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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

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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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agradecimentos / acknowledgements

Adicionar agradecimentos...

Add acknowledgments...

Palavras-chave Chave, palavra.

Resumo

Este é o primeiro parágrafo do resumo.
Segundo parâgrafo.
Terceiro parâgrafo.

Keywords Key, word.

Abstract

This is the first paragraph of the abstract.
Second paragraph.
Third paragraph.

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CAPEX	Capital Expenditure
FTTH	Fiber-to-the-home
IP	Internet Protocol
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] In response, as operators are undergoing a heavy pressure to reduce the cost per bit transported, they have been investing in

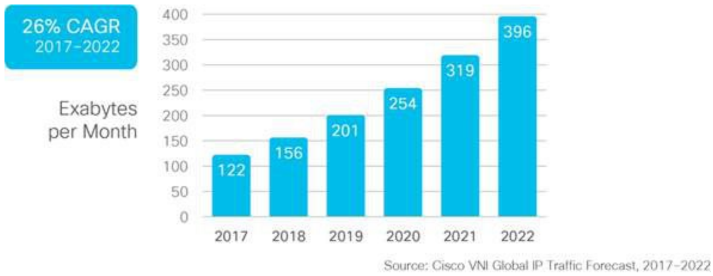

Figure 1.1: Cisco forecasts per month of IP traffic from 2017 until 2022.

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 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 models for transparent networks without survivability.

3. Elaborate a comparative study, regarding the subject of capital expanditure, with the results obtained analytically, through ILP methods and the Heuristics developed.

1.3 Thesis outline

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 transparent optical networks is a vast and highly multidisciplinary field in the modern telecommunication world as it shall be seen further along this dissertation.

As it was previously mentioned, connections to the Internet are growing unbelievably fast mainly due to the expansion of optical fiber to customers homes in the access network area, the recurrent variety of new broadband services, and business virtual private networks with remote access to huge databases, which translates in a major increase of IP traffic[2]. Another relevant and emerging services like cloud storage or online social networks who have also been implemented over Internet require a suitable network design for huge traffic requirements and so an efficient utilization of the physical resources available becomes a factor of even greater importance over time, so that networks of the future can ensure a reliable and efficient adaptation to the constant needs for improvement. Thus, routing and network dimensioning became key technical factors in optical WDM networks which have high impact on networks cost and performance[11]. The direct consequence of a well structured network is the minimization of node components and,as a result, lower Capital Expenditure (CAPEX) which is the main objective of this dissertation. In the transparent transport mode there is used a single-hop approach grooming method and so the signals travel through the network in the optical domain between lightpaths, which are high-bandwidth end-to-end circuits, occupying a wavelength on each link of the path between a pair source and destination nodes[12].

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.[14] 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.

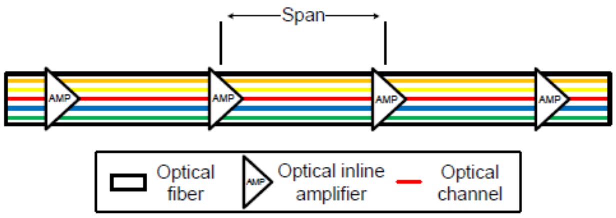

Figure 2.1: Schematic of a link: optical fiber and inline optical amplifiers.[13]

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[15]. 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.[15] 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.[16]

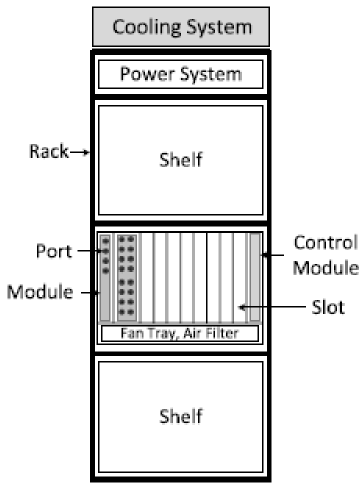

Figure 2.2: Schematic of a node structure.[15]

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 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].

2.2.1 Physical Topology

Different networks usually possess different physical topologies. It represents the set of routing and end nodes, and in the case of OTN networks the optical fiber links interconnecting them[17].

2.2.2 Logical Topology

2.3 Reference Network

2.3.1 Physical Topology

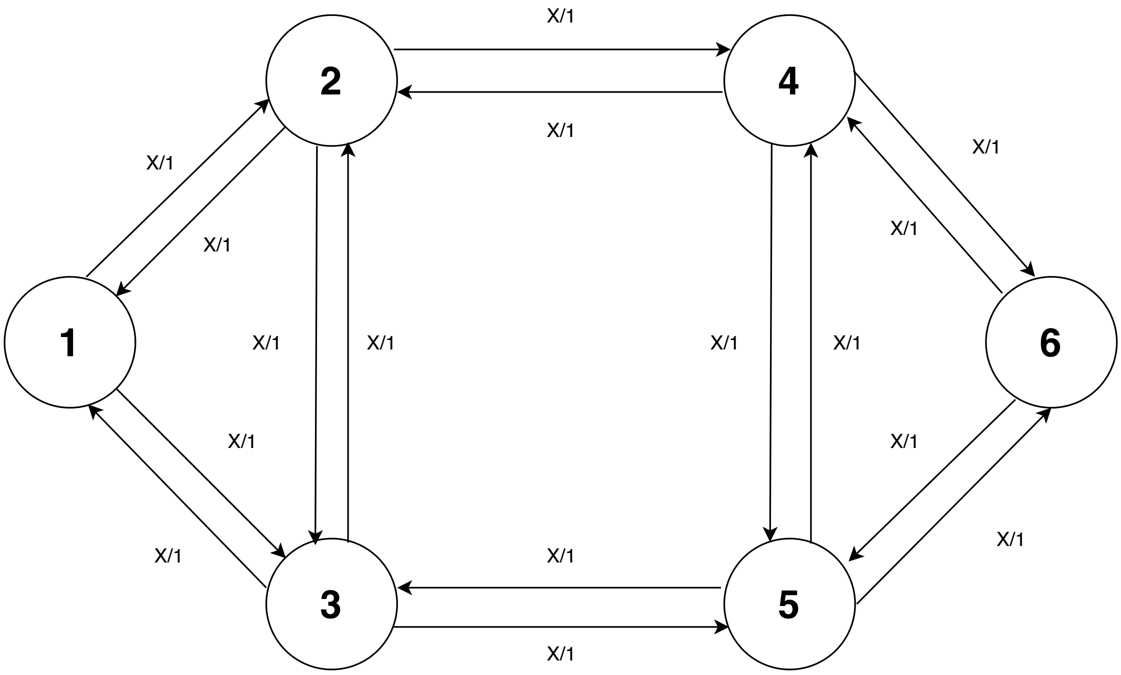

Figure 2.3: Reference network physical topology pictorial representation.

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 $\qquad T_1^1 = 50\text{x}2.5 = 125$ Gbits/s $\qquad T_1^2 = 30\text{x}10 = 300$ Gbits/s

$T_1^3 = 10\text{x}40 = 400$ Gbits/s $\qquad T_1^4 = 6\text{x}100 = 600$ 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 = 240x1.25 = 300 Gbits/s $\quad$ T_1^1 = 200x2.5 = 500 Gbits/s $\quad$ T_1^2 = 120x10 = 1200 Gbits/s

T_1^3 = 40x40 = 1600 Gbits/s $\quad$ T_1^4 = 24x100 = 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

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.[18] 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.[16] The costs can be mainly divided into two branches: the 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, those include rent, equipment, inventory costs, insurance, and funds allocated for research and development. [8][19] The current chapter proposes and describes the model used to calculate capital expenditures of the network using analytical models. 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 is calculated through equation ??. 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 are operators to lease fiber-optic cables instead of installing them.[8] It is also important to stress the fact 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.

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

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

where

- $\gamma_0^{OLT} \rightarrow$ OLT cost in euros
- $L \rightarrow$ 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

Assuming that τ is 100 Gbits/s the only remaining unknow parameter is the number of optical amplifiers and the average number of optical channels [16].

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) [16].

Through the equation 3.4 we can calculated the average number of optical channels[20], $< w >$, as

$$< w >= \left(\frac{\lceil D \times < h > \rceil}{L_u} \right) (1+ < k >) \tag{3.4}$$

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

$$D = \left(\frac{1}{2} \right) (1 + \xi) \left(\frac{T_1}{\tau} \right) \tag{3.5}$$

where ξ is the grooming coefficient, T_1 is the total unidirectional traffic and τ is the line bit rate [20].

3.2 Nodes Cost

On the other hand, the nodes' cost, C_N, in monetary units (e.g. euros, or dollars), is calculated by the equation 3.6

$$C_N = C_{EXC} + C_{OXC} \tag{3.6}$$

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)

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)

Chapter 4

CAPEX Estimation Approaches

4.1 Analytical

4.2 ILP Models

4.3 Heuristics

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.[21] Heuristics are usually developed to have low time complexity and applied to complex problems, and are able to produce a solution individually or be used to provide a good baseline and are supplemented with optimization algorithms.[22] There are some commonly used heuristics such as genetic algorithms, artificial neural networks and support vector machines.[21] 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 major objective of minimizing the total CAPEX of the network. In order to get the total network cost for the reference network in the tested traffic scenarios, the CAPEX is calculated by scheduling, routing and grooming heuristic algorithms amongst others, and implemented in C++ language running over the NetXPTO simulator. Furthermore, it is considered that all network equipment is treated individually, thus being unidirectional and forming bidirectional connections when in pairs. This chapter consists in demonstrating how the physical and logical topologies are created and how the heuristic algorithms perform with the information given to them.

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

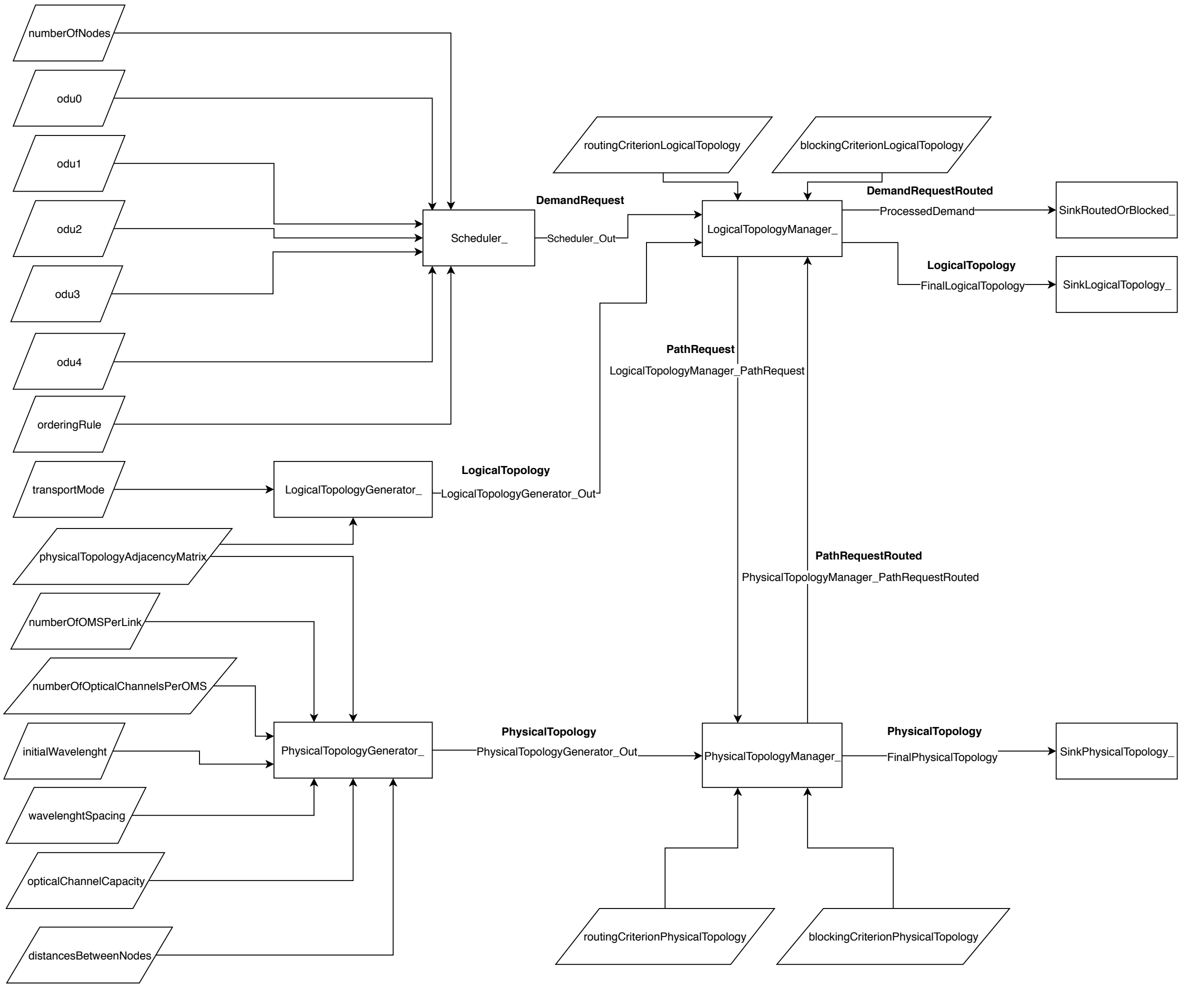

Figure 4.1: High level diagram of the heuristic algorithm performed.

4.4 Input Parameters System

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

4.4.1 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 4.1: System input parameters.

4.4.2 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 (FALTA A IMAGEM).

4.4.3 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.

4.5 Log File

4.5.1 Parameters

4.5.2 Output File

4.6 Type signals structure

4.6.1 LogicalTopology

The logical topology of the network 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 demostrated 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 4.2: 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 4.3: 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 4.4: 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 4.5: 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 Optical-Electronic-Optical (O-E-O) conversion in between[23], "opticalChannels" and finally the "logicalTopologyAdjacencyMatrix".

4.6.2 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 4.6: 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 4.7: 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.

4.6.3 DemandRequest

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

Table 4.8: 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.

4.6.4 PathRequest

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

Table 4.9: 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.

4.6.5 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 4.10: pathInformation variable structure.

lightPathsTable

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

Table 4.11: 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.

4.6.6 DemandRequestRouted

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

Table 4.12: 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.

4.7 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.

4.8 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.

4.9 Scheduling

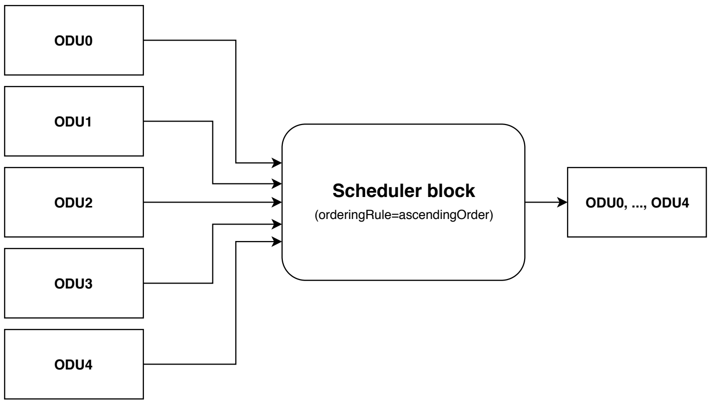

Figure 4.2: Scheduler algorithm illustration for the case of ascending ordering rule.

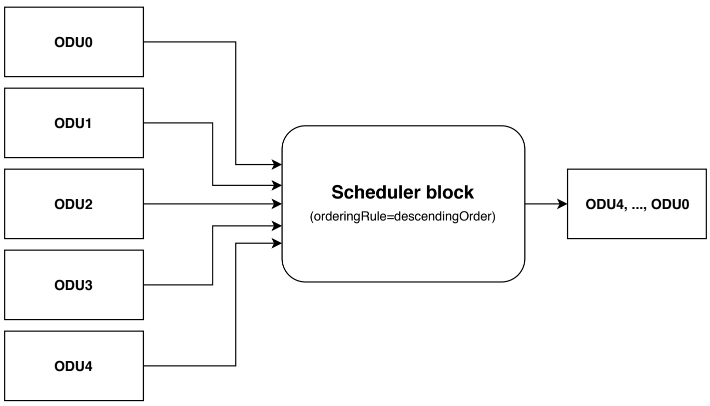

Figure 4.3: Scheduler algorithm illustration for the case of descending ordering rule.

As it is shown above in figures 4.2 and 4.3, before the demands entering the network can 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 demands ODU type. That becomes the order by which they will become ready to be processed and routed. The signal exiting from this block will be of the "DemandRequest" type and will contain information of the 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.

4.10 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, amongst other aspects, on the logical topology of the network.

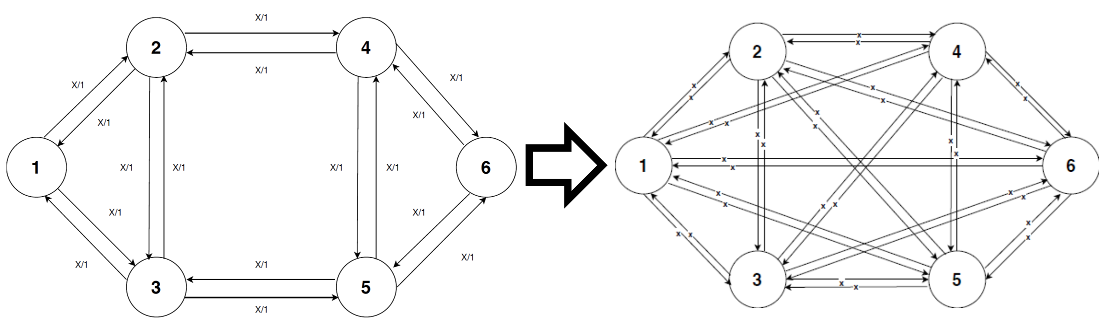

Figure 4.4: Logical topology algorithm: conversion from physical topology adjacency matrix (left side) to the logical topology adjacency matrix (right side).

4.11 Routing

Routing is the process of assigning of a unique path through the network for a traffic demand, from a set of all all available paths[2].

4.12 Grooming

4.13 Final Report

Chapter 5

Results

5.1 Reference Network

5.1.1 Analytical

Low traffic

Medium traffic

High traffic

5.1.2 ILP Models

Low traffic

Medium traffic

High traffic

5.1.3 Heuristics

Low traffic

Medium traffic

High traffic

5.1.4 Comparative Analysis

5.2 Realistic Network

5.2.1 Analytical

5.2.2 Heuristics

5.2.3 Comparative Analysis

Chapter 6

Conclusions and future directions

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