 (1.25 Gbit/s), ODU1 (2.5 Gbit/s), ODU2 (10 Gbit/s), ODU3 (40 Gbit/s) and ODU4 (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.

#### Low Traffic Scenario

In this case it was chosen to have a total unidirectional traffic of 1.5 Tbit/s. That amount of traffic was distributed through the different ODU type matrices as it can be seen below.

$$ODU0 = \begin{bmatrix} 0 & 5 & 1 & 3 & 1 & 3 \\ 5 & 0 & 0 & 1 & 5 & 0 \\ 1 & 0 & 0 & 1 & 4 & 1 \\ 3 & 1 & 1 & 0 & 1 & 1 \\ 1 & 5 & 4 & 1 & 0 & 3 \\ 3 & 0 & 1 & 1 & 3 & 0 \end{bmatrix} \qquad ODU1 = \begin{bmatrix} 0 & 2 & 4 & 2 & 0 & 5 \\ 2 & 0 & 0 & 3 & 1 & 1 \\ 4 & 0 & 0 & 1 & 1 & 0 \\ 2 & 3 & 1 & 0 & 1 & 3 \\ 0 & 1 & 1 & 1 & 0 & 1 \\ 5 & 1 & 0 & 3 & 1 & 0 \end{bmatrix}$$

$$ODU2 = \begin{bmatrix} 0 & 1 & 2 & 2 & 0 & 0 \\ 1 & 0 & 0 & 0 & 2 & 0 \\ 2 & 0 & 0 & 2 & 2 & 0 \\ 2 & 0 & 2 & 0 & 2 & 0 \\ 0 & 2 & 2 & 2 & 0 & 2 \\ 0 & 0 & 0 & 0 & 2 & 0 \end{bmatrix} \qquad ODU3 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ODU4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 2 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Through these ODU's we can calculate the total network traffic for this specific scenario:

$T_1^0 = 60\text{x}1.25 = 75$ Gbits/s $\quad T_1^1 = 50\text{x}2.5 = 125$ Gbits/s $\quad T_1^2 = 30\text{x}10 = 300$ Gbits/s

$T_1^3 = 10\text{x}40 = 400$ Gbits/s $\quad T_1^4 = 6\text{x}100 = 600$ Gbits/s

$T_1 = 75 + 125 + 300 + 400 + 600 = 1500$ Gbits/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.

#### Medium Traffic Scenario

In this case it was chosen to have a total unidirectional traffic of 6 Tbit/s. That amount of traffic was distributed through the different ODU type matrices as it can be seen below.

$$ODU0 = \begin{bmatrix} 0 & 20 & 4 & 12 & 4 & 12 \\ 20 & 0 & 0 & 4 & 20 & 0 \\ 4 & 0 & 0 & 4 & 16 & 4 \\ 12 & 4 & 4 & 0 & 4 & 4 \\ 4 & 20 & 16 & 4 & 0 & 12 \\ 12 & 0 & 4 & 4 & 12 & 0 \end{bmatrix} \qquad ODU1 = \begin{bmatrix} 0 & 8 & 16 & 8 & 0 & 20 \\ 8 & 0 & 0 & 12 & 4 & 4 \\ 16 & 0 & 0 & 4 & 4 & 0 \\ 8 & 12 & 4 & 0 & 4 & 12 \\ 0 & 4 & 4 & 4 & 0 & 4 \\ 20 & 4 & 0 & 12 & 4 & 0 \end{bmatrix}$$

$$ODU2 = \begin{bmatrix} 0 & 1 & 2 & 2 & 0 & 0 \\ 1 & 0 & 0 & 0 & 2 & 0 \\ 2 & 0 & 0 & 2 & 2 & 0 \\ 2 & 0 & 2 & 0 & 2 & 0 \\ 0 & 2 & 2 & 2 & 0 & 2 \\ 0 & 0 & 0 & 0 & 2 & 0 \end{bmatrix} \qquad ODU3 = \begin{bmatrix} 0 & 4 & 0 & 0 & 0 & 0 \\ 4 & 0 & 4 & 0 & 0 & 4 \\ 0 & 4 & 0 & 0 & 8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 8 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ODU4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 8 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4 \\ 0 & 8 & 0 & 0 & 4 & 0 \end{bmatrix}$$

Through these ODU's we can calculate the total network traffic for this specific scenario:

$T_1^0 = 240\text{x}1.25 = 300$ Gbits/s $\quad T_1^1 = 200\text{x}2.5 = 500$ Gbits/s $\quad T_1^2 = 120\text{x}10 = 1200$ Gbits/s

$T_1^3 = 40\text{x}40 = 1600$ Gbits/s $\quad T_1^4 = 24\text{x}100 = 2400$ Gbits/s

$T_1 = 300 + 500 + 1200 + 1600 + 2400 = 6000$ Gbits/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.

$$ODU0 = \begin{bmatrix} 0 & 40 & 8 & 24 & 8 & 24 \\ 40 & 0 & 0 & 8 & 40 & 0 \\ 8 & 0 & 0 & 8 & 32 & 8 \\ 24 & 8 & 8 & 0 & 8 & 8 \\ 8 & 40 & 32 & 8 & 0 & 24 \\ 24 & 0 & 8 & 8 & 24 & 0 \end{bmatrix} \qquad ODU1 = \begin{bmatrix} 0 & 16 & 32 & 16 & 0 & 40 \\ 16 & 0 & 0 & 24 & 8 & 8 \\ 32 & 0 & 0 & 8 & 8 & 0 \\ 16 & 24 & 8 & 0 & 8 & 24 \\ 0 & 8 & 8 & 8 & 0 & 8 \\ 40 & 8 & 0 & 24 & 8 & 0 \end{bmatrix}$$

$$ODU2 = \begin{bmatrix} 0 & 2 & 4 & 4 & 0 & 0 \\ 2 & 0 & 0 & 0 & 4 & 0 \\ 4 & 0 & 0 & 4 & 4 & 0 \\ 4 & 0 & 4 & 0 & 4 & 0 \\ 0 & 4 & 4 & 4 & 0 & 4 \\ 0 & 0 & 0 & 0 & 4 & 0 \end{bmatrix} \qquad ODU3 = \begin{bmatrix} 0 & 8 & 0 & 0 & 0 & 0 \\ 8 & 0 & 8 & 0 & 0 & 8 \\ 0 & 8 & 0 & 0 & 16 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 16 & 0 & 0 & 0 \\ 0 & 8 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ODU4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 16 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 8 \\ 0 & 16 & 0 & 0 & 8 & 0 \end{bmatrix}$$

Through these ODU's we can calculate the total network traffic for this specific scenario:

$T_1^0 = 480\text{x}1.25 = 600$ Gbits/s $\quad T_1^1 = 400\text{x}2.5 = 1000$ Gbits/s $\quad T_1^2 = 240\text{x}10 = 2400$ Gbits/s

$T_1^3 = 80\text{x}40 = 3200$ Gbits/s $\quad T_1^4 = 48\text{x}100 = 4800$ Gbits/s

$T_1 = 600 + 1000 + 2400 + 3200 + 4800 = 12000$ Gbits/s

## 2.4 Realistic Network

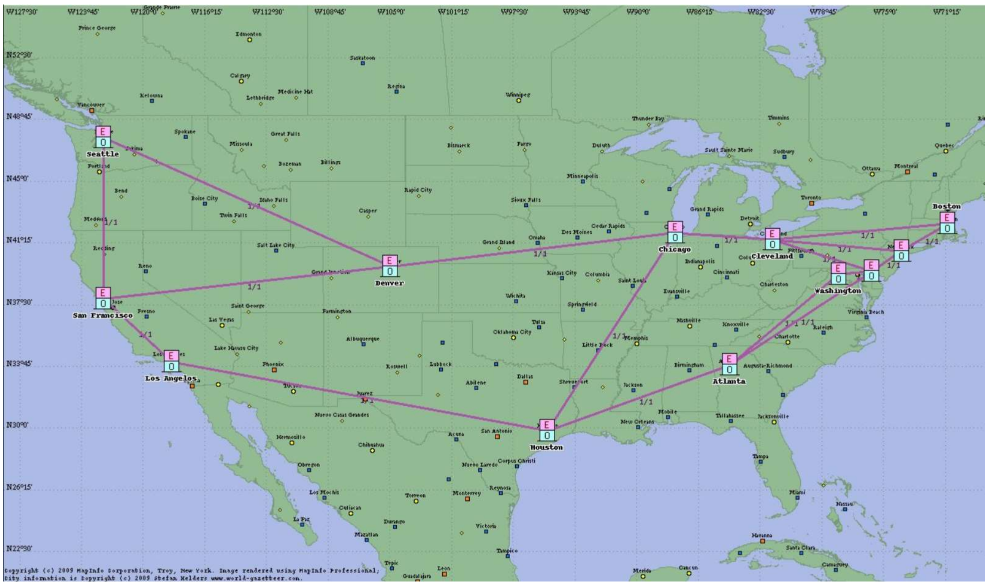



Figure 2.5: The Very-High Performance Backbone Network Service[20].

In order to validate the heuristic algorithms created it was decided to apply them to a real network. The chosen Network was the vBNS (very high-speed Backbone Network

Service), which is a National Science Foundation sponsored high-performance network service implemented in the United States 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[21].

### 2.4.1 Physical Topology

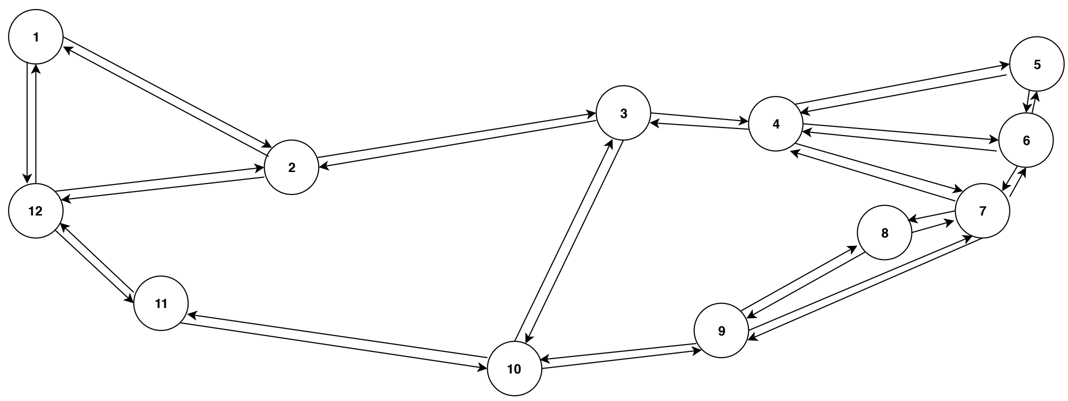



Figure 2.6: Physical topology graph representation.

| **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.

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 |
| $<\delta>$ | Node degree | 2.83 |
| <len> | Mean link length (km) | 965 |
| <h> | Mean number of hops for working paths | 2.40 |
| <h’> | Mean number of hops for backup paths | 3.90 |

Table 2.4: Table of reference network values.

### 2.4.2 Traffic Matrices

**Low traffic**

**Medium traffic**

**High traffic**

# Chapter 3

# Capital Expenditure Model

In this chapter the network economics aspects will be in focus. The dimensioning of a telecommunication network involves identifying the required resources and their respective quantities [22]. As both setting up and operating large telecommunications infrastructures require large amounts of money any network investment must be carefully evaluated, once it directly affects network operators and service providers competitiveness [17]. The costs can be mainly divided into two branches: the Capital Expenditure (CAPEX) and the Operational Expenditure (OPEX). The first will be analyzed more closely 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][23]. The current chapter proposes and describes the models used to the calculate capital expenditures of the network. These calculations are made based on the transparent transport mode without survivability case.

## 3.1 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 equations 3.1 or 3.2 depending on whether the links are considered bi or unidirectional, respectively. In transport networks, links are point-to-point connections that interconnect two network nodes.[8] The cost of links 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 expanditure once it is commom pratice in telecommunications for operators to lease fiber-optic cables instead of installing them [8]. It is also important to stress the fact that for calculation purposes that each link is considered to be unidirectional in such a way that the combination of a pair of links creates a bidirectional connection between nodes.

The following equation 3.1 would be used if we were considering bidirectional links but as previously stated we are using unidirectional links to perform these calculations so the previous equation must be updated in a way that all its terms must be divided by 2 resulting in equation 3.2.

$$C_L = \left(2L_2\gamma_0^{OLT}\right) + \left(2L_2\gamma_1^{OLT}\tau < w >\right) + \left(2N^R c^R\right) \tag{3.1}$$

$$C_L = \left(L_1\gamma_0^{OLT}\right) + \left(L_1\gamma_1^{OLT}\tau < w >\right) + \left(N^R c^R\right) \tag{3.2}$$

where

- $\gamma_0^{OLT} \rightarrow$ OLT cost in euros
- $L_1 \rightarrow$ Number of unidirectional links
- $L_2 \rightarrow$ 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

Through equation 3.3 it is possible to reach the number of optical amplifiers, $N^R$, as

$$N^R = \sum_{l=1}^{L} \left( \left\lceil \frac{len_l}{span} \right\rceil - 1 \right) \tag{3.3}$$

where $len_l$ is the length of link $l$ and $span$ is the distance between amplifiers (assuming 100 km) [17].

Assuming that $\tau$ is 100 Gbits/s the only remaining unknown parameter is the number of optical amplifiers and the average number of optical channels [17]. 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 utilized the optimal values found by the algorithms.

## 3.2 Nodes Cost

In transparent nodes it is necessary to consider both the optical and the electrical parts of the node, as it can be seen below in figure. 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[17]. So as the nodes have an electrical part and an optical part it is obvious that the cost of the nodes, $C_N$, is given by the sum of these two parts, thus, obtaining the equation **??**

$$C_N = C_{EXC} + C_{OXC} \tag{3.4}$$

where

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

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

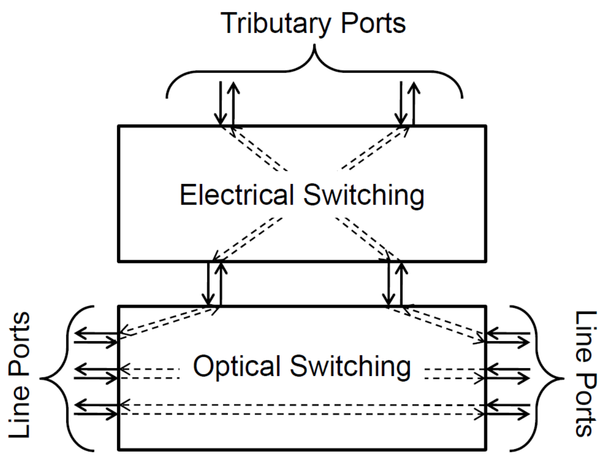



Figure 3.1: Electrical and optical node structure[17].

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 3.5

$$C_{exc} = N \times (\gamma_{e0} + (\gamma_{e1}\tau < P_{exc} >)) + \gamma_{e1} P_{TRIB} \tag{3.5}$$

where:

- $N \rightarrow$ Number of nodes
- $\gamma_{e0} \rightarrow$ EXC cost in euros
- $\gamma_{e1} \rightarrow$ EXC port cost in euros
- $\tau \rightarrow$ Line bit rate
- $< P_{exc} > \rightarrow$ Average number of ports of the electrical switch
- $P_{TRIB} \rightarrow$ Total number of tributary ports

In relation to the optical part, $C_{oxc}$, to know the optical cost of the nodes that is given by equation 3.6

$$C_{oxc} = N \times (\gamma_{o0} + (\gamma_{o1} < P_{oxc} >)) \tag{3.6}$$

where:

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

Once more, we have to take into account that the calculated value for the variables $< P_{exc} >$ and $< P_{oxc} >$ will depend on the mode of transport used and the variable $P_{TRIB}$ will depend on the scenario but in next subsections will be explained how these values are calculated for each specific transport mode. Finally, for this we will also have to take into account the cost of the equipment used that can be consulted in table 3.1.

| Equipment | Symbol | Cost |
|---|---|---|
| OLT without transponders | $\gamma_0^{OLT}$ | 15 000 € |
| Transponder | $\gamma_1^{OLT}$ | 5 000 €/Gb |
| Unidirectional Optical Amplifier | $c^R$ | 4 000 € |
| EXC | $\gamma_{e0}$ | 10 000 € |
| OXC | $\gamma_{o0}$ | 20 000 € |
| EXC Line Ports | $\gamma_{e1}$ | 100 000 €/port |
| EXC Tributary Ports | $\gamma_{e2}$ | 20 €/port |
| OXC Port | $\gamma_{o1}$ | 2 500 €/port |

Table 3.1: Table of costs used to calculate CAPEX using analytical models [**aulas**].

## 3.3 Total Cost

To calculate the total network cost it has to be considered the sum of the two previous components: the links and the nodes costs. The CAPEX value of a network, $C_C$, in monetary units (e.g. euros, or dollars), can be calculated by the equation 3.7

$$C_C = C_L + C_N \tag{3.7}$$

where

- $C_L \rightarrow$ Link cost in monetary units (e.g. euros, or dollars)
- $C_N \rightarrow$ Node cost in monetary units (e.g. euros, or dollars)

## 3.4 CAPEX Estimation

### 3.4.1 Analytical Approach

Through the equation 3.8 we can calculated the average number of optical channels[24], $< w >$, as

$$< w >= \left( \frac{\lceil D\times < h > \rceil}{L_u} \right) (1+ < k >) \tag{3.8}$$

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

$$D = \left( \frac{1}{2} \right) (1 + \xi) \left( \frac{T_1}{\tau} \right) \tag{3.9}$$

where $\xi$ is the grooming coefficient, $T_1$ is the total unidirectional traffic and $\tau$ is the line bit rate [24].

### 3.4.2 ILP Methods

### 3.4.3 Heuristics

# Chapter 4

# Heuristics Methodology

Heuristic algorithms are approaches designed for solving a given problem in a faster and more efficient fashion than traditional methods by sacrificing optimality, accuracy, precision, or completeness for speed. Are often used to solve problems where there is no known efficient way to find a solution quickly and accurately [25]. Heuristics are usually developed to have low time complexity and applied to complex problems. 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 some 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 we present 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.

In figure 4.1 a top level diagram is presented in which it is represented the heuristics approach implemented behind the developed algorithms.

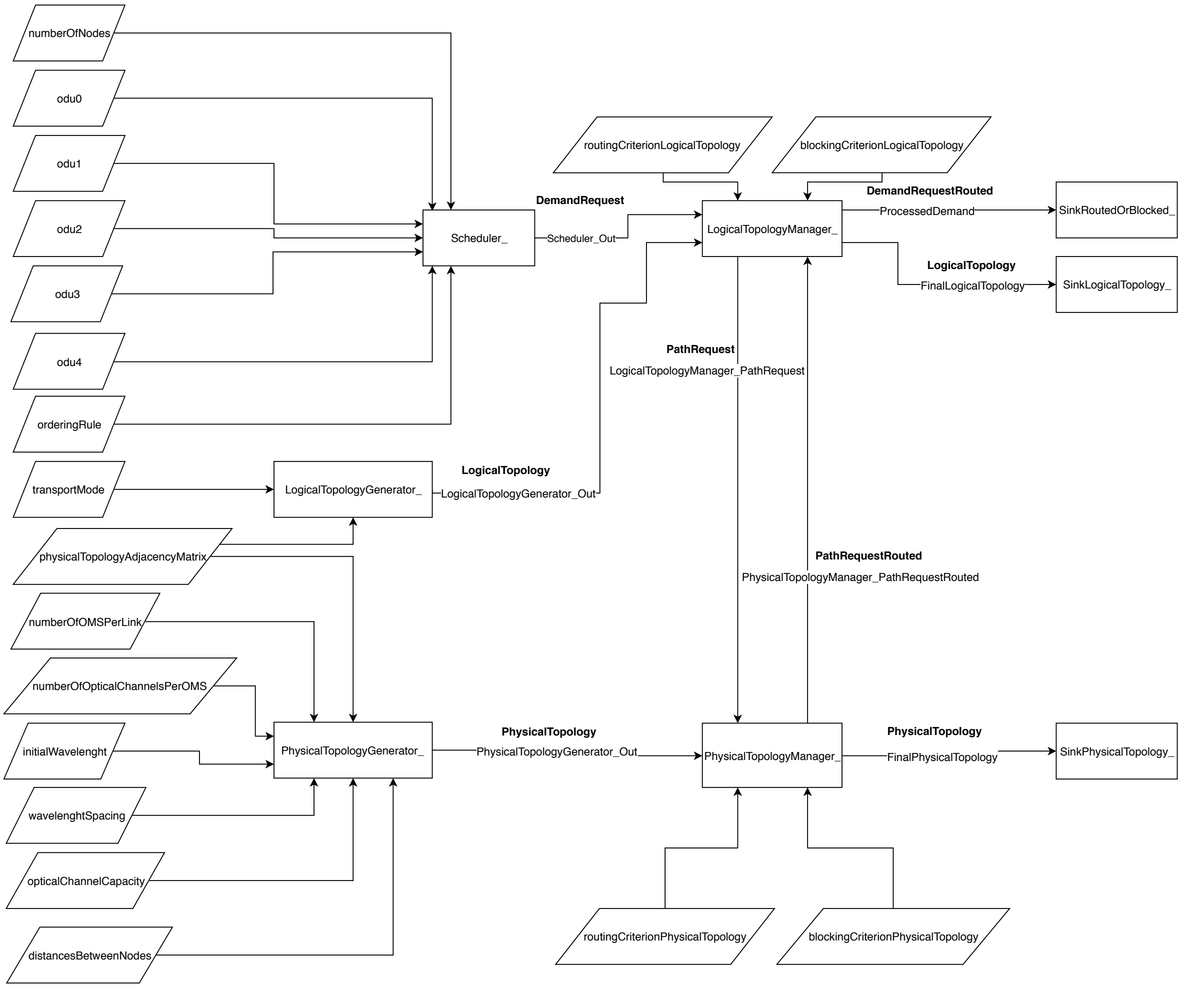



Figure 4.1: High level diagram of the heuristic algorithm performed.

The pseudo code developed for the various algorithms will be shown next 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, the rectangle shape processes where can occur the simple assignment of a value to a variable, constant or parameter or other more complex tasks.

## 4.1 Scheduling

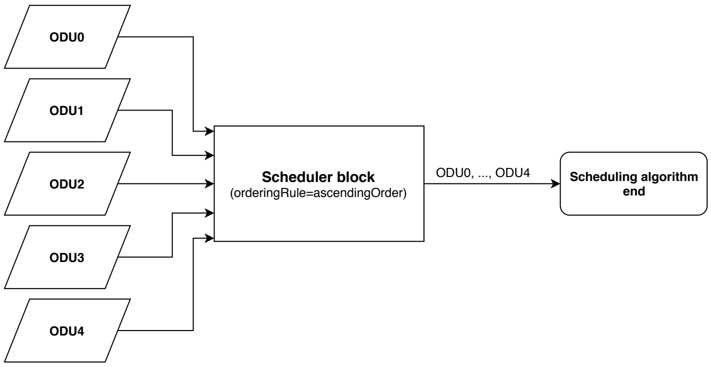



Figure 4.2: Scheduler algorithm illustration for the case of ascending ordering rule.

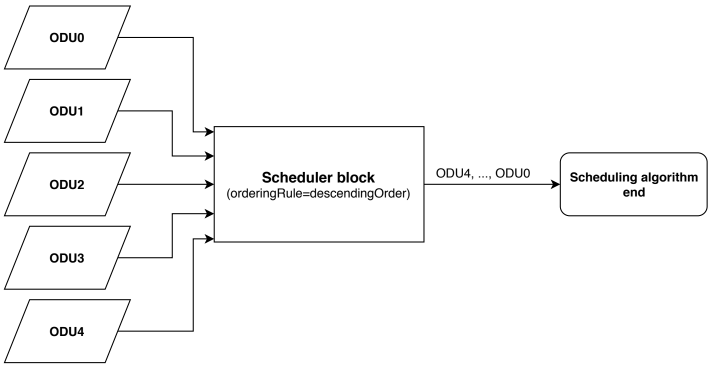



Figure 4.3: Scheduler algorithm illustration for the case of descending ordering rule.

As it is shown above in figures 4.2 and 4.3, prior to the demands traffic entering the network being able to be processed it is needed a Scheduler block which will be responsible for the creation of an ordered queue, in which, all those demands are organized into a specific order, based on the demand's ODU type. That becomes the order by which they will become ready to be processed and routed. 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 a backwards order. This choice may potentially affect the efficiency of the grooming process. The signal exiting from this block will be of the "DemandRequest" type and will contain information of each demand's index, source and destination nodes, ODU type and survivability method to be used if any. This signal is then sent to the "LogicalTopologyManager_" block. It is assumed that although multiple demands can be added at once to the network, each of the demands is processed individually before moving on to the next[2]. Since in this case all the traffic requests are known our network traffic is said to be static.

## 4.2 Logical Topology

The Logical Topology algorithm accepts two input parameters at the beginning of the simulation, being them the transport mode, which in these case is the transparent mode, and the physical topology adjacency matrix and is performed in the "LogicalTopologyGenerator_" block. From here, there are created new structures of data that ultimately will comprise a "LogicalTopology" type signal named "LogicalTopologyGenerator_Out" which in his turn will be the output signal of the block. A "LogicalTopology" type signal stores valuable information about the paths, lightpaths and optical channels existent in the network. That information will later on be used to route demands in the most efficient way possible considering the heuristic grooming and routing algorithms implemented which depend directly, among other aspects, on the logical topology of the network. 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 [19].

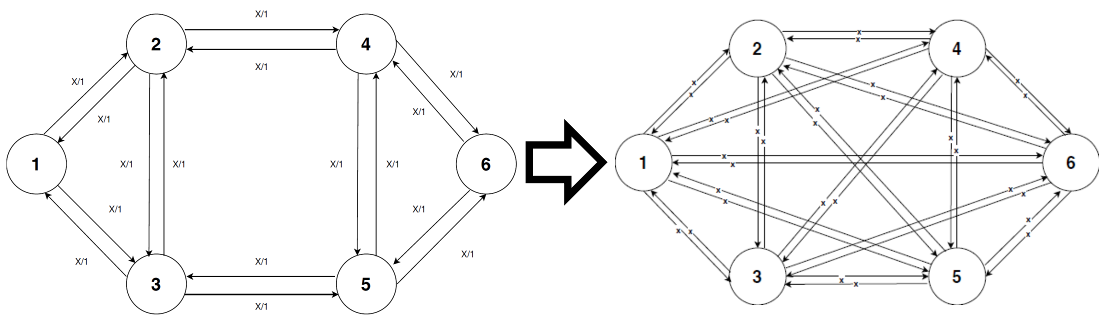



Figure 4.4: Logical topology algorithm: conversion from physical topology (left side) to the logical topology (right side).

## 4.3 Routing

Routing is the process of assigning a unique path through the network for a traffic demand between source and the destination nodes [2]. This algorithm begins by generating a set of candidate paths for a given demand. The number of paths generated will depend directly of the user and the key factor of Dijkstra's algorithm, in order to sort paths, can be the number of links in the path (hops) or the distance of each path, once this can be an indicator of the bandwidth occupied by the path, which is intended to minimize [2]. The first step to take into account when a demand request is received by the network is to look in the "LogicalTopologyManager_" block for prior existent paths 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 through the network, having no need to communicate with the physical topology. In this case only the remaining capacities of the paths need to be updated once the process of routing a demand through this same path had already occured before. 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 this new path then the demand request is blocked by the network. Below in sections 4.3.1 and 4.3.2 the steps taken to create a new path are analysed in more detail.

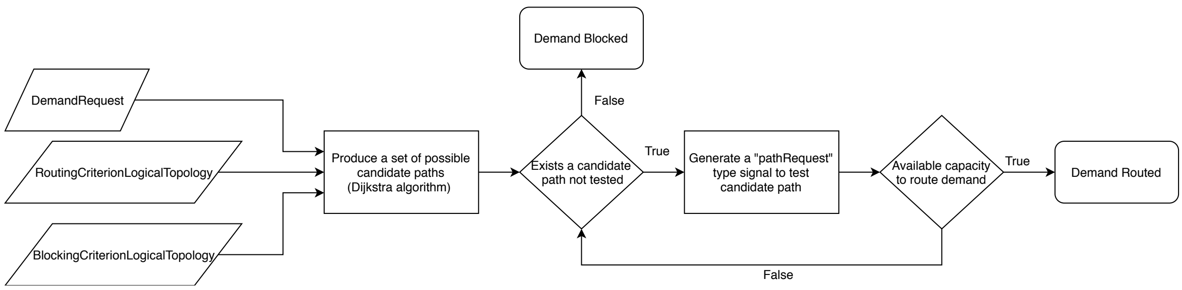



Figure 4.5: Routing algorithm code flow.

### 4.3.1 Producing a set of candidate paths

Our routing strategy incorporates the use of a K-shortest path algorithm, Dijkstra algorithm, in order to find the K-shortest paths between a source and a destination node[2]. The number of shortest paths found will depend only of the user decision, through "BlockingCriterionLogicalTopology" variable. In transparent networks, with optical bypass, 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 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 futher in section 4.4. So it was decided to use the number of hops as the metric to find the shortest paths in the studies conducted.

### 4.3.2 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].

## 4.4 Wavelength Assignment Strategy

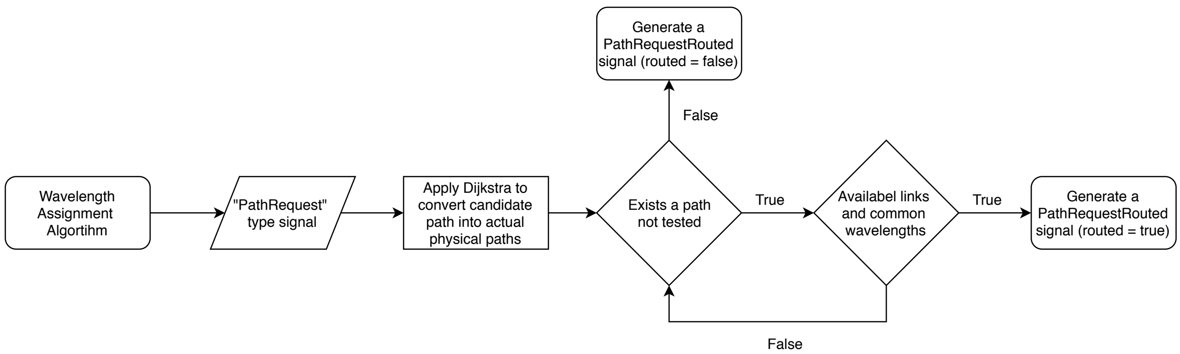



Figure 4.6: Wavelength Assignment algorithm code flow.

This is one crucial step in transparent networks planning once they require wavelength continuity in all nodes from source to the destination, meaning that signals entering a source node are kept in the optical domain at every intermediate nodes of the path until reaching its destination[2]. Optical-Electronic-Optical (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 through the network. 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 is commonly know as First-Fit[2], where every wavelength is numbered and the one with the lowest number 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].

## 4.5 Grooming

As the majority of the traffic going through a network usually requires a minor bit-rate than that of a full wavelength, i.e., line-rate traffic or wavelength services, a need arised for a process capable of diminishing the percentage of wasted wavelength capacity, making networks more efficient[2]. This process is called 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.

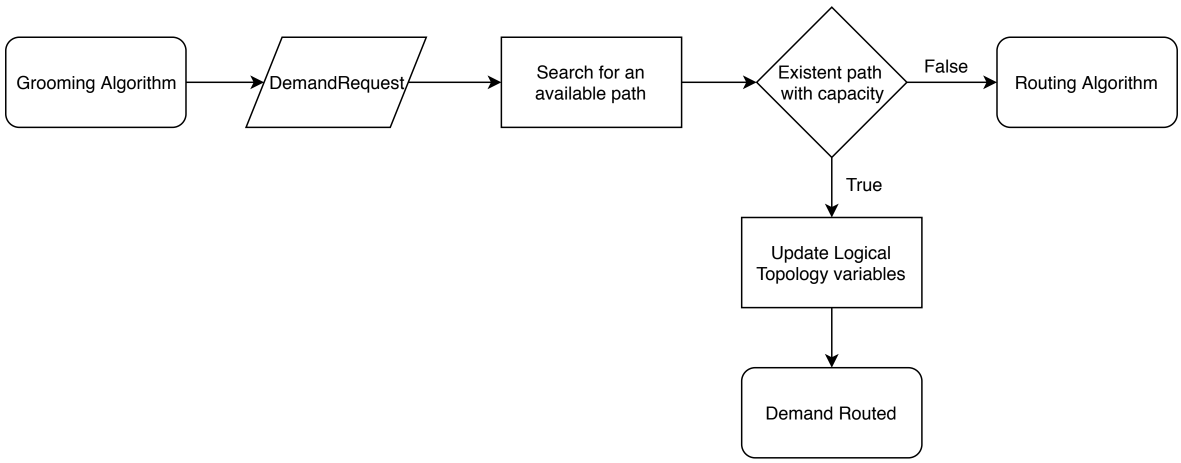



Figure 4.7: Grooming Algorithm code flow.

In our simulator the grooming stage occurs in the "LogicalTopologyManager_" block where a demand being processed looks for an available path between the same pair of source and destination nodes, previously established and with still 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 5

# Heuristics NetXPTO Implementation

In this chapter a demonstration of how the simulator works and how the heuristic algorithms perform with the information given to them.

## 5.1 Input Parameters System

With the Input Parameters System (IPS) it becomes possible to read the input parameters from any text file.

### 5.1.1 Entry variables

| 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] | Physical connections between nodes of the network. |
| numberOfOMSPerLink | 1 | Number of optical multiplexing systems existing in each physical link. |
| numberOfOpticalChannelsPerOMS | 100 | Number of optical channels per optical multiplexing system. |
| 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 5.1: System input parameters.

### 5.1.2 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

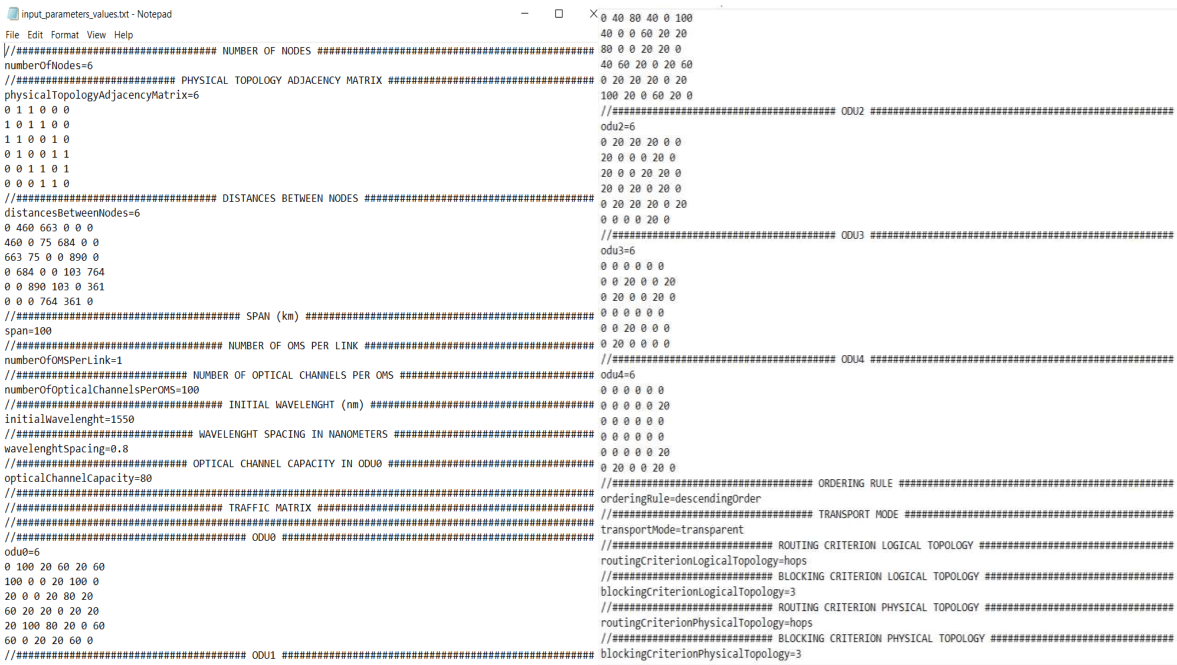
and logical topologies, newValue will assume the value of existing elements per line or column and the matrix value must be specified below this line.

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



```
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 5.1: .

### 5.1.3 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.

## 5.2 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.

## 5.3 Type signals structure

### 5.3.1 LogicalTopology

The logical topology of the ne5twork is an approach that defines how components are interconnected. 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 **??**, where 0/1 indicates the possibility of establishing a logical connection between nodes.

Below are represented the variables that constitute a LogicalTopology type signal.

**logicalTopologyMatrix**

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

Table 5.2: Allowed logical topology for a matrix of N nodes.

N represents the number of nodes present in the network.

Therefore, these shorter optical paths along the route imposed by logical topology lead to a situation of three possible transport modes: Opaque, Transparent and Translucent. During this dissertation the focus will be on transparent models, where each node connects to all others creating direct links between all nodes of the network.

The next variables are distributed in an hierarchical mode, a Path consists in one or more Light Paths which in its turn are formed by one or more Optical Channels.

**paths**

| pathIndex | sourceNode | destinationNode | capacity (ODU0s) | numberOfLightPaths | lightPathsIndex |
|---|---|---|---|---|---|
| 0 or greater | 1...N | 1...N | 0...80 | 0 or greater | [lp_1, lp_2, ...] |

Table 5.3: Structure of a path variable.

**lightPaths**

| lightPathIndex | sourceNode | destinationNode | capacity (ODU0s) | numberOfOptical-Channels | opticalChannels-Index |
|---|---|---|---|---|---|
| 0 or greater | 1...N | 1...N | 0..80 | 0 or greater | [och_1, och_2,...] |

Table 5.4: Structure of a light path variable.

**opticalChannels**

| opticalChannel-Index | sourceNode | destination-Node | capacity (ODU0s) | wavelenght (nm) | numberOf-Demands | demands-Index |
|---|---|---|---|---|---|---|
| 0 or greater | 1...N | 1...N | 0...80 | [to define] | 0 or greater | [d_1, ...] |

Table 5.5: Structure of an optical channel variable.

If the network starts with no initial information or files given then these three last variables will be created and sent to the LogicalTopologyManager_ block void, where later on will be updated.

The structures previously mentioned that constitute this new layer are named as it follows: "paths" which are a list of unique routes assigned to each specific connection request, "lightPaths" which are a list of paths from a source to a destination node in the optical domain, meaning data remains in optical domain without any O-E-O conversion in between[28], "opticalChannels" and finally the "logicalTopologyAdjacencyMatrix".

### 5.3.2 PhysicalTopology

The physical topology can be seen as a layout of a real optical network. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 2 unidirectional optical multiplexing systems, that will behave like a bidirectional connection between a pair of nodes, and each site supports up to 1 node.

Below are represented the variables that constitute a PhysicalTopology type signal.

**physicalTopologyMatrix**

| **Nodes** | 1 | 2 | ... | N |
|---|---|---|---|---|
| 1 | **0** | 0/1 | ... | 0/1 |
| 2 | 0/1 | **0** | ... | 0/1 |
| . . . | . . . | . . . | . . . | . . . |
| N | 0/1 | 0/1 | ... | **0** |

Table 5.6: Allowed physical topology for a matrix of N nodes.

0/1 indicates the possibility of existing a physical connection between nodes.

Based on the previous adjacence matrix a data structure is created for each of the unidirectional optical multiplexing systems interconnecting nodes.

**opticalMultiplexingSystems**

| opticalMultiplexing-SystemIndex | sourceNode | destination-Node | numberOf-Wavelenghts | wavelenghts | available-Wavelenghts |
|---|---|---|---|---|---|
| 0 | 1...N | 1...N | OC | [w_1, w_2, ...] | [0/1 ... 0/1] |
| ... | ... | ... | ... | ... | ... |
| L-1 | 1...N | 1...N | OC | [w_1, w_2, ...] | [0/1 ... 0/1] |

Table 5.7: Structure of the opticalMultiplexingSystems variables.

OC represents the number of optical channels present in a physical link.
L represent the total number of existent unidirectional physical links in the network.
w_1 and w_2 represent values of possible wavelengths to be used.
In the availableWavelenghts array 0/1 dictates if the corresponding wavelenght value of wavelenghts array is available or not to be used, 1 and 0 respectively.

All Optical Multiplexing Systems existent in the network are created in the PhysicalTopologyGenerator_ block. They all contain an index in order to be identified all the time, source and destination nodes, numberOfWavelenghts which translates in capacity in terms of quantity of available wavelenghts, and finally the actual values of wavelenghts and a matrix wich specifies which of them are still available to be used, initially all.

### 5.3.3 DemandRequest

| **demandIndex** | **sourceNode** | **destinationNode** | **oduType** | **survivabilityMethod** |
|---|---|---|---|---|
| 0...D-1 | 1...N | 1...N | 0...4 | none<br>protection_1_plus_1<br>restoration |

Table 5.8: Constitution of a DemandRequest type signal.

D represents the total number of demand requests entering the network. It is possible to know this value for the fact that 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, this traffic is said to be dynamic.

### 5.3.4 PathRequest

| requestIndex | demandIndex | oduType | sourceNode | intermediateNodes | destinationNode |
|---|---|---|---|---|---|
| 0 or greater | | | 1...N | 1...N | 1...N |

Table 5.9: PathRequest type signal.

The PathRequest type signal will be sent from the LogicalTopologyManager_ block into the PhysicalTopologyManager_ block asking for a path to be created between source and destination nodes of a certain demand. In order establish that path one or more light paths are required. In this specific case, transparent transport mode, only direct logical connections will be taken into account, because 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 light path. This means that there will be no intermediate nodes.

### 5.3.5 PathRequestRouted

A PathRequestRouted type signal is formed the following two structures, pathInformation and lightPathsTable, that will inform the LogicalTopologyManager_ block about the possibility of establishing the path requested.

**pathInformation**

| requestIndex | demandIndex | oduType | routed | numberOfLightPaths |
|---|---|---|---|---|
| 0 or greater | | | true/false | 0 or greater |

Table 5.10: pathInformation variable structure.

**lightPathsTable**

| sourceNode | destinationNode | numberOfIntermidiateNodes | intermediateNodes | wavelenght |
|---|---|---|---|---|
| 1...N | 1...N | 0...N-2 | [1...N ... 1...N] | W |
| ... | ... | ... | ... | ... |

Table 5.11: lightPathsTable variable structure.

The lightPathsTable structure will numberOfLightPaths-1 elements.

This signal represents the response that the PhysicalTopologyManager_ block sends back to the LogicalTopologyManager_ block when asked to establish a path. There is an requestIndex variable that identifies this signal as a reponse to the pathRequest signal with the same requestIndex. 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 on the lighPathsTable, 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 fill with invalid information. Furthermore, this signal contains, in the lightPathsTable, various information about each of the light paths needed to establish the path required in the case it is possible to do so.

### 5.3.6 DemandRequestRouted

| demandIndex | routed | pathIndex |
|---|---|---|
| 0...D-1 | true/false | 0 or greater |

Table 5.12: DemandRequestRouted type signal.

This signal contains information regarding one demand and whether it was routed or not. In the case variable "routed" assumes a true value it is presented in the final block (SinkRoutedOrBlocked_ ) of the diagram of figure **??** information about the path used. In the case where variable "routed" assumes value false only the information about the demandIndex is presented meaning that that demand was blocked. In the case a demand is routed combining the information of the DemandRequestRouted signal with the one present in the LogicalTopologyManager_ block it is possible to know every piece of information about the route taken by the demand, lightPaths and opticalChannels used as well as wavelengths.

## 5.4 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 5.13: Blocks input parameters and signals.

## 5.5 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 5.14: Blocks state variables and output signals.

## 5.6 Final Report

After running a simulation a text file named **FinalReport.txt** is created containg the final results of the same. Detailed information regarding the network nodes and links constitution, a routing scheme of the demands processed and the final CAPEX values obtained are present in this file.

# Chapter 6

# Results

## 6.1 Reference Network

### 6.1.1 Analytical

#### Low traffic

#### Medium traffic

#### High traffic

### 6.1.2 ILP

#### Low traffic

#### Medium traffic

#### High traffic

### 6.1.3 Heuristics

#### Low traffic

#### Medium traffic

#### High traffic

### 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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