Cost Optimization Strategies for Multi-Layer Telecommunications Networks

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Abstract

Traffic in telecommunication networks does not cease to increase, and the need for a rapid transformation and adaptation of fibre optic networks is a mandatory requirement to serve this continuous growth. The increase of the fibre’s capacity through the consideration of wavelengths with 100, 200 and 300Gb/s capacities, and techniques such as service grooming and balancing were studied throughout this work.

As such, different heuristic algorithms were implemented to enable end-to-end grooming as well as intermediate grooming, aiming to lower the implementation cost of the network and use the available bandwidth effectively. Different algorithms for routing, balancing and wavelength assignment were also implemented and their results were compared.

Different network topologies were tested, using transparent, opaque and translucent networks. For the latter, the enabling of regeneration was tested using regeneration cards or Back-to-Back (B2B) muxponders. Considering that the transparent and translucent with regenerators architectures only allow for end-to-end grooming, and that opaque and translucent with muxponders for regeneration architectures allow for intermediate grooming, a comparison between the implementation cost for each one of these solutions is made. Also, the use of Sliceable Bandwidth-Variable Transponder (SBVT) muxponders and regeneration cards were considered and compared to other results.

Comparisons are made between the different topologies, architectures and capacities, with respect to the use of wavelengths, blocked services and global cost of the network using different cards. It is concluded that the use of B2B muxponders for regeneration, boosts the intermediate grooming, improves the cost solution and uses the wavelengths more efficiently.

Keywords

Traffic Grooming, OTN Switching, CAPEX, WDM, Heuristic Algorithms, OTUC
Resumo

O tráfego nas redes de telecomunicações está continuamente a aumentar, assim como a rápida necessidade de transformação e adaptação das redes de fibras ópticas. O aumento da capacidade na fibra, através da consideração de comprimentos de onda com débitos de 100Gb/s, 200Gb/s e 300Gb/s, e de técnicas como agregação de serviços e balanceamento, foram estudadas durante este trabalho.

Para tal, foram implementados diferentes algoritmos heurísticos que possibilitam a agregação ponto-a-ponto e agregação intermédia, cujo objectivo é baixar o custo de implementação da rede, fazendo uso eficaz da largura de banda disponível. Foram também implementados algoritmos de encaminhamento, balanceamento e atribuição de comprimentos de onda e os seus resultados comparados.

Foram testadas diferentes topologias de rede, usando redes transparentes, opacas e translúcidas. Para as últimas, testou-se a possibilidade de regeneração através de uma carta regeneradora ou muxponders costas-com-costas. Considerando que as arquitecturas transparentes e translúcida com regeneradores apenas possibilitam agregação ponto-a-ponto e que arquitecturas opacas e translúcidas com uso de muxponders para regeneração possibilitam agregações intermédias, é feita uma comparação do custo de implementação de cada uma das soluções. O uso de cartas muxponder e regeneradora SBVT é também considerado, e os resultados analisados.

Comparando-se as diferentes topologias, arquitecturas e capacidades, no que diz respeito ao uso de comprimentos de onda, serviços bloqueados e custo global da rede usando diferentes cartas, conclui-se que o uso de muxponders costas-com-costas conduz a melhores resultados, e, balanceando os mesmos, a um uso eficiente do comprimento de onda.

Palavras Chave

Agregação de tráfego, Comutação OTN, CAPEX, WDM, Algoritmos Heurísticos, OTUC
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Abbreviations

3R  Reamplification, Reshaping and Retiming

ADM  Add-drop Multiplexer

B2B  Back-to-Back

CapEx  Capital Expenditure

DWDM  Dense Wavelength Division Multiplexing

DXC  Digital Cross-Connects

E/O  Electrical-Optical

FEC  Forward Error Correction

ITU  International Telecommunication Union

LFAP  Longest First Alternate Path

O/E/O  Optical-Electrical-Optical

O/E  Optical-Electrical

OADM  Optical Add-drop Multiplexer

OCh  Optical Channel

ODU  Optical channel Data Unit

OMS  Optical Multiplex Section

OpEx  Operational Expenditure

OPU  Optical channel Payload Unit

OSNR  Optical Signal-to-Noise Ratio

OTM  Optical Terminal Multiplexer

OTN  Optical Transport Networks

OTS  Optical Transmission Section
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<td>Optical Transport Section</td>
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<td>OTU</td>
<td>Optical Transport Unit</td>
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<td>PDH</td>
<td>Plesiochronous Digital Hierarchy</td>
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<td>QoS</td>
<td>Quality of Service</td>
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<td>ROADM</td>
<td>Reconfigurable Optical Add-drop Multiplexer</td>
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<td>RWA</td>
<td>Routing and Wavelength Assignment</td>
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<td>SBVT</td>
<td>Sliceable Bandwidth-Variable Transponder</td>
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<td>SC</td>
<td>Star Coupler</td>
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<td>SDH</td>
<td>Synchronous Digital Hierarchy</td>
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<tr>
<td>SDH</td>
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<td>SONET</td>
<td>Synchronous Optical Networking</td>
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<tr>
<td>TCM</td>
<td>Tandem Connection Monitoring</td>
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<td>VCAT</td>
<td>Virtual Concatenation</td>
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<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
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1.1 Evolution of Telecommunication Networks

The first big telecommunications system appeared as a telegraph, which propelled the implementation of the first big network, connecting the globe. Following this, the fixed-telephone arose, enabling perceptible voice transmission. In the last 20 years, the expansion of mobile communications occurred.

In the past, communication was made by the use of coaxial and copper cables. In the 80s, telecommunications carriers started migrating much of the physical layer to fibre-optic cables with the invention and maturity of semiconductor lasers. This happened because optical fibre provides low loss capacity and has a tremendous potential capacity.

Telecommunication networks are divided into two main layers, the service layer and transport layer, the first being responsible for services such as voice, video or data, and the second having the purpose of transport end-to-end communications, being an optimized layer which provides a good ratio between cost and data transportation. Because of that, a lot of importance is put into the design of the network, always looking for potential advances in technology which would enable the improvement of optical networking.

Before the boost of internet traffic, most of the traffic was created by voice calls, so the developed hierarchies were based on that traffic. The Plesiochronous Digital Hierarchy (PDH) and Synchronous Digital Hierarchy (SDH) were normalised and acted as the dominant hierarchies for some time. However, as shown before and in figure 1.1, internet traffic far surpassed the traffic generated by voice calls. Soon, the need of adaptation by the telecommunication providers was evident, or the cost per bit would constantly increase.

![Figure 1.1: Global information and communication technology developments, 2001-2016](image)

In the 90s, the introduction of optical amplifiers and Wavelength Division Multiplexing (WDM) technologies offered increased cost effectiveness and virtually unlimited capacity potential for the transport network. The ability to carry multiple channels in one single fibre, where different lightpaths (wavelengths) could be carried in the same fibre, at different optical frequencies and multiplexed,
was then made possible. Nowadays, it is possible to see fibres with the capacity to carry 80-100 wavelengths [6].

Statistics shown by International Telecommunication Union (ITU) [1] show that the annual (2016) growth of fibre subscriptions in Organisation for Economic Cooperation and Development increased by almost 20%. In countries such as Japan and Korea, almost 76% of the connections in total broadband are made by the use of fibre connections.

Optical Transport Networks (OTN) is defined as a set of optical network elements, connected by optical fiber, which provide functionalities as transport, multiplexing, switching, management, survivability and supervision of optical channels. OTN technology is indispensable for telecommunication operators to construct reliable and cost-effective high-capacity optical networks. It is expected that OTN will continue to play a significant role in the evolution of operator networks supporting future high-bandwidth services and increased network efficiencies.

1.2 Motivation

Different services have requested fibre optic networks to transport traffic. Due to this, the necessity of increasing the capacity and the exploring of efficiency techniques is a key issue to face in the present and future. The emerging of new services such as cloud computing, Internet Protocol Television (IPTV), Voice over Internet Protocol (VoIP), the increase of Ethernet traffic, among others, generate a world where people start to see these services as an essential good. Statistics presented by ITU [1] show the decrease of fixed-telephone subscriptions and an increase of mobile-cellular ones. In 10 years (2006-2016), for developed countries, there was a decrease of almost 100 million fixed-telephone subscriptions, and an increase of almost 600 million subscribers for the mobile-cellular telephone. On the other hand, both the active and fixed broadband subscriptions are constantly increasing, and nowadays more than 50% of houses in the world have access to the internet. Because of this importance, the spending in telecommunication subscriptions has now grown to 5% of the family budget[11], and the household budget surveys which Eurostat collects show that there is a constant increase [12].

As a consequence of that, it is essential to carefully plan and increase the bandwidth management in order to reduce the costs in the transport network implementation. A poor planning of the network can lead to an excessive use of elements and inefficient use of the OTN technology, causing overinvestment in a solution for a certain required traffic.

OTN is considered to be indispensable technology from the operator’s point of view. In order to construct a reliable and cost-effective high capacity optical network, OTN is the current solution and will continue to play a significant role in the evolution of operator networks [10]. The current WDM technology allows the wavelengths to be transported without Reamplification, Reshaping and Retiming (3R) for long distances, decreasing the number of operations in the network and respective Capital Expenditure (CapEx).

Other techniques such as grooming, which enables the multiplexing of several client signals in the
same Optical Channel (OCh) (lightpath), allow the OTN to improve the efficiency of the bandwidth and wavelength used.

It is expected that the OTN will continue to play a significant role in the evolution of operator networks supporting future high-bandwidth services and increased network efficiencies. Grooming, which enable the best use of bandwidth, is the main technique tested in this work. A thorough study was made in grooming techniques for network design in work [13] and book [14]. In studies [?] and [?] the authors proposed methods for traffic grooming in OTN with different signal capacities and the use of Virtual Concatenation (VCAT), which in this work is not considered.

The monthly IP traffic generated per capita in 2020 is expected to be 21Gb, compared to 10Gb in 2015. Also, the network has to be prepared for the busiest times of the day, where the traffic has been increasing even faster compared to the growth in average traffic [15]. This continuous increase reinforces the need for exploring the techniques which enable effectiveness of the network.

Recommendation G.709, in [7], describes and standardizes the communications using optical networks. The ITU continued to improve the standard, and in 2016 [7] introduced the ODUC-n which standardizes the transport of signals beyond 100Gb/s. Also elements such as Sliceable Bandwidth-Variable Transponder (SBVT), which is provides Optical-Electrical (O/E) conversions to variable optical flows, are an example of the continuous evolution of solutions for OTN. Recent publications have been testing and evaluating the possible advantages of using flex-rate technology, such as [16] where the hardware requirements with incremental traffic are evaluated over time. It was concluded that the implementation of this technology solution for small to medium sized networks is beneficial knowing that extra regeneration is unnecessary. This technology has shown cost-benefits compared to individual interfaces, because of better compatibility between different data rates and simplification of wavelength allocation [17].

Some considerations on the architectures of Reconfigurable Optical Add-drop Multiplexer (ROADM) and Wavelength Selective Switch (WSS) are done in [5, 18, 19] where a comparison is made between different implementations, different features such as colourless, directionless and contentionless, and the possibility of scalability.

The book referenced in [6], focuses on network planning, overviewing its several aspects. Many studies show that Optical-Electrical-Optical (O/E/O) conversion is responsible for most of the CapEx and studies such as [20, 21] have been made proposing methods to minimize regeneration.

1.3 Objective and Outline

The main objective of this work is to develop a framework and algorithm to design an OTN network, with the goal of minimising the global cost solution. The framework should receive multiple service requests of 10Gb/s and the optical channels will work in three signal capacities: OTU4, OTUC-2 and OTUC-3. The use of muxponders, hence referred to as OTU4 Muxponder, OTUC-2 Muxponder and OTUC-3 Muxponder will be considered. Regenerators with the same capacities are also used. The use of SBVT cards is also tested for cost minimisation solution.
In this work, four different node structures are tested. The first uses a transparent architecture with only source-to-source grooming. It is composed by one ROADM and uses muxponders to groom the client signals into the same OCh. The opaque architecture is composed by OTU switches and considers the possibility of intermediate grooming of the traffic in all the nodes since the O/E/O conversion happens in all the nodes. In case of translucent networks two regeneration possibilities are considered: the use of regenerators, or the use Back-to-Back (B2B) muxponders for regeneration. Also, the influence of WSS cost is taken into account.

The use of intermediate grooming will lead to a better use of the wavelength, although more muxponders will be needed in the network, compared to the architecture considering only transparent nodes and using regenerators to allow 3R function. The comparison between the number of elements needed and respective cost for each node configuration is going to be made.

In this work, the optical reach depends on the capacity of the optical signal. This data was retrieved from [22].

With the goal of minimising the use of the network elements and global cost of the network, some algorithms proposed in the literature are used, and one is implemented in order to choose the solution for each traffic service for intermediate grooming architectures. The traffic used in this work is invariable in time.

Furthermore, frameworks to study the impact of routing, balancing and Routing and Wavelength Assignment (RWA) heuristic algorithms are also implemented.

In chapter 2 some considerations on the important concepts introduced are presented, as well as a few considerations on previous work that was done. An exhaustive explanation on OTN is done, presenting the different elements in detail. Moreover, the routing, balancing and RWA heuristic algorithms used in this work, which were not designed by the author, are also presented in this chapter.

In chapter 3 the developed frameworks are explained. First, the framework which studies the different routing algorithms is presented. The frameworks for Load Balancing and RWA are also explained in detail. Additionally, the node architectures are defined. The main framework and implemented algorithms are also explained in subsection 3.5. The methods used to count the different elements are explained with the use of mathematical expressions, flowcharts and pseudocodes to allow for a better understanding.

Chapter 4 explains the results, but first defines the testing computer set. Some considerations about the results of Routing, Balancing and RWA frameworks are made. Following this, the result of the Cost Optimisation Framework is analysed, the two different node architectures results are compared, and finally, the costs of the different solutions are analysed and compared in order to be able to take conclusions.
State Of the Art

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2.1 Basic Concepts

In the following sections some concepts will be explored.

2.1.1 Physical and logical topologies

In telecommunication networks there are different components and equipments, such as computers, switches, routers, ROADM multiplexers, optical fibres, coaxial cables, among others. The equipment can be classified as network elements or transmission link, being the first devices which originates, route or terminate information and the second responsible for the transmission. To perform a theoretical study of these networks, the components are defined as abstract entities, so that the network can be represented as a graph [8]. Graphs are used in several network problems such as routing, and are represented by a set of nodes, also known as vertices), and links or edges. A network topology is divided between physical and logical. On one hand, a physical network represents the connections between all nodes using different types of hardware, for example, optical fibres for the links and switches for the nodes. On the other hand, a logical network is defined by the information exchanged between the existing nodes. In this study, each network has a certain number of nodes, N, and edges, E. A graph is represented as \( G = (V, E) \), which means the graph is a set of \( V = \{v_1, v_2, \ldots, v_N\} \) vertices and \( E = \{e_1, e_2, \ldots, e_L\} \) edges. The physical topology is also represented using the adjacency matrix \( g \). This \( N \times N \) matrix has two different elements, 1 or 0. Element \( g_{xy} = 0 \) means that from node \( x \) there is no connection to \( y \), while \( g_{xy} = 1 \) denotes a connection between two nodes.

\[
g = \begin{bmatrix}
0 & 1 & 1 & 0 & 1 \\
1 & 0 & 1 & 1 & 0 \\
1 & 1 & 0 & 1 & 1 \\
0 & 1 & 1 & 0 & 1 \\
1 & 0 & 1 & 1 & 0
\end{bmatrix}
\]  

(2.1)

Matrix 2.1 originates the graph illustrated in Figure 2.1.

A link connects one node to another, and that node has an associated cost, which can be distance,
delay or price, among others. Moreover, a link can either be unidirectional or bidirectional, which creates directed or undirected graphs, according to the type of link. This work focuses on optical networks that frequently use undirected graphs (representing bidirectional communications), in which, if vertex \( v_y \) is connected to \( v_z \) through edge \( e_x \), the connection from \( v_z \) to \( v_y \) is given by the same edge that is bidirectional.

In telecommunication networks it is important to define the used physical topology since it is possible to design a network with star, tree or mesh topology, between others.

Additionally, it is important to study the network traffic load, exchanged between nodes, which are defined by the traffic \((T)\) matrix. It is possible to have a time-variant or a time-invariant \(T\)-matrix. The load inserted into the network from \( v_x \) to \( v_y \) is defined in the \(T\)-matrix as \( t_{x,y} \). If the value is \( t_{x,y} = 0 \) that means the node does not communicate from \( x \) to \( y \). The worst case scenario is the one where all the nodes have demands to reach all the other ones.

\[
T = \begin{pmatrix}
0 & t_{1,2} & \cdots & \cdots & t_{N,N} \\
t_{2,1} & 0 & \ddots & \ddots & \vdots \\
\vdots & \ddots & \ddots & \ddots & \vdots \\
\vdots & \ddots & \ddots & 0 & t_{(N-1),N} \\
t_{N,1} & \cdots & \cdots & t_{N,(N-1)} & 0
\end{pmatrix}
\]  
(2.2)

Another relevant study parameter is the node degree, given by the number of existing links connected to one single node. Equation (2.3) calculates the relationship between the total number of nodes and edges in a physical network, which is called average node degree.

\[
<\delta> = \frac{1}{N} \sum_{i=0}^{N} \delta_i = \frac{2 \times L}{N}
\]  
(2.3)

Through these distinct representations and study parameters it is possible to define and examine a telecommunications network. The \( \delta_i \) is the node degree of node with index \( i \).

### 2.1.2 Transparency in optical networks

The optical network can be defined by its transparency. This property defines the capability of transmitting regardless of the type of protocol, coding format, data rates and modulation techniques [23].

Thus, is possible to work in full transparency or with none at all and, as such, networks are separated in to three types, (i) opaque, (ii) transparent and (iii) translucent. Nowadays, the optical networks are moving from the opaque architectures to the transparent. Because of that, several studies has been made in this topic.

An opaque network converts, in each node, an O/E signal and its inverse. This type of network enables signal regeneration in each physical link, which requires hardware to O/E that results in an increase of CapEx.

A transparent network is one where it is not necessary to regenerate a signal between source and destination. These networks are defined by the capacity of sending signals between two nodes using
a lightpath, which does not require an optical-electrical conversion. The lightpath defines the route followed by and optical signal between two nodes in the network, using the same wavelength in all physical links. Further on in this work, multiple services that use the same lightpath, using grooming techniques, are presented.

The use of full transparent networks has some limitations, since they do not use signal regeneration. If on one hand, the optical reach increases with the introduction of Forward Error Correction (FEC) in OTN networks [24], on the other, passing through different optical nodes and their corresponding physical distance introduces degradation in the signal, causing a limitation in the optical reach.

The principal network element in a transparent node is the ROADM, explained in section 2.2.2.A. Transponders and muxponders are other elements used in these nodes, and they are detailed in section 2.2.2.B. Figure 2.2 shows two possible configurations of transparent nodes. Client cards can work with different signals, and the figure shows one using 100GbE and another 10GbE. The left ROADM uses transponders that enable the mapping of client signals into optical channels. The right one represents a transparent node using muxponders to map client cards. In the case of transponder-based nodes, OTU4 is used to handle the client card rates. The use of a OTU3 muxponder is chosen to map 3x10GbE signals.

A translucent network is the network which enables O/E conversions between source and destination, but not mandatory. Ca have the capacity of switching signals in the optical and electrical domains. Is also necessary to enable regeneration between intermediate nodes, allowing the signal to travel from the source to the destination, even for larger distances.

Figure 2.3 represents multi-layer network, which uses Optical channel Data Unit (ODU) switches and ROADM. The former is responsible for the electrical switching, while the latter for the optical switching. This configuration can allow intermediate grooming and, if possible, new traffic is allocated into an existing lightpath, saving wavelength.
2.1.3 Routing

Routing is the process of selecting a path for a certain traffic demand according to certain metrics: minimizing the cost, hops, distance, among others. To achieve this, different algorithms were presented in several works. Dijkstra, in [25], designed the most well-known routing algorithm to find the shortest path. Bellman [26] and Ford [27] also contributed with an algorithm that is able to find shortest paths using negative cost links. Yen [28] brought the possibility of finding the first K-Shortest paths, as an extension of the Dijkstra algorithm. Among others, the routing problem is solved through the use of different algorithms that enable the network to find distinct routes given different constraints.

2.1.4 Balancing

In telecommunication networks, load balancing is the technique of distributing traffic across the network, so that no single link is overloaded [29]. The main goal consists of being able to re-route traffic from the most loaded links to the least loaded links, thus reducing the difference. In a balanced network, the resources are used in an optimal manner and the services are provided faster and with a better result.

To better understand the importance of load balancing, an example is presented. A company has a given job to be done, and it has two employees. One is able to do the work within 10 hours, while the other takes 12 hours. However, if the work is divided by the two, it only takes six hours to perform as it is divided between the two resources. By analogy, the company is a network and the resources are the correspondent links and nodes. This enables the network to give a faster answer as well as a better service.

A balanced network can become more inexpensive compared to an unbalanced one, offering a better quality of service. The capacity of each fibre along with the number of wavelengths needed in each fibre connection must be aimed at being as low as possible, since it decreases the network’s global cost [11]. In this work, the aim is to study the minimization of a network’s cost, therefore the study of decreasing the use of bandwidth in each fibre and the number of wavelengths needed is crucial.

Different works propose several algorithms to achieve load balancing in a network. Murugesan
et al. [29], propose an adaptive granularity algorithm for dynamic load balancing in MPLS networks, while Bertsekas et al. [30] present a comparison between the effectiveness of the proposed algorithm, as well as static and dynamic load algorithms solutions.

In thesis [11], one simple balancing algorithm is proposed. The network, that is defined through a mesh logical topology, with one demand from each node to all the others, uses routing by applying the Dijkstra algorithm. After manually selecting routes from the most loaded link, re-routing is done using different routing algorithms – Yen and Random.

2.1.5 Grooming

The amount of bandwidth of an optical fibre can be divided into a certain number of wavelengths, using wavelength division multiplexing (WDM) technology [31]. The wavelength capacity it is not fully exploited, providing higher capacities compared to the service needs. Grooming is commonly defined as the optimization of network transmissions that encompasses multiple distinct transmission channels [13]. The process of grouping several small flows into larger ones is a necessary technique for the future of telecommunication networks, where optimization of bandwidth usage is a big concern. Thus, the process of grouping different signals into the same signal, using only one wavelength instead of two is an important feature for network scalability and effectiveness. The amount of bandwidth of an optical fibre can be divided into a certain number of wavelengths using WDM technology [31].

In the work of Zhu et al., several grooming techniques are presented [14]. It has been shown that the consumption of energy in the network is mostly influenced by the electrical portion and not the optical one [32], and since traffic grooming is enabled by the electrical portion, several works compared algorithms using source and intermediate grooming. Lin et al. [33] presented an approach to this problem, proposing one algorithm and comparing to others using intermediate grooming and minimizing the OEO conversions, increasing the bandwidth usage of a wavelength channel and reducing the required transmitters/ receivers.

2.1.6 Regeneration

In telecommunications, the process of restoring a signal and recovering its original characteristics is known as regeneration. In optical communication, each connection has a different distance reach, depending both of the signal and transmission system characteristics. The reach is dependent on several components, such as distance or the number of network elements in the route.

The 3R, standing for re-amplification, re-shaping and re-timing is an important function for optical networks. In this work, the regeneration is enabled mainly through two distinct elements, the regenerators and the transponders/muxponders. The first presents an input and an output, receives an optical signal and retransmits it, allowing its recovery. The second uses a back-to-back solution that enables regeneration, also taken into account for cost optimization. These elements are further detailed.
2.2 Optical Transport Network

The transport networking in SDH was primarily performed by broad classes of network elements: terminal multiplexers (TMs), Add-drop Multiplexer (ADM), and Digital Cross-Connects (DXC) [34].

In the following sections, for a clear understanding of OTNs, the main advantages and disadvantages of their use are presented. As defined by ITU-T in [35], an OTN is a set of optical network elements connected by optical fibre links, capable of providing optical channel transport, multiplexing, routing, management, supervision and survivability.

The optical transport networks have been migrating from Synchronous Optical Networking (SONET) and SDH technology to WDM architectures over the past years [36]. For telecommunication carriers this migration translates in cost savings.

OTN standards were defined by ITU in recommendation G.709. The ITU standards are essential to combine the benefits of SONET/SDH with the capabilities of Dense Wavelength Division Multiplexing (DWDM).

OTN specifies a digital wrapper, which is a method for encapsulating an existing data frame, regardless of the native protocol, to create an ODU similar to the ones used in SDH/SONET. It has the intention of carrying virtually any customer, not being limited to Ethernet clients [37].

An OTN provides the network management functionality of SDH and SONET on a wavelength basis. A digital wrapper, illustrated in Figure 2.4, is flexible regarding frame size and allows multiple existing frames of data to be wrapped together into a single entity that can be more efficiently managed through lesser amounts of overhead in a multi-wavelength system [4]. Considering this, it is possible to take signals from different protocols as IP, Ethernet, SDH/SONET, among others, and transport it in an OTN network.

![Figure 2.4: OTN Wrapper - adapted from (?)](image)

The biggest advantages of OTN networks are:
• Transparent Client Signals: Enables, virtually, the possibility of transport any signal. The Optical channel Payload Unit (OPU), which contains all the information from different types of signals, adds the overhead, which is required in OTN transport, so it is possible to access the sent information at the end of the route.

• FEC: The error detection and the correction are other improvements provided by OTN. The FEC enhances the Optical Signal-to-Noise Ratio (OSNR) from 4 to 6 dB, resulting in longer spans and fewer regeneration requirements [36, 37].

• Scalability: OTN were designed with different expectations regarding telecommunications growth. Compared to SONET/SDH, designed for carrying voice circuits and without an expectation of big expansion, OTN aims to carry a payload of greater bulk. It allows the transmission of high capacity signals like 100 Gb/s [4].

• Offers efficiency and cost reduction, by using simple multiplexing and demultiplexing techniques [4].

• Tandem Connection Monitoring (TCM): It includes six connections for network monitoring, which allows an operator to have information of a signal that passed through another operator network. This feature is crucial for assuring Quality of Service (QoS).

The disadvantages of OTN are mainly due to new hardware needs and requirement of management systems.

2.2.1 OTN Hierarchy

With the development of optical technologies and the growth of traffic in the network, the need to adapt the existing network infrastructures to the new optical networks became clear. In the 90s, the structure of OTNs was defined in ITU Recommendation G.709, to maximize the efficiency of the transition systems and provide integration IP/WDM. This recommendation used a format similar to the SONET/SDH frame. One of the biggest improvement was the possibility to encapsulate multiple protocols, as SDH, ATM or Ethernet and transport them in the OTN network.

![OTN Layer Termination](image)

**Figure 2.5:** OTN Layer Termination - extracted from [3]

The OPU is originated at the lightpath's source, ending in the destination where the client signal is extracted. As shown in Figure 2.5 the OPUk is an end-to-end signal. The ODU is created and
commonly terminates in the same location as the OPU. For the Optical Transport Unit (OTU), the signal is created and ended in all the network points, where Electrical-Optical (E/O) conversion is made. Afterwards, the OTU is converted into an optical signal, called OCh.

![OTN Hierarchy Diagram](image)

Figure 2.6: OTN Hierarchy - adapted from [4]

Figure 2.6 represents the OTN hierarchy, which is divided into two main domains: electrical and optical. In the first, a client signal is adapted at the OPU layer by adding one overhead, which contains information to support this adaptation. After, the OPU is mapped into an ODU, adding one more overhead that ensures the supervision and the TCM. Adding one more overhead to ODU maps it into an OTU, providing framing, section monitoring and FEC [3].

In the optical domain, the OCh represents an end-to-end optical path and is responsible for the transportation of OTU signals. Each OCh is assigned to one specific free wavelength. The Optical Multiplex Section (OMS) is responsible for identifying wavelengths and assigning them to their respective communication channels, composed by multiplexers as Optical Add-drop Multiplexer (OADM)s or ROADM's [36, 38]. This layer is responsible for the multiplexing of optical channels. The Optical Transport Section (OTS) is responsible for managing optical amplifiers [39].

Table 2.1 presents the standard transmission rates, defined by G.709 for ODU sub-layers. Different types of OUDUs, \(k (k = 1, 2, 3 \text{ and } 4)\), 2e, 0 and Flex, are presented in the table. The defined rates support different types of client signals. However, nowadays distinct signals are being added to the network, like video and variable rate packet flows. As such, the existing ODU rate became insufficient to carry these new client signals, demanding the introduction of new rates.

The ODU Flex offers a possibility to range the rate of the ODU closer to the carried signal, minimizing bandwidth waste. The introduction of ODU 0 slot opens the possibility to have slots working in...
1.25 Gb/s, in a much more efficient way to allocate bandwidth with a thinner granularity.

The extended (OPU 2e/ ODU 2e), 0 and flex versions are only specified in the OPU and ODU layers. These extensions are considered to be low-order as they operate in lower transmission rates, being mapped in high-order layers. For OTU, these extensions do not present a standard, and are therefore not considered in the right side of Table 2.1.

The new release of G.709 [7], extends the rates beyond 100Gbit/s. ITU chooses to use a strategy between the solution for OTN ODUk, which had been using an asynchronous multiplexing approach to increase optical signal capacity, and a SONET/SDH strategy which increases rate signal by interleaving an integer multiple of base rate signals. In this strategy, a base signal frame was established at 100Gb/s and multiplies this base frame, and several of these base frames are interleaved to increase beyond 100Gbit/s signals. The chosen terminology was to call the base frame ODUC (100Gb/s) and to call a signal \( n \times 100 \text{Gb/s} \) ODU\( -n \) [40]. An OPUC-1 must be capable of carrying an ODU4 client and an OPUC3 must be capable of carrying a 300Gb client. Higher rates that are not possible to map using a ODU4 are mapped into an ODUflex, which is then multiplexed into an OPUC. This new release further defines the bit rates for ODUC and OTUC and are presented in Table 2.1.

<table>
<thead>
<tr>
<th>ODU</th>
<th>ODU nominal bit rate</th>
<th>OTU</th>
<th>OTU nominal bit rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>ODU0</td>
<td>1 244 160 kbit/s</td>
<td>OTU1</td>
<td>255/238 \times 2 488 320 kbit/s</td>
</tr>
<tr>
<td>ODU1</td>
<td>239/238 \times 2 488 320 kbit/s</td>
<td>OTU2</td>
<td>255/237 \times 9 953 280 kbit/s</td>
</tr>
<tr>
<td>ODU2</td>
<td>239/237 \times 9 953 280 kbit/s</td>
<td>OTU3</td>
<td>255/236 \times 39 813 120 kbit/s</td>
</tr>
<tr>
<td>ODU3</td>
<td>239/236 \times 39 813 120 kbit/s</td>
<td>OTU4</td>
<td>255/227 \times 99 532 800 kbit/s</td>
</tr>
<tr>
<td>ODU4</td>
<td>239/227 \times 99 532 800 kbit/s n</td>
<td>OTUC-n</td>
<td>n \times 239/226 \times 99 532 800 kbit/s</td>
</tr>
<tr>
<td>ODU-n</td>
<td>n \times 239/226 \times 99 532 800 kbit/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ODU2e</td>
<td>239/237 \times 10 312 500 kbit/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ODUflex</td>
<td>239/238 \times \text{client signal bit rate}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As depicted in appendix [A] figure A.1 illustrates the multiplexing and mapping for the OTU. The client signal is mapped into an OPU. Afterwards, the signal is multiplexed in the ODU\( k \), subsequently multiplexed into an OTU\( k \). At this point, the signal is in accordance with the defined OTN standards, ready to be transmitted into the network optical layer. Low order ODU\( k \), with \( k = 0 \) must be mapped into high-order ODU\( k \)s, with \( k = 1, 2, 3 \) or 4. After the high-order, the ODU\( k \)s is mapped into the respective OTU. For OPUC-n, the information structure consists of \( n \) times the information of the OPU.

### 2.2.2 Network Elements

In this subsection, the most relevant network elements are detailed, with particular focus on those used in the present work.

#### 2.2.2.A ROADM’s

The ROADM is an important component in transparent networks, as it offers the possibility of multiplexing, demultiplexing as well as the option to select which wavelengths to add or remove from the network, in optical domains. This element is capable of optical switching, having optical-bypass
technology. Moreover, the OADM is capable of routing traffic from west to east, in the optical domain, by only adding or dropping to the electric domain the required signals.

A ROADM, which is a reconfigurable OADM, is now one of the main networks elements, and is used for optical transparent switching in metro and long-haul networks. This component is a core element for the development of backbone transport networks [5, 41]. It allows to add and drop any channel, anywhere in the network, introducing flexibility and scalability to a static optical network. This enables cost savings (CapEx) by eliminating network elements used for O/E/O conversion and lowers Operational Expenditure (OpEx) by removing the need of manual engineering and maintenance [5, 18].

The reconfiguration is achieved by using wavelength selective switches WSS, which are the core switching elements for today’s ROADM. WSS is an element with $1 \times n$ bidirectional device, meaning either one single input for $n$ outputs or $n$ inputs and one output, under software control. WSS allows the selection of wavelengths, from the input signal to the right output [5]. As it has the possibility to be remotely and dynamically configured, WSS use the network elements efficiently, which results in cost reduction.

![Figure 2.7: WSS](image)

WSS is based on technologies like Micro-Electro-Mechanical System mirror arrays, Liquid Crystal on silicon phased array beam steering and Liquid Crystal based polarisation/phase [19, 41].

A WSS is represented in Figure 2.7, which illustrates a WSS element with three inputs and one output. In that scenario, the first and second input have one colour, or wavelength, while the third has three colours. A WSS is used to select and combine wavelengths. In Figure 2.7, the output selected the wavelengths from the first and second inputs, but only one from the third input.

WSS enabled the possibility of adding new features in ROADM such as being (i) colourless, (ii) directionless and (iii) contentionless. Being colourless is the ability to drop or add different wavelengths at any drop or add port, respectively; being directionless means that it has the ability to route a wavelength in all directions; being contentionless allows the use of the same wavelength multiple times in a ROADM.

A colourless and directionless architecture, enabled by WSS technology, provides valuable fea-
tures like dynamic optimization of lightpaths by optical bridge-and-roll or alternate paths for protection, in a mesh optical network. Moreover, the architecture is truly scalable regarding the handling of additional wavelengths and efficient routes [42]. The bridge-and-roll is a management tool, valuable in mesh optical networks, as it allows the network to perform hitless re-routing, in case of new nodes or protection, enabling the optimization of network resources [42].

The colourless feature is provided by using tunable wavelength sources, with the implementation of add/drop structures that are not colour specific and the use of WSS at the drop-side [19]. Former OADM implementations used DEMUX to separate optical signals with different wavelengths, however the dropped wavelengths had to be fixed. The WSS is an answer to this problem since it is able to switch any wavelength from input to output, allowing the implementation of the reconfiguration in OADM [5, 19].

A CD (colourless and directionless) ROADM has two types of ports: fibre, which connects the ROADM to other ROADMs, and add/drop ports that connect to transponders of receivers/transmitters.

Figure 2.8 represents the diagram for CD ROADMs. The received signals are connected to the first Star Coupler (SC) that aggregates all the input traffic, later splitting the signal to all existing directions. The drop-side is implemented with two WSSs. The first WSS is responsible for receiving all different wavelengths and sending them to the second WSS, which switches and selects each wavelength to the correct drop port.

The CD ROADM blocks a lightpath which uses a wavelength already used in the add/drop module,
a problem which is known as wavelength congestion. This situation is overcome with the implementation of the contentionless feature, achieved by adding multiple add/drop modules. Comparing Figure 2.8 with Figure 2.9 the latter presents an additional module. The number of add/drop modules represent wavelengths with the same colour that can be added or dropped, in the same node. This feature guarantees scalability.

As traffic and correspondent number of wavelengths is constantly increasing, it is mandatory to guarantee that the networks are capable of being scalable. Scalability refers to the service flexibility, while minimizing operation complexity and increasing the data amount [42]. For this, changes in the add/drop scheme need to be considered.

One possibility for the required changes is presented by Notarnicola et al. [5], which is illustrated in Figure 2.10. In part b), the add side of the module has a WSS with 6 inlets. This WSS presents a variable input number, according to the need for more or less input signals. Different sets of WSS are connected to a single SC, aggregating all signals from the WSS. Figure 2.10 presents seven inputs for a SC. Likewise, the number of inlets can increase or decrease, according to the number of wavelengths to be added in the ROADM.

The size of the first WSS and the SC determine the number of possible lightpaths to add in the ROADM, as the number of wavelengths is given by multiplying the inputs of these network components. For example, a ROADM with a $8 \times 1$ SC is able to handle eight WSS connections. If the WSS has $1 \times 6$ connections, the ROADM handles 48 wavelengths. Similarly, a $1 \times 20$ WSS represents 160 lightpaths.

Even though the maximum capacity for each optical fibre is approximately 80 to 100 wavelengths, the presented calculations refer to the number of wavelengths to be added or dropped, meaning that it is possible to add, for instance, 160 distinct lightpaths in a third degree node, as the wavelengths are divided and switched into the existing fibres.
Likewise, the module’s drop side must also change to handle the scalability of the "add" side, since communications are bidirectional.

In case of failure, the CDC (colourless, directionless and contentionless) feature also improves the network’s reliability and recovering capacity.

2.2.2.B Transponders and muxponders

The transponder is a crucial element of an optical network, as it sends and receives optical signals from a fibre, being able to perform O/E/O wavelength conversion.

Transponders have the role of being a key element in the system, enabling the conversion of signals into coloured optical ones, which can be multiplexed into a single fibre. This operation is also known as DWDM technology. Specifically, the transponder receives/transmits generated signals, typically client signals like STM-16, STM-64, 1 GbE, 10 GbE, 100 GbE, among others, and, using a laser, converts the signal into the optical domain and re-transmits the signal in the DWDM. Typically, the transponder is prepared to generate wavelengths set by the ITU in the 1550 nm wavelength window \[43\]. At 1550 nm, the loss of any optical fibre is minimal, and both the regenerator and optical amplifiers are less necessary in this window. The transponder often adds different overhead for network management and FEC.

In the Optical Terminal Multiplexer (OTM), the transponders represent a big part of the system investment \[43\]. Because of that, the minimization of this element is an important aspect for reaching better network costs. It is possible to distinguish between two types of transponders: fixed and tunable. The fixed transponder allows the conversion between two pre-defined wavelengths. In the 90’s, most of the deployed transponders were of fixed wavelengths, but nowadays tunable transponders gained market. These use a tunable WDM laser and broadband receiver to grant the capacity to receive any wavelength. Since the early 2000s, tunable transponders are used in most of equipments, since they improve the flexibility and simplify network management \[6\]. This element also supports 3R function. Additionally, it is responsible for generating OPU, ODU, OTU in the electrical domain, was well as Och in the optical one.

Figure 2.11 contains a simple block diagram, which represents a transponder. The client interface
inputs a 100 GbE optical signal in the component. Then, the signal is converted to the electrical domain. In this domain, all the procedures explained in section 2.2.1 are executed. First, the respective OPU overhead is added and the ODU 4 is created. After, the OPU is encapsulated in the ODU layer and, next, the OTU 4 is created by adding the OTU overhead and FEC bytes. The client signal passes through all these processes of encapsulating and, in the end, the signal is converted again to the optical domain OCh in the ITU-T compliant wavelength and sent in to the ROADM.

**Figure 2.11: Transponder OTU4**

Following the OTN normalization, the muxponder was added to telecommunications networks, as it is capable of grooming signals with a higher wavelength efficiency. Additionally, it also allows the multiplexing of multiple low-order ODUks into higher-order ones, as presented in Figure A.1 of appendix A. Even though the use of transponders is most common for higher rates like ODU 3, ODU 4 and ODUC, the client signals often create lower traffic networks. In these cases, it is important to have the ability to groom signals, which is offered by muxponders.

This element is a variation of the transponder, offering multiple client side connections instead of having 1:1 input and output, which can be observed by comparing Figures 2.11 and 2.12. In the muxponder figure, 10 client interfaces with 10 GbE ports are presented.

**Figure 2.12: 10:1 Muxponder OTU4**
The multiplexing of ODU2e into ODU4 is illustrated in Figure 2.12. In this figure, it is possible to visualize the framing of a client signal and the creation of an ODU2 frame. Observing Figure A.1 of appendix A, it can be seen that ODU4 can carry 10 ODU2 signals. In the end, the remaining overheads to create OTU4 are added to the multiplexed ODU4.

The muxponders have competitive prices when compared to transponders, therefore these elements should be taken into consideration when planning a telecommunication network.

2.2.2.C SBVT

A transponder capable of generating multiple optical flows, which can be routed into (configurable) wavelengths and can be directed into different directions is the SBVT. This element enables bandwidth efficiency through the adjustment of parameters such as bitrate, FEC, coding, modulation format and shaping of optical spectrum [44]. The SBVT can be used with different architectures, such as multiple output ports which can be used to route into different destinations or just one, transmitting super channels. This work is going to use single output ports SBVT.

By the time the SBVT is added to the network, the full cost has to be supported and this can act as a potential drawback since the full traffic volumes may not justify the use of SBVT. However, the flexibility provided by this element can be a good investment made by the network operator, distributing CapEx along the network’s life cycle [16].

2.3 Network Algorithms

In this section, the studied Routing, Balancing and RWA heuristic algorithms are presented and explained.

2.3.1 Routing heuristic algorithms

As stated before, routing is the process of choosing a path along a network to connect a source to a certain destination according to a certain metric, which is a main concern in telecommunication networks.

In order to generate possible paths to route a required connection, several algorithms with different metrics were designed. The following sections describe the heuristic algorithms used in the routing problems for OTN networks.

For a given network routing problem it becomes important to choose the best path, and the heuristic algorithms provide a good and theoretical solution in finding such path. Even though these algorithms are not guaranteed to achieve an optimal costly solution, they are useful to gather data and results in optimal conditions and without many constraints in the physical network.

2.3.1.A Shortest path routing

The shortest path is a well-studied problem since it is applicable in many cases and areas. Dijkstra proposed the most well-known algorithm [25] that solves a single shortest path problem with non-
negative edge path costs. Additionally, Richard Bellman [?] and Lester Ford Jr [45] published a
different algorithm, the Bellman-Ford algorithm which is slower when compared to Dijkstra’s algorithm,
but more flexible since it is capable of finding shortest paths in graphs with negative cost edges path
costs. In this work, the cost edges are all positive. Therefore the Dijkstra algorithm was chosen over
the Bellman-Ford algorithm as it presents lower complexity and the edges metrics are all positive.

The goal of Dijkstra algorithm is to find the shortest path between two nodes with known positive
weighted links in a graph. In this case, the cost of each link is considered to be the geographical
distance, and the shortest path between two points is the aggregation of the links with the smallest
sum of distances. This algorithm can also be used to find the path with the minimum number of hops
which is particularly important for opaque networks.

The algorithm uses as an input a traffic matrix $T$ and designs the shortest-path based on graph
$G(V, E)$ with a load on the edges. The pseudocode for the Dijkstra algorithm is shown in [1]
Algorithm 1: Dijkstra

Input : netCostMatrix - Matrix with the costs of edges
        s - Source node
        d - Destination node

Output: Shortest-Path
        Cost of the path

Data: shortestPath - List of nodes in the shortest path from source to destination
       totalCost - Total cost of the shortest path
       n - Number of nodes in the network
       visited - Visited nodes
       parent - Parent nodes
       distance - Distance to initial node

1 begin
2     n ←− size of netCostMatrix;
3     for each node as i do
4         visited[i] ←− 0;
5         parent[i] ←− 0;
6         cost[i] ←− inf;
7         [i] ←− 0;
8     end
9     visited[s] ←− 1;
10    cost[s] ←− 0;
11    current_node ←− s;
12    while current_node is different than d do
13       for each neighbour of current_node do
14          Calculate the cost from neighbour to source;
15          if cost calculated < cost then
16             cost[neighbour] ←− cost calculated;
17             parent[neighbour] ←− current_node;
18          end
19       end
20       current_node ←− non-visited node with min(cost);
21       visited[current_node] ←− 1;
22    end
23    while current_node is different than s do
24       shortestPath ←− current_node;
25       current_node ←− parent[current_node];
26    end
27 end

2.3.1.B K-Shortest path routing

Besides the shortest path, it is also relevant to consider other algorithms to obtain the k-Shortest paths. One of such examples is the Yen algorithm that finds the k-th shortest path without assuring node disjointness [28]. The algorithm uses a traffic matrix $T$ and designs the k-Shortest path based on graph $G(V, E)$ with a load on the edges, as presented in algorithm 2.
Algorithm 2: Yen

Input: netCostMatrix - Matrix with the costs of edges
       s - Source node
       d - Destination node
       K - Number of shortest paths to calculate

Output: Shortest-Path
        Cost of the path

Data: shortestPaths - Set of k-Shortest path from source to destination
      totalCosts - Set of total cost of each shortest path
      P - Set of candidate paths and costs
      X - Set of sub-paths

1 begin
2     Execute Dijkstra to get the shortest path and cost;
3     Add the shortest path, calculated in 2, in X;
4     Add the shortest path, calculated in 2, in shortestPaths;
5     currentPath ←− shortest path calculated in 2;
6     while k < K & size(X) ≠ of zero do
7         Remove the currentPath from X;
8         vertex ←− vertex node of currentPath;
9         while currentPath have nodes to read do
10            vertex ←− next node of currentPath;
11            if X not empty then
12                Remove temporarily the nodes from source to vertex;
13                Remove the link ahead of vertex;
14            end
15            Calculate the cost from source to vertex;
16            Execute Dijkstra to get the shortest path and cost from vertex to destination;
17            Add cost calculated in 15 and 16;
18            Add path removed in 12 and 16;
19            Add the result of 17 and 18 to P and X;
20     end
21     Find the shortest path in P and add it to shortestPaths;
22     currentPath ←− shortest path calculated in 21;
23 end
24 end

2.3.1.C Edge disjoint and node disjoint K-Shortest path routing

In this section, the same algorithm is presented, with two different path routing: Shortest Path with Edge Disjoint guarantee and the Node Disjoint path.

To prevent primary path failure, it is essential to have multiple path strategies that ensure the existence of one or more backup paths. Additionally, it is also relevant to provide load balancing in traffic engineering schemes. Multiple paths have some constraints such as being node-disjoint or edge disjoint. Node disjoint paths are usually harder to find but assure more robustness in case of failure [46].

The Edge Disjoint shortest path assures that the next shortest path does not contain the same edges as previous shortest paths discovered, but can include their nodes. This is a simple algorithm, in which, each time a path is discovered, the used edges are removed from the network.

The Node Disjoint shortest path algorithm uses Dijkstra to retrieve the shortest path and cost for each K-path, removing the links of each node of the path discovered, between iterations. These
two results are important in telecommunication networks due to the reliability of exchanges between source and destination [47].

The implementation procedure is described in algorithm 3.

<table>
<thead>
<tr>
<th>Algorithm 3: Edge Disjoint and Node Disjoint K-Shortest paths</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input:</strong> netCostMatrix - Matrix with the costs of edges</td>
</tr>
<tr>
<td>s - Source node</td>
</tr>
<tr>
<td>d - Destination node</td>
</tr>
<tr>
<td>K - Number of shortest paths to calculate</td>
</tr>
<tr>
<td><strong>Output:</strong> Shortest-Path</td>
</tr>
<tr>
<td>Cost of the path</td>
</tr>
<tr>
<td><strong>Data:</strong> shortestPaths - Set of K-Shortest path from source to destination</td>
</tr>
<tr>
<td>totalCosts - Set of total cost of each shortest path</td>
</tr>
</tbody>
</table>

```
1 begin
2 k = 1;
3 for k=1:K do
4   Execute Dijkstra to get the shortest path and cost;
5   Include the path and cost from 4 in shortestPaths and totalCost;
6   if Edge Disjoint then
7     Remove from netCostMatrix all the edges in the path from 4
8   end
9   if Node Disjoint then
10      Remove from netCostMatrix all the links from the nodes in path from 4
11  end
12 end
```

2.3.2 Balancing heuristic algorithms

In this subsection the heuristic balancing algorithm is presented and the chosen metrics are explained.

The use of the Dijkstra algorithm to route all the traffic demands in the network, results most probably in an unbalanced network. Using just the shortest path algorithm leads to a solution with high-congestioned links, while other physical links may be lightly used. To avoid such situations, a balancing algorithm was developed using different routing algorithms – Yen, K-Shortest Edge Disjoint Paths and K-Shortest Node Disjoint Paths. These routing algorithms were chosen in order to compare results using different types of re-routing strategies. In the case of Yen, which finds the next shortest path regardless of the links or nodes used in the previous shortest path, there is a higher probability of finding paths using the previously most loaded link that does not improve the network solution. The problem was mitigated by using two other routing algorithms. This algorithm was based on the solution presented in [11] but employs different routing algorithms. Moreover, it implements a program that automatically chooses the most loaded link and which routes must be re-routed. This implementation brings the possibility of comparing computation times since no manual intervention is needed.

The algorithm is designed in the following manner: First, all the traffic is routed using Dijkstra. The most loaded link is chosen and it finds the longest path using this link. Afterwards, it finds the next
shortest path depending on the used routing algorithm. If some route is chosen twice to be re-routed, the program has the information of which shortest path is being used and finds the next one, meaning if the route from A to Z has been re-routed once, the algorithm finds the third shortest path to re-route. At most, the algorithm re-routes the demand using the third shortest path. The algorithm removes the demands from the links of the shortest path used, adding in the next shortest path. The algorithm’s stopping condition is when the most loaded link in the network has not improved after 10 iterations, as it chooses automatically the routes to re-route. In [11], where this algorithm was based, the traffic is re-routed for a fixed number of demands, which corresponds to the difference between the value of traffic in the most loaded link and the mean value of traffic between all the links.

In order to facilitate the comparison between the results of the algorithm using different routing algorithms, distinct names are used: the Balancing Algorithm, which refers to the presented algorithm using Yen routing algorithm to find the next shortest path; the Balancing Edge Disjoint Algorithm, refers to the implementation of the general balancing algorithm using Edge Disjoint routing algorithm to find the next path; and the Balancing Node Disjoint Algorithm which uses Node Disjoint algorithm to find the next path.

The algorithm is explicitly presented in 4.

Algorithm 4: Load Balancing

| Input      : netCostMatrix - Matrix with the costs of edges       |
| Edges      - Structure with information of all the edges (cost and paths) |
| Output: EdgesBalance - Matrix with information of load in each link |
| Data: randomPath - List of nodes in the random path from source to destination |
| totalCost - Total cost of the random path |

1 begin
2 while In the last 10 reroutes improved the most loaded link do
3   Discover the most used link;
4   Discover, randomly, one path using the link discovered in 3;
5   K←− iteration of Node Disjoint K-Shortest paths used for the path discovered in 4;
6   Execute K-Shortest paths (k=K+1) depending on type of balance;
7   Remove load from the path 4 and add load to 6;
8 end
9 end

2.3.3 Routing and wavelength assignment

The RWA problem results from the goal of maximizing the number of optical connections while minimizing the number of wavelengths.

The problem of routing and wavelength assignment for optical telecommunication networks and data transmission is known as the RWA problem [48, 49]. In section 2.1.3, routing was defined and the most used heuristic algorithms to find the shortest paths were described. In this sub-section the problem of routing is extended with wavelength assignment.

Depending on the network, which can be transparent, translucent, or opaque, it may result in different metrics to obtain the best efficiency and least cost in the network [8].

The “all-optical” communication, for the transparent the network needs to assign the same wave-
length to each connection between two nodes. That means all the physical links of the lightpath need to reserve the same wavelength for that connection. This constraint is one of the biggest challenges of the RWA and is often called wavelength-continuity constraint [50]. The RWA problem has another basic constraint: all the lightpaths using the same link must be assigned with different wavelengths [8]. In case of having O/E/O conversion in the nodes, it enables the use of a different wavelength after the conversion but, on the other hand, it adds power consumption and network equipment (muxponders/transponders/transceivers) and its associated cost [51].

### 2.3.3.3.1 Heuristic algorithms

To do wavelength assignment with the goal of minimizing the number of wavelengths for WDM network engineers have been using heuristic algorithms. In the work of [50] different wavelength assignment heuristics are presented and compared. The conclusion of these simulations reveal similar results as well as similar computation complexity. The heuristic algorithms with slightly better results needed higher computation times. To better understand the heuristics, the analysis is performed in the network, using different traffic and network sizes.

The work of Zang et al. [50] studies the algorithms of First-FitRWA, Most-Used and RandomRWA. Additionally, two types of traffic demand ordering were also considered, the Longest-First and the Random. The first one orders the demands based on the size of the path generated by the routing of demand. The second chooses randomly one of the demands, without any metric.

The First-FitRWA tries to assign the lightpath to the lowest wavelength index available in all the links. If it is not possible to assign a lightpath in a given wavelength, a new wavelength must be added, and the algorithm starts again.

The Most-Used algorithm starts by analysing the entire network and searching for the most used wavelength, where, in that particular time, the lightpath can be assigned. If two or more candidate wavelengths with the same used ratio exist, it is assigned to a random one.

The RandomRWA algorithm chooses an arbitrary wavelength, with the same probability, from the set of wavelengths where it is possible to assign the lightpath.

In the above mentioned algorithms, if more than one path is available to make a communication between source and destination, the chosen one is the one that minimizes the number of wavelengths in the link with the most used wavelengths. If two or more paths are possible, the path is chosen randomly.

From work [52], the proposed Longest First Alternate Path (LFAP) is also taken into consideration, since it presents better results when compared to other heuristic algorithms. In the RWA problem with the goal of minimizing the number of used wavelengths, the computation time is one of the most relevant challenges.

The LFAP algorithm starts by attempting to assign the wavelength to the longest lightpath from a list of candidates requests paths. If a lightpath is not assigned, the next shortest path is calculated and placed in the list of candidates. It tries to maximize the number of lightpaths per wavelength. When the next shortest path for a certain connection from source to destination does not exist, another
wavelength is added.
# System Architecture

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3.1 Path routing

A framework to test the link load of the network after routing the traffic was designed. Different heuristic algorithms, presented and explained in subsection 2.3.1 were implemented in order to compare results after routing different amounts of traffic.

In Marisa’s work [11], the results of the Dijkstra algorithm are analysed, and followed by a comparison between the results of the shortest-path algorithm and the balancing algorithm. A similar comparison will be produced in this thesis.

In this framework, it is considered that the traffic route is the same in both directions, i.e., between source and destination is the same as the one used in the traffic between the same destination and the source node, in order to save computation time. The optical reach and the infinite resources in the nodes and links are not considered in this case. Therefore, there are no restrictions in the number of wavelengths that are used in each link or node, and all the lightpaths can reach the destination without requiring regeneration.

![Figure 3.1: Routing Framework Flowchart](image)

The flowchart in figure 3.1 was made to allow better understanding each step of this framework. First the traffic matrix is received as an input parameter. Following this, the traffic is routed through the network based on algorithm decisions.

![Figure 3.2: Routing in simple network](image)

Figure 3.2 shows the routing in a simple network, with unitary distance unit in each link, using Dijkstra algorithm. It uses a logical mesh topology with 1 traffic unit between all the nodes. In this
example, link 3-5 has the highest load among all the links: 5 traffic units. There are 4 links which have the minimum load of the network, which is 2 units.

The results of this framework will be presented later in section 4.2.

3.2 Load balancing

A new framework was designed to implement another algorithm and to enable the comparison between the results provided by the framework presented in 3.1. This framework uses the algorithm described in 2.3.2 to balance the results obtained from the Dijkstra algorithm.

It is important to refer that the algorithm considers infinite resources on each link and node, and the route used between source and destination is considered to be the same in the opposite direction.

The flowchart in figure 3.3 was made to facilitate the understanding of this framework. First, the traffic matrix is received as an input parameter, then the traffic is routed using the Dijkstra algorithm and finally, the results are used as input parameters in each balancing algorithm.

The balancing algorithm presented in subsection 2.3.2 was designed in two different ways. Firstly, the number of re-routings were fixed and pre-defined to be 10. Secondly, a stop condition explained in the subsection 2.3.2 was defined. Both results will be analysed and the computation time will be compared in order to conclude if the increase of iterations is beneficial, without compromising the computational time.

The results of this framework will be presented later in section 4.5.

3.3 Routing and wavelength assignment

For a better understanding of the different influences of the various heuristic algorithms used in the literature and presented in subsection 2.3.3, a framework to get results of the RWA problem is implemented.
In this framework, different loaded traffic matrices where used and routed, and a certain wavelength is assigned to each traffic demand using different algorithms. In the end, it will be possible to compare the results between the usage of different algorithms and the increase of the traffic. It is important to clarify that in the LFAP algorithm the number of shortest paths found for each connection was limited to 10 in order to lower the algorithm complexity.

The physical distance was used as routing metric to get the path between each source and destination. Each link is considered to have unlimited resources and there is no limit of wavelengths considered for a link. The final result taken into account is the number of wavelengths needed to connect all traffic demands. The tests were completed using the networks topologies presented in Appendix B.

Figure 3.4: RWA Framework Flowchart

The framework was made to allow the best understanding of all RWA framework steps. First, it receives the traffic matrix, afterwards, all the traffic demands are routed using the Yen algorithm. The Yen algorithm is used before the heuristics to allow faster processing times, specially for LFAP.

Figure 3.5: RWA in simple network

Figure 3.5 shows the RWA in a simple network using Longest First for demand ordering, Shortest Path algorithm for routing and FirstFitRWA algorithm for wavelength assignment. Using a logical mesh topology, as already despicted in figure 3.2 with 1 traffic flow between all nodes. In this example, link 3-5 needs 5 wavelengths to guarantee non-blocking signals. It is possible to see the longest paths having the lowest order wavelength assigned.

All results of this framework will be presented in section 4.4.
3.4 Node Architecture

In this work, four different node architectures are going to be considered. First, the network is based on transparent nodes, without any regeneration and considering only source-grooming. Opaque nodes are also considered.

Translucent nodes with two different architectures are considered. The first allows 3R with regenerator cards while the second uses back-to-back muxponders.

Some considerations about transparency in the network, and the nodes architectures are done in 2.1.2.

3.4.1 Translucent Node Architecture with Regenerator

This is considered to work in full optical domain but, in order to provide regeneration, the possibility of O/E/O conversion by the use of a regenerator is considered.

Note that, this configuration does not consider the possibility of intermediate grooming.

Figure 3.6 represents the translucent node using regenerator cards. The ROADM is considered to have 3 contentionless degrees. This is assumed because previous simulation on RWA shows an increase of wavelength blocking in the add/drops modules with the decrease of the contentionless degree. Thus, with 3 degrees, an acceptable tradeoff is attained between the number of new wavelengths and the amount of necessary equipment. This value is used also for WSS accounting.

For mapping services, this architecture uses OTU4, OTUC-2 and OTUC-3 muxponders with 10, 20 or 30 ports of 10Gbit/s. Since the traffic granularity is 10GbE, the use of muxponders allowing grooming and mapping of several services into a single ODU. This is considered to work in full optical domain but, in order to provide regeneration, the possibility of O/E/O conversion by the use of an regenerator is also available.

![Figure 3.6: Node using Regenerator cards to 3R](image-url)
3.4.2 Translucent Node with B2B Muxponder Regeneration

This node architecture, using B2B muxponder to allow regeneration at the client channel level, brings the possibility of grooming new services in the previously assigned lightpaths.

In this node it is also considered the use of muxponders for mapping new services, this architecture uses OTU4, OTUC-2 and OTUC-3 muxponders with 10, 20 or 30 client ports, respectively. Note that each muxponder added can be later used for regeneration purposes.

Figure 3.7 was added to show the node configuration. It is possible to see the use of back-to-back muxponders for regeneration and new services being groomed into the same lightpath.

![Node using B2B muxponders to 3R](image)

3.5 Cost Optimization

The main framework of this work is explained in this section. The framework was designed to solve the RWA problem and select the equipment installed in the network with the goal of minimizing the global cost solution.

The O/E/O conversion is responsible for the bigger part of the global cost in the network. Thus an algorithm was designed to minimize the number of elements responsible for the O/E/O conversion in the network using intermediate grooming, further detailed in section 3.5.2. An algorithm for counting the number of elements responsible for the O/E/O conversion in source grooming architectures is also implemented and presented in the section 3.5.1. The number of WSS is accounted depending on the type of ROADM and used add/drop wavelengths, explained in detail in section 3.5.3. Also, the amount of unused ports is estimated along with the number blocked services.

As explained in the node architecture section 3.4, different nodes use a particular regeneration configuration.

The opaque networks are tested using muxponders with only one line rate option (OTU4, OTUC-2
or OTUC-3) or a mix of all line rates, minimizing the cost implementation. The case of translucent networks considers the same muxponder configurations, and can use regeneration cards or B2B muxponder for regeneration.

All the configurations use the muxponders to map the service demands and groom the signals into an high order OCh. All the traffic demands are considered to have granularity of 10GbE, thus ODU2e are groomed into ODUx (x = 4, C-2, C-3). The opaque and translucent with B2B muxponder regeneration allows for intermediate grooming.

As mentioned before, ROADMs are considered to be colorless, directionless and 3 degree contentionless. For more information about the architecture please refer to 2.2.2.A. The WSS is also accounted and it is considered the use of this element with 2, 5, 9 and 20 inputs.

### 3.5.1 Source Grooming Accounting

This section describes the used methods to element accounting for the network architectures using source grooming:

- Translucent Node using OTU4 muxponder and regenerator;
- Translucent Node using OTUC-2 muxponder and regenerator;
- Translucent Node using OTUC-3 muxponder and regenerator;
- Translucent Node using OTU4/OTUC-2/OTUC-3 muxponder and regenerator;
- Transparent Node using OTU4 muxponder;
- Transparent Node using OTUC-2 muxponder;
- Transparent Node using OTUC-3 muxponder;
- Transparent Node using OTU4/OTUC-2/OTUC-3 muxponder;

The translucent networks with B2B muxponder regeneration and opaque scenarios consider source grooming, but apart from that, they consider also intermediate grooming.

Because of that, another algorithm was designed for these cases, explained further on in section 3.5.2.

The algorithms in the following subsections were primarily designed to account for the results from translucent network with regenerators. Therefore, all the explanations are made considering this node architecture, detailed in 3.4.1. Additionally, to obtain results for transparent networks a small change was made in the algorithm: if a regenerator is required to assign a lightpath, the services are considered to be blocked since this configuration does not allow 3R.

### 3.5.1.A Source Grooming Accounting Algorithm

This section presents the algorithm developed to account for the equipment needed responsible for O/E/O conversions, for the networks using source grooming. A pseudocode is presented in Algorithm 5 to enable better understanding of this algorithm.
This algorithm receives the $T$ and $g$ matrix.

The algorithm works while the $T$ matrix still has traffic demands to route. Because it is only considered the use of muxponders with 10, 20 and 30 input ports, it is calculated the remainder after division of the $T$ by 30 ($itT$). Right after, the $itT$ is deducted from $T$ matrix.

Next, for each element of the $itT$, it finds the best possible solution cost using OTU4, OTUC-2 or OTUC-3 signal capacity. For that, the input and output muxponders are accounted and the number of regenerators needed depending on the optical reach, which are calculated using the algorithm explained in 3.5.1.C. Note that, in this work it searches between the three first shortest paths since the shortest path does not result always in the best solution, like shown previously in the balancing study and exemplified in section 3.5.1.C.

The best path solution is divided into multiple sub-paths between the source, nodes considered for regeneration and destination. It is important to mention that each sub-path is considered to be a particular lightpath. The maximum number of wavelengths in each fibre is considered to be 80.

The function 3RegCost, receives the source and destination node, the number of traffic demands and the $g$ matrix. With the use of FirstFit (Regenerator Placement), explained in Algorithm 3.5.1.C the number of regenerators required for the amount of traffic received is calculated. The muxponders from the source and destination node are also accounted using Muxponder Account, explained in [6]. This function returns the cost and the sub-paths division for each capacity solution. If, as a consequence of optical reach limitation or lack of free wavelengths, the lightpath is impossible to assign, the function returns infinity.

If a transparent network is being tested, one small change has to be made to the 3RegCost function. If there is a need of at least one regenerator, this means that it is impossible to connect source and destination using this path and it returns infinity.

If all the cost solutions are equal to infinite, this means at least one sub-path is not possible to assign due to lack of available wavelength and all the traffic demands are considered to be blocked, on the other hand if the lightpath is possible to be assigned the returned sub-paths for the best cost solution is later assigned with the use of RWA the First-FitRWA algorithm.

If $T$ matrix is empty, this means all the traffic demands were routed or blocked and the number of WSS are accounted using the formulas presented in 3.5.3.
Algorithm 5: Cost Opt Algorithm - Source Grooming

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>Traffic matrix</td>
</tr>
<tr>
<td>$G$</td>
<td>Adjacency matrix</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$itT$</td>
<td>Traffic matrix for iteration</td>
</tr>
<tr>
<td>$NetworkSize$</td>
<td>Size of analysed network</td>
</tr>
<tr>
<td>$d_{path}$</td>
<td>Distance between source/regeneration node and regeneration node/destination</td>
</tr>
<tr>
<td>$Reg^{sd}$</td>
<td>Number of regeneration nodes for the route between $s$ and $d$</td>
</tr>
<tr>
<td>$block$</td>
<td>Number of blocked services</td>
</tr>
</tbody>
</table>

begin
while $T$ is not empty do
    $iT \leftarrow$ remainder after division $T$ and 30;
    for $s = 1:NetworkSize$ do
        for $d = 1:NetworkSize$ do
            $100GSolution = 3RegCost(T(s,d),s,d,G)$;
            $200GSolution = 3RegCost(T(s,d),s,d,G)$;
            $300GSolution = 3RegCost(T(s,d),s,d,G)$;
            finalSolution cost = min($100GSolution cost, 200GSolution cost, 300GSolution cost$);
            if finalSolution cost is equal to $\infty$ then
                $block = block + T(s,d)$;
            else
                First-FitRWA(finalSolution);
                Muxponder Accounting;
                3R Accounting;
            end
        end
    end
    WSS Accounting;
end

One example of the use of $3RegCost$, presented in the Algorithm 5, is shown by the use of figures. In this case, the function receives 30 traffic demands, from source 1 to destination 4. The function considers the following constrains:

**Costs:**
- OTU4 muxponder - 1 unit;
- OTUC-2 muxponder - 1.4 units;
- OTUC-3 muxponder - 2.1 units;
- OTU4 regenerator - 1.7 unit;
- OTUC-2 regenerator - 2.4 units;
- OTUC-3 regenerator - 3.6 units;

**Optical Reach:**
- OTU4 [OCh] - 3 links;
- OTUC-2 [OCh] - 2 links;
- OTUC-3 [OCh] - 1 links;

Figure 3.8 is one example of finding the best solution between OTU4, OTUC-2 and OTUC-3 signal capacity. For 30 traffic demands of 10GbE it is needed 3 lightpaths using OTU4 muxponders, 2 lightpath using OTUC-2 and 1 using OTUC-3.

In case of OTU4 [OCh], the lightpath between source and destination does not need any regeneration, resulting in cost of: $3 \times 2 \times OTU4\text{MuxponderCost} = 6\text{units}$.

For OTUC-2 [OCh] the final solution needs 1 regeneration node for each lightpath and the source muxponders and the final cost solution: $2 \times (2 \times OTUC2\text{MuxponderCost} + OTUC2\text{RegeneratorCost}) = 10.4$.

The final solution for OTUC-3 needs source muxponders and 2 regeneration nodes for each lightpath, lead to a cost of: $2 \times OTUC3\text{MuxponderCost} + 2 \times OTUC3\text{RegeneratorCost} = 11.4$.

The use of OTU4 lightpaths result best solution since is the cheapest one.

![Figure 3.8: Translucent with Regenerator - Example 1](image)

Next, a second example in Figure 3.9 is presented. Taking into account enough optical reach to get to the destination without regeneration for all the [OCh] capacities. Cost for OTU4 [OCh] solution: $3 \times 2 \times OTU4\text{MuxponderCost} = 6\text{units}$. The same, compared to the previous example. For OTUC-2 solution, $2 \times 2 \times OTUC2\text{MuxponderCost} = 5.6$. In the case of using OTUC-3 [OCh] cost solution is $2 \times OTUC3\text{MuxponderCost} = 4.2$.

In this case, the grooming all the traffic demands into an single OTUC-3 [OCh] is the cheapest and final considered solution.
3.5.1.B Muxponder Accounting

Muxponders are one of the main elements in this framework. The usage of this element in the source of each lightpath is mandatory, but the chosen muxponder size depends on the number of traffic demands flowing from the source to destination of the generated OCh.

The network architectures in this section are defined by the use of muxponders only to map service signals in the source to the destination.

The following algorithm was designed to account for the needed muxponders for source grooming solutions. The algorithm receives as parameter the number of traffic demands to route and account and with simple logic returns the number of muxponders needed. This value depends on the function of the lightpaths required to service the number of traffic requests.

<table>
<thead>
<tr>
<th>Algorithm 6: Muxponder Account</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong>: $T$ - Traffic matrix</td>
</tr>
<tr>
<td><strong>Data</strong>: 100GMux - Number of needed OTU4 Muxponders</td>
</tr>
<tr>
<td>200GMux - Number of needed OTUC-2 Muxponders</td>
</tr>
<tr>
<td>300GMux - Number of needed OTUC-3 Muxponders</td>
</tr>
</tbody>
</table>

1 begin
2   if $20 < t_{xy} \leq 30$ then
3      300GMux = 2;
4      200GMux = 4;
5      100GMux = 6;
6   end
7   if $10 < t_{xy} \leq 20$ then
8      300GMux = 2;
9      200GMux = 2;
10     100GMux = 4;
11   end
12  if $0 < t_{xy} \leq 10$ then
13     300GMux = 2;
14     200GMux = 2;
15     100GMux = 2;
16  end
17 end
3.5.1.C Regenerator Accounting

At some point in the network, some signals need regeneration to clean the signal and allowing the traffic to reach the destination. Depending on the type of signal, transmission system and characteristic of the fibres different optical reaches should be considered \[6\].

One algorithm was implemented to find where regenerators should be added to allow regeneration and it is pseudocoded in algorithm 7. The algorithm First-Fit, adapted from [11], is going to be called First-Fit (Regenerator Placement) in this work to not to confuse with the previous algorithm employed for RWA with the same name.

Algorithm 7: First-Fit (Regenerator Placement)

<table>
<thead>
<tr>
<th>Input</th>
<th>lightpath - route to calculate the number regeneration nodes;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>Number of regeneration nodes</td>
</tr>
<tr>
<td>Data</td>
<td>(d_{\text{max}}) - Optical signal reach without regeneration</td>
</tr>
<tr>
<td></td>
<td>(d_{\text{link}}^{ij}) - Physical distance of link (e_{ij})</td>
</tr>
<tr>
<td></td>
<td>(d_{\text{path}}) - Distance between source/regeneration node and regeneration node/destination</td>
</tr>
<tr>
<td></td>
<td>(\text{Reg}^{sd}) - Number of regeneration nodes for the route between (s) and (d)</td>
</tr>
</tbody>
</table>

1 begin
2 \(d_{\text{path}} \leftarrow 0;\)
3 \(\text{Reg}^{sd,k} \leftarrow 0;\)
4 for each physical connection \(e_{ij}\) in lightpath do
5   \(d_{\text{path}} = d_{\text{path}} + d_{\text{link}}^{ij};\)
6   if \(d_{\text{path}} > d_{\text{max}}\) then
7     \(\text{Reg}^{sd} = \text{Reg}^{sd} + 1;\)
8     \(d_{\text{path}} = d_{\text{link}}^{ij};\)
9 end
10 end
11 end

For each lightpath, the nodes where regeneration is considered are calculated by the use of First-Fit (Regenerator Placement) algorithm. For the case of using regenerators for regeneration, each regeneration node should have 1 regeneration card by opposition to B2B muxponders regeneration which needs to account for 2 cards. This algorithm is important to calculate the final solution of the architectures using transparent network described previously.

Because the main goal is to minimize the number of elements responsible for the O/E/O conversion in the network, it is important to refer that the use of the shortest path is not always the cheaper solution. Figure 3.10, adapted from [6], is one example of traffic demand that, if only searches for the shortest path to connect the lightpath, the number of regenerators required are higher compared to the results using the second shortest path. The routing metric is considered the distance of the path. Considering the optical range of 2000km, the path 1 needs 2 regeneration nodes (C and E) instead of 1 node (G) of the path 2. In this example path 2 may be chosen instead of the first one.
Figure 3.10: Regeneration: Path 1 vs Path 2 - adapted from [6]

Figure 3.11 shows one scenario where $5 \times 10\text{GbE}$ traffic demands from node 1 to 5 are groomed into one OCh in the node 1, regenerated using a regenerator in the node 4 and re-transmitted to the node 5. Another $5 \times 10\text{GbE}$ traffic demands have the same source node (1) and the same regeneration node (4) but since the destination node is different than the first group, it is not possible to use any element previously added in the network. This solution requires 2 OCh in the path between node 1 and 4 but each lightpath only uses 50% of its full capacity.

Figure 3.11: 3R Regeneration example

### 3.5.2 Intermediate Grooming Accounting

In this section will be specify the used method to account the several elements used for each solution using translucent networks with B2B muxponder regeneration and opaque networks:

- Opaque Node using OTU4 muxponder
- Opaque Node using OTUC-2 muxponder
- Opaque Node using OTUC-3 muxponder
- Opaque Node using OTU4/OTUC-2/OTUC-3 muxponder
- Translucent Node using OTU4 muxponder
- Translucent Node using OTUC-2 muxponder
• Translucent Node using OTUC-3 muxponder

• Translucent Node using OTU4/OTUC-2/OTUC-3 muxponder and regenerator

The muxponder can be used, as seen before, to map new services into the network but also can be used to regenerate signals. Processing the signals at the electrical level with muxponders boosts the use of intermediate grooming, which means that it is possible to save in number of wavelengths needed and equipment to add in the network.

Figure 3.12: Back-to-Back Muxponder Regeneration example

Figure 3.12 shows one possible configuration using muxponders to regenerate the signal. Like image 3.11, the traffic demands are $5 \times 10\text{GbE}$ traffic units from node 1 to node 6 and $5 \times 10\text{GbE}$ traffic units from node 1 to node 5. The difference between the configurations used in the previous section, is the possibility of reusing previously added muxponders for intermediate grooming in order to save equipment cards and bandwidth usage. Employing muxponders for regeneration allows using only one wavelength to connect all the traffic between node 1 and node 4 and after part of that traffic is sent to the node 5 and the other to the node 6. Comparing to figure 3.11 one more OTU4 muxponder is used, but on the other hand 2 regenerator and one wavelength are saved.

It is important to notice that the algorithms described next were first designed to obtain the cheapest solution for translucent network with B2B muxponder regeneration, minimizing the points of regeneration. The opaque network does not minimize this solution, and uses mandatory O/E/O conversion in all the nodes making this case a particular solution of the implemented algorithm, where the first found node is considered to be the first regeneration node.

The implementation of translucent network with B2B muxponder regeneration is further explained.

3.5.2.A Intermediate Grooming Accounting Algorithm

This section presents the developed algorithm which enables the accounting of the network elements for a translucent node architecture.
Because of the multiple possible configurations, this represents the most complex algorithm implemented to achieve results of a network design.

Pseudocode 8 was made to allow a better understanding of the algorithm designed to search for the cheapest solution for the network planning. This algorithm receives as input parameters the services to route which contains all the shortest paths candidates to route the traffic demands. Also, a structure paths is received, which contains the 3 shortest paths between all the nodes, to save computation time. If a traffic demand is impossible to route, because of the minimum optical reach, it is considered to be blocked in the services calculation, and the number of blocked services is registered in the parameter block.

As studied before, satisfying demands using only the shortest path algorithm does not generate the best solution and the most balanced one. It was decided to search among the first three shortest path for each service the solution which needs less investment.

<table>
<thead>
<tr>
<th>Algorithm 8: Cost Opt Algorithm - Intermediate Grooming</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong>: services - set of paths to RWA</td>
</tr>
<tr>
<td>paths(s_i^d) - first (i) shortest paths between source (s) and destination (d)</td>
</tr>
<tr>
<td>block - number of blocked services</td>
</tr>
<tr>
<td><strong>Data</strong>: (d_{\text{max}}) - Optical signal reach without regeneration</td>
</tr>
<tr>
<td>(d_{\text{link}}) - Physical distance of link (e_{ij})</td>
</tr>
<tr>
<td>(d_{\text{path}}) - Distance between source/destination node and regeneration node/destination</td>
</tr>
<tr>
<td>(\text{Reg}_{sd}) - Number of regeneration nodes for the route between (s) and (d)</td>
</tr>
</tbody>
</table>

\begin{verbatim}
begin
while services is not empty do
  path ← max hop path in services;
  s ← first node of path;
  d ← last node of path;
  mincost ← ∞;
  for \(i = 1:3\) do
    path ← paths\(s_i^d\);
    cost = CostFunction(path);
    if cost < mincost then
      if RWA is possible then
        finalpath ← path;
        mincost = cost;
      end
    end
  end
  if mincost is equal to ∞ then
    block = block + 1;
  else
    First-FitRWA(finalpath);
  end
end
3RCostMinimization;
Muxponder Accounting;
WSS Accounting;
end
\end{verbatim}

For each service request, this algorithm finds between the 3 first shortest paths, the one which needs less investment to connect the new service. The algorithm also verifies if the candidate shortest
path is possible to assign since the maximum number of wavelengths defined for each optical fibre is 80.

For that, the use of a recursive function (CostFunction) which uses the logic of First-Fit (Regenerator Placement) algorithm to find the first regeneration node or the destination and answers the best solution to connect the candidate lightpath.

The recursive function CostFunction, presented in the pseudocode, either finds the first node where the optical reach is exceeded or finds the destination. If it finds the destination, it returns the necessary investment to assign the path. If it finds one node, which is not the destination, it means it needs regeneration. The former path is divided into two sub-paths, and the CostFunction is called with the sub-paths as input parameters.

The flowchart of the CostFunction [3.13] was made to allow a better understanding of the function, which is responsible for most of the computation time consumed in the cost optimisation algorithm. This function searches for the best solution to assign the received service request. Here, the best solution is the solution which needs less investment to allow the new service. The function works as a recursive function, it defines three maximum optical reach for each considered signal capacity (OTU4, OTUC-2 and OTUC-3).

For each optical reach, the last node where the optical reach is not exceed is identified and represented as XRegNode. If the XRegNode is not found, it means the destination is reached. In that case, we consider the possibility of adding the signal to a previously added lightpath. If muxponder ports are free, there is no need to add any new resource since a wavelength is already reserved for this channel and the muxponders can be used to groom this new service into the already assigned OCh. If reuse of an existing lightpath is not possible, the possibility of adding two OTU4 muxponders to allow the connection is considered. If full capacity of OTU4 muxponder is reached, there is a possibility of replacing the OTU4 muxponders for one OTUC-2 allowing, using the same lightpath. The same process is done in the case of using OTUC-2, facing OTUC-3 muxponders.

The recursive applied in case of finding one XRegNode. In that case, the path is divided in sub-path1 and sub-path 2, which will be considered two different lightpaths, being the first the former path between the first node and the XRegNode and the second path between XRegNode and the destination node. Before the return, the cheapest solution is chosen between the three optical reaches tested. If two solutions have the same cost, the solution considering the higher optical reach is chosen. The CostFunction returns the cheapest solution for the received path and the concatenation of the returned solution for sub-path 1 and sub-path 2 is considered to be a solution for the complete path.

Figure 3.13 is representing the flowchart for OTU4 optical reach. The full flowchart can be consulted in the attached appendix [C].
If any candidate, from the first 3 shortest paths, are not possible to assign due to lack of free wavelengths, the service is considered to be blocked. If some candidate has the minimum cost solution, it is chosen as the final solution and RWA First Fit algorithm is used to assign the respective wavelengths.

An example is described to allow a better understanding of the recursive function utilization.

Optical reach:

- OTU4 - 3;
- OTUC-2 - 2;
- OTUC-3 - 1;

The function receives a lightpath and should return the cheapest solution to connect one service.

First, it searches for the first node where the optical reach, using an OTU4 signal, is exceeded. In this figure 3.14, the destination node does not exceed the optical reach. Thus, the algorithm finds the best case solution between the possibility of grooming the signal into an existing lightpath, adding a new lightpath or changing a previous added equipment to allow the use of a previous added lightpath.
This process is repeated for OTUC-2. Then, using the OTUC-2 signal reach, the function searches for the last node where the optical reach is not exceeded. In this example, this occurs in node 3. It splits the received service route in two sub-routes: sub-path 1 ([1-2-3]) and sub-path 2 ([3-4]). Afterwards, the CostFunction is called using both sub-paths. The OTUC-2 cost solution for the path will be the sum of what both functions return. The OTUC-2 cost solution will be the sum of the costs and the concatenation of paths returned from the CostFunction calls.

For the OTUC-3 optical signal reach, the same logic is applied. This time, the generated sub-path 1 is [1 2] and sub-path 2 [2-3-4]. The OTUC-3 cost solution for the path will be the addition of CostFunction(sub-path 1) and CostFunction(sub-path 2).

Finally, at the end of the algorithm, one last script is inserted in order to minimize the cost of the solution and, at the same time, the number of wavelengths needed. This script is pseudocoded in Algorithm 9 and searches all the nodes, if it is possible to replace the regeneration using 2 muxponders with a regenerator. If some service without the same source or destination is using one muxponder, the replacement of the muxponders by one regenerator is considered impossible and not feasible. A single regenerator is considered to be always cheaper compared to the price of 2 muxponders. Note that, since the minimization of wavelengths and grooming is a priority, the use of regeneratorS is not expected to occur frequently.
Algorithm 9: 3RCostMinimization

Data: 
- $\text{Signals}_{100SD}$ - traffic demands using OTU4 Muxponders from S to D
- $\text{Signals}_{200SD}$ - traffic demands using OTUC-2 Muxponders from S to D
- $\text{Signals}_{300SD}$ - traffic demands using OTUC-3 Muxponders from S to D

1 begin
2     for each node $T$ in the network do
3         for each node $S$ in the network do
4             for each node $D$ in the network do
5                 while $z$ signals, between 0 and 10, from $S$ to $D$ are using OTU4 Muxponders in $R$ to regeneration do
6                     $\text{Signals}_{100ST} = \text{Signals}_{100ST} - z$;
7                     $\text{Signals}_{100TD} = \text{Signals}_{100TD} - z$;
8                     $\text{Reg}_{100SD} = \text{Reg}_{100SD} + 1$;
9                 end
10                while $z$ signals, between 11 and 20, from $S$ to $D$ are using OTUC-2 Muxponders in $R$ to regeneration do
11                    $\text{Signals}_{200ST} = \text{Signals}_{200ST} - z$;
12                    $\text{Signals}_{200TD} = \text{Signals}_{200TD} - z$;
13                    $\text{Reg}_{200SD} = \text{Reg}_{200SD} + 1$;
14                end
15                while $z$ signals, between 21 and 30, signals from $S$ to $D$ are using OTUC-3 Muxponders in $R$ to regeneration do
16                    $\text{Signals}_{300ST} = \text{Signals}_{300ST} - z$;
17                    $\text{Signals}_{300TD} = \text{Signals}_{300TD} - z$;
18                    $\text{Reg}_{300SD} = \text{Reg}_{300SD} + 1$;
19                end
20             end
21         end
22     end
23 end

Also, the number of signals using OTU4, OTUC-2, OTUC-3 capacity signals $\text{OCh}$ in each link is saved for components accounting later.

Variations of this algorithm are also implemented, which only consider the use of OTU4 muxponder, OTUC-2 muxponder, or the OTUC-3 muxponder.

3.5.3 WSS Accounting

This routine was implemented to count the number of WSS for each node architecture. It was designed based on different formulas for each implementation solution and each constrain in the nodal perspective. It is assumed the input/output ports as symmetrical and bidirectional connections.

- $\delta$ - Nodal Degree;
- $C_d$ - Contentionless Degree;
- $I$ - Total number of input/output wavelengths from different fibres;
- $t$ - Total number of transmitters/receivers;
- $\Lambda$ - Total number of connections added;
- $W$ - maximum number of wavelengths supported by DWDM system;
- $SC_{in}$ - SC number of port inputs;
- $WSS_{in}$ - WSS number of port inputs;
- Q - number of WSS cards;

The next constraint defines the maximum number of transmitters/receivers of each node. It is conditioned by the number of $WSS_{in}$, $SC_{in}$ and $C_d$.

$$t = WSS_{in} \times SC_{in} \times C_d$$  \hspace{1cm} (3.1)

The maximum number of input/output wavelengths from different directions is bounded by:

$$I \leq W \times \delta$$  \hspace{1cm} (3.2)

The number of input/output connections cannot be great than the number of transmitters/receivers:

$$\Lambda \leq t$$  \hspace{1cm} (3.3)

In each the input/output fibre ports the number of WSS inlets cannot be less than the sum of nodal degree and contentionless degree. This is considered to be always fulfilled since the analysed networks does not use higher nodal degrees.

$$\delta + C_d \leq WSS_{in}$$  \hspace{1cm} (3.4)

For the use of ROADM CDC solution, the accounting is formulated in equation 3.5.

$$Q = \delta + C_d + 2 \times C_d \times \left\lceil \frac{I}{WSS_{in}} \right\rceil$$  \hspace{1cm} (3.5)

Next a figure where the add/drop modules of a CDC ROADM is represented for node 5 in the network shown in 3.5.

![Figure 3.17: Add/Drop Modules of CDC ROADM after RWA](image-url)
As is possible to see by the observation of final formula 3.5, the number of WSS inlets is one important information to calculate the final number of WSS in the node. Figure 3.17 is showing $1\times3$ WSS just because of the size of the image. The number of add/drop modules is 3, having 3 contentionless degree, the maximum defined in this framework.
4.1 Testing set-up

4.1.1 Environment

All simulations and tests were run in a computer using 64bit Windows 7 with an i7-6700 3.4Ghz processor and 16Gb of RAM. All testing scripts were implemented using MatLab R2015a software.

4.1.2 Input Parameters

For the algorithms explained in sub-section 3.1, 3.2 and 3.3, the use of a logical mesh topology is considered, where each node has a logical link with all the other nodes in the network. To see the influence of the increase of traffic in the network, the algorithms are tested by using mesh logical topology with Tmax = 1, 2, 4, 6 and 8, being Tmax the number of traffic units between each node.

For the framework detailed in 3.5, the test was made using randomly generated traffic matrices, generated using a Matlab script. Different networks need different sized traffic matrices to reach results with different amounts of traffic demands. In this case, a script was made, which receives as parameter the physical network topology and uses the size of each network to generate 10 different traffic matrices with random values. For the simulation, the different network architectures are tested having a total of 10Tb/s, 20Tb/s, 50Tb/s, 80Tb/s and 100Tb/s in service demands.

Results were obtained from different physical topology networks with different dimensions, link distances, number of nodes and edges. In appendix B, the characteristics of the network topologies used are detailed. These are all well-known networks that are often used as benchmark.

The optical reach for each rate transmission is retrieved from [22], where for 100G, 200G and 300G transmission modes for a fixed 50GHz grid, optical reaches of 3750km, 675km and 150km, are considered respectively.

The costs, in case of O/E/O conversion elements such as muxponders and regenerators, were loosely based on work [53]. The costs of WSS were based on work [54].

- OTU4 Muxponder: $C_{M100} = C$
- OTU4 Regenerator: $C_{R100} = (1 - A) \times 2 \times C_{M100}$
- OTUC-2 Muxponder: $C_{M200} = (1 - B) \times 2 \times C_{M100}$
- OTUC-2 Regenerator: $C_{R200} = (1 - A) \times 2 \times C_{M200}$
- OTUC-3 Muxponder: $C_{M300} = (1 - B) \times 3 \times C_{M100}$
- OTUC-3 Regenerator: $C_{R300} = (1 - A) \times 3 \times C_{M300}$
- SBVT Muxponder: $C_{MSBVT} = (1 + D) \times C_{M300}$
- SBVT Regenerator: $C_{RSBVT} = (1 - A) \times 2 \times C_{MSBVT}$
- 1x2 WSS: $C_WSS1 \times 2 = (1 - E) \times C_{M100}$
- 1x4 WSS: $C_WSS1 \times 4 = (1 - G) \times 2 \times C_WSS1x2$
• 1x8 WSS: $C_{WSS1} \times 8 = (1 - G) \times 2 \times C_{WSS1x4}$;

• 1x16 WSS: $C_{WSS1} \times 16 = (1 - G) \times 2 \times C_{WSS1x8}$;

The variables expressed above can be edited and the tests were done with the following values:

• $C = 1.00$;

• Difference between rates - $B = 0.30$;

• Difference between muxponder and regenerators - $A = 0.15$;

• Difference between fixed and flex element - $D = +0.10, -0.10$;

• Difference between muxponder and wss - $E = 0.95$;

• Difference between N of $1 \times N$ WSS - $G = 0.20$;

### 4.2 Shortest Path Results

In Table 4.1, the results obtained from the implementation of the framework presented in 3.1 are shown. In this table, different values are presented. The traffic in the most loaded link (maximum), the traffic units in the least loaded link (minimum) and mean value of traffic between all the links in the network are presented. Furthermore, the difference between the most loaded link compared to the least loaded is also present.

<table>
<thead>
<tr>
<th></th>
<th>Yen Edge Disjoint SP</th>
<th>Node Disjoint SP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dijkstra K=2 K=3</td>
<td>K=2 K=3</td>
</tr>
<tr>
<td><strong>Cost239</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>3.73 4.96 5.65</td>
<td>4.88 5.77</td>
</tr>
<tr>
<td>Minimum</td>
<td>0 0 1</td>
<td>2 1</td>
</tr>
<tr>
<td>Maximum</td>
<td>11 12 14 12 16</td>
<td>10 10</td>
</tr>
<tr>
<td>Difference</td>
<td>11 12 13 12 14</td>
<td>9 9</td>
</tr>
<tr>
<td>Total</td>
<td>194 258 294 254 300</td>
<td>240 288</td>
</tr>
<tr>
<td><strong>NSFNet</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>12 17 19.62 16.24 18.14</td>
<td>15.5 12.2</td>
</tr>
<tr>
<td>Minimum</td>
<td>1 6 7 5 7</td>
<td>3 1</td>
</tr>
<tr>
<td>Maximum</td>
<td>35 37 37 27 32</td>
<td>24 22</td>
</tr>
<tr>
<td>Difference</td>
<td>34 31 30 22 25</td>
<td>21 21</td>
</tr>
<tr>
<td>Total</td>
<td>504 714 824 682 762</td>
<td>652 514</td>
</tr>
<tr>
<td><strong>UBN</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>19.44 23.82 25.44 24.29 25.8</td>
<td>24.1 18.1</td>
</tr>
<tr>
<td>Minimum</td>
<td>0 0 0 0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>Maximum</td>
<td>64 76 67 67 71</td>
<td>50 52</td>
</tr>
<tr>
<td>Difference</td>
<td>64 76 67 67 71</td>
<td>50 52</td>
</tr>
<tr>
<td>Total</td>
<td>1750 2144 2290 2186 2322</td>
<td>2168 1626</td>
</tr>
</tbody>
</table>

As expected, since a comparison is being made between the first, second and third shortest path, using the Yen, Edge Disjoint and Node Disjoint algorithms for shortest path, the mean value increases since it is expected that the number of hops increase with the increase of distance. It may be interesting to look at the difference between the minimum and maximum loaded link in the network. The use of Dijkstra algorithm is not always the algorithm which results in the most balanced network.
On one hand, it is important to minimise the mean traffic load in the network however because results in a network less loaded in general, on the other hand, the importance of a balanced solution must be a critical concern.

As it is possible to see in table 4.1, results coming from the use of Node-Disjoint SP are more well balanced in comparison to the results using Dijkstra. The solution which always uses the second and third shortest path is not optimized, since the increase of average traffic in each link increases and the difference between the most and least loaded link. However these results prove that Dijkstra is not optimised either. The next sub-section tries to achieve a better solution, with a more balanced solution while, at the same time, having better mean values.

The computation time of routing algorithms are shown in table 4.2 for the different algorithms and networks. The algorithms finding multiple routes have higher computation times compared to the Dijkstra which only finds one route between the source and destination. Within the algorithms that compute multiple routes, the times presented are reached testing the routing for the first three shortest paths. The Yen algorithm has the highest result time, and the Edge and Node Disjoint algorithms have a similar computation time. These results were expected since computation time is directly related to the number of possible routes, and the Node Disjoint has less route possibilities compared to the Edge Disjoint algorithm, which in turn has less possibilities compared to the Yen algorithm.

<table>
<thead>
<tr>
<th>Table 4.2: Computation Time of Routing Algorithms in ms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost239</strong></td>
</tr>
<tr>
<td>Dijkstra</td>
</tr>
<tr>
<td>Yen (k=3)</td>
</tr>
<tr>
<td>3-Shortest Paths - Edge Disjoint</td>
</tr>
<tr>
<td>3-Shortest Paths - Node Disjoint</td>
</tr>
</tbody>
</table>

4.3 Balancing Results

The results obtained through the implementation of the framework presented in 3.2 are shown in tables 4.3, 4.4 and 4.5. In addition to the results from the proposed balancing algorithm 2.3.2 the best results from different routing algorithms in section 4.2 are included to facilitate the comparison.

In Cost239, the most effective algorithm was the Balancing Node Disjoint. All parameters are presented in table 4.3

<table>
<thead>
<tr>
<th>Table 4.3: Balance Algorithm Results in Cost239</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dijkstra</strong></td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>Maximum</td>
</tr>
<tr>
<td>Difference</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

For NSFNET, by observing table 4.4 Balancing reveals to be the best algorithm to balance the network for these types of medium sized networks. However, the difference compared to Balancing Node Disjoint is not obvious since the average traffic in each link is lower compared to the Balancing
The results show that the Balancing Node Disjoint algorithm achieved the best results when balancing the traffic through the network. Despite the increase in the average load of the links, there was a substantial decrease in the difference when compared to the other algorithms.

**Table 4.5: Balance Algorithm Results in UBN**

<table>
<thead>
<tr>
<th></th>
<th>Dijkstra</th>
<th>Balancing</th>
<th>Balancing Edge Disjoint</th>
<th>Balancing Node Disjoint</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong></td>
<td>19.4</td>
<td>19.3</td>
<td>19.62</td>
<td>19.76</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>64</td>
<td>52</td>
<td>56</td>
<td>46</td>
</tr>
<tr>
<td><strong>Difference</strong></td>
<td>64</td>
<td>52</td>
<td>56</td>
<td>46</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1750</td>
<td>1740</td>
<td>1766</td>
<td>1778</td>
</tr>
</tbody>
</table>

From the observation of the three tables, the balancing algorithms achieved the goal of getting more balanced results. The results prove that if a decision was made to route all the traffic using the Dijkstra algorithm, this would not be the best way to get a balanced network, since this solution leaves some connections without any usage, whereas others are over-used. Analysing the results and choosing between the three balancing algorithms, the Node Disjoint Balancing is the most effective within the three studied networks. The result can be explained because of the use of the Node Disjoint routing algorithm, which enables the possibility of finding alternative routes to re-route the traffic demands. These routes are not normally explored using the Yen algorithm.

Figure 4.1 shows the load distribution along the network, comparing the use of the Dijkstra algorithm and the Edge Disjoint balancing algorithm. Observing the figure, it is easy to see a more homogeneous distribution resulting from the Edge-Balancing algorithm.
Figure 4.1: Dijkstra vs Edge Disjoint Balancing Load Distribution in NSFNET

The computation time of the balancing algorithms is presented in Table 4.6. These results are conditioned by the distance of the alternative routes chosen. The computation times are similar between the balancing algorithms.

Table 4.6: Computation Time of Balancing Algorithms in µs

<table>
<thead>
<tr>
<th></th>
<th>Cost239</th>
<th>NSFNET</th>
<th>UBN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balancing</td>
<td>5.41</td>
<td>8.11</td>
<td>18.93</td>
</tr>
<tr>
<td>Balancing - Edge Disjoint</td>
<td>5.71</td>
<td>6.91</td>
<td>18.63</td>
</tr>
<tr>
<td>Balancing - Node Disjoint</td>
<td>6.31</td>
<td>7.81</td>
<td>18.93</td>
</tr>
</tbody>
</table>

4.4 RWA Results

Some considerations on the results from the implementation of the framework described in Section 3.3 are going to be made in this section. Table 4.7 has the number of wavelengths necessary depending on the traffic in the network and the different algorithms.

The results mentioned as FirstFitRWA, refer to the result of demand ordering using Random algorithm and RWA using FirstFitRWA. LongestFirst, presented in the table, refers to the result of using demand ordering with LongestFirst and FirstFitRWA for RWA. RandomRWA orders the demands using random and resolves the RWA problem with RandomRWA algorithm. The Most-Used uses random algorithm for ordering the demands. These algorithms are explained in 2.3.3.A.
As expected, the results are better using the most complex algorithm – LFAP - compared to the other studied RWA algorithms. The LFAP, as explained previously, is a much more complex algorithm and, naturally, gets better results in the number of wavelengths used compared to the other algorithms, for the same traffic matrix and network.

The computation time is an important piece of data in algorithm analysis. In figure 4.2, the results of the computation times for each algorithm and for each network are presented.

As can be seen the computation time for LFAP is much higher than for the other heuristics, which is an expected result in face of the algorithm complexity. Between all the other algorithms, like the results of the number of wavelengths used, the computation time is also similar with better results for Longest-First algorithm.
4.5 Cost Optimization Results

The results obtained by applying of framework detailed in 3.5 are presented next. In general, it is expected that costs will increase with the increase of traffic and the size of the network because of the existence of more combinations of node pairs. Then, when the results are mentioned, Mixed Capacities refers to the solution in case of using s capacities of OTU4, OTUC-2 and OTUC-3. The results presented with Translucent Mux refers to the translucent architecture and considers the use of muxponders coupled with muxponder configuration for regeneration and intermediate grooming. It can also use regenerators if the replacement of muxponders by one regenerator is possible, in the end of the algorithm solution, as explained previously. The results mentioned as Translucent Reg, refer to the translucent node architecture using regenerators to provide 3R function.

4.5.1 Wavelength count results

It is important to mention that this work was not orientated to the minimization of wavelengths used, but the wavelength continuity constraint was always taken into account. For a certain traffic unit, if two paths get the same cost of implementation, the one which minimizes the number of wavelengths in the most loaded link is considered. For wavelength assignment the First-FitRWA is used.

First, the number of wavelength used for mixed capacity solution is shown in the figure 4.3. The wavelength on the most loaded link increases with the increase of traffic and the size of the network. In larger networks, since the use of high capacity channels is impossible because of optical reach limits, it quickly reaches the maximum number of wavelengths that can be used in each fibre.

The results showing the transparent network using less wavelengths in the most loaded link is related with the blocked services and the results using intermediate grooming have better results compared to the ones using regenerator cards.

![Figure 4.3: Number of Wavelengths used for Mixed Capacities](image_url)

In appendix D, figures D.1, D.2 and D.3 can be consulted to see the number of wavelengths for solutions with single capacities. For the OTU4 capacity solution, it can be seen that the wavelengths...
reach the limit for Finland and UBN networks. Using OTUC-2 capacity, the wavelengths’ limits are not reached and for UBN almost all wavelengths are blocked due to optical reach limitations and the number of blocked services is almost 100%. The result for OTUC-3 capacity shows that it is possible to get results for small sized networks, like Finland, reaching half of the limit imposed by fibre optical limits.

4.5.2 Service blocking accounting results

The percentage of blocked services is also analysed. It is important to mention that in all tested conditions for the different capacities, service blocking occurs. Figure 4.4 shows that, for the OTU4 solution, the percentage of blocking services grows with the increase of traffic. As expected, the opaque network gets the best results in comparison to the other solutions, reaching a better usage of bandwidth by enabling obligatory intermediate grooming in all the nodes. The impossibility of regeneration in transparent networks leads to a high percentage of blocked services for larger networks, as it is possible to see in UBN where about half of the traffic is blocked by the optical reach limitation. For the Finland network, with the increase of traffic, it reaches the wavelength limit in the fibres and gets a high percentage of blocked services.

![Figure 4.4: Blocking Service for OTU4 capacity](image)

Naturally, the percentage of blocked services increases with the use of OTUC-2 and OTUC-3 only data-rates. In the use of OTUC-2 capacity, as is possible to see in figure 4.5 UBN gets almost 100% of blocked services, even with regeneration. This was an expected result, since the physical topology only has three fibres smaller than the OTUC-2 optical reach. In Finland and Cost networks, where regeneration is considered, it is possible to connect all the services. In turn, in the transparent network, the Cost network gets almost 50% of blocked services because of the optical reach limitation. Comparing the percentage of blocking for OTUC-2 and OTU4 capacities, Finland enables the aggregation of more services in the same lightpath, resulting in no blocking and getting better results.
For OTUC-3 capacity solutions, as it is possible to see in figure 4.6, 100% of services are blocked for Cost and UBN networks, since none of them has fibres smaller or equal to the OTUC-3 optical reach. On the other hand, the Finland network can connect all the lightpaths in architectures which consider regeneration. In the case of the transparent architecture, about 35% of the traffic services are blocked for limitation of optical reach.

The mixed capacity solution, only gets service blocking in the UBN network in the transparent network and translucent using regenerators. The solution for the percentage of blocked services per traffic, node architecture and node solution is shown in figure 4.7. Here it is possible to see the greatest advantage between regeneration methods. Using the muxponders for regeneration, it enables the intermediate grooming, and the wavelength capacity is never reached leading to a non-blocking solution.
4.5.3 Cost comparison

The accounting of conversion elements, for the Finland network, shows preference by the use of high capacity signals as OTUC-2 and OTUC-3. The number of elements is higher in the opaque network, as expected. The other networks get the same results since no regeneration is required. Figure 4.8 shows the contribution of different elements for the total network cost, per traffic for each architecture in Finland network. The transparent architecture gets similar results to the translucent using regenerators since the grooming is done in the source/destination and no regeneration is needed. The results for translucent using muxponder for regeneration get similar but more economic results compared to transparent, because this architecture considers the re-use of muxponders already added in the network. As it is possible to see, the use of high capacity muxponders increases with traffic.

The cost results for each element as a function of traffic and architectures in Cost230 are shown in figure 4.9. As expected, after the analysis of blocking percentage, no OTUC-3 muxponders are added because of the optical reach limitations. The use of OTU4 capacities enable the solution with no need of regeneration, and, as a result of that no regenerators are added. The opaque architecture,
again, gets the most expensive solution and the source/destination grooming solutions get equal cost solutions. The slightly better result for translucent using muxponders for regeneration happens because it uses already added muxponders in the network to reach a destination.

Figure 4.9: Cost Distribution for Mixed Capacity in Cost239 Network

Figure 4.10 shows the results which enable the comparison of the cost element distribution in UBN for different traffic and node architecture. Again, the most expensive solution is the opaque. The transparent architecture, since the percentage of blocking shown in 4.7 is quite high, gets less costly results compared to the translucent architectures. Comparing the translucent solutions, it can be seen that the cheaper solution lies in the architecture using muxponders for regeneration. Despite the use of more muxponders, the cost added by regenerators is higher compared to the cost of muxponders because they do not provide any grooming functionality.

In the case of solution using only OTU4 capacity signals, for Cost239, figure 4.11 is presents with the cost influence of OTU4 muxponder and OTU4 regenerator. By the observation of figure 4.4, no service was blocked in this network so no influence of that parameter is expected in the next result. As it is possible to see, there is no regeneration. The opaque is the most expensive, as expected and the others are equal or similar. The source/destination grooming, as expected because no regeneration
is needed, gets the same results between them. The use of muxponders and the enabling of the use of intermediate grooming, in the algorithm used for translucent networks using muxponders for regeneration, enables a slightly better cost result which cannot be seen in the figure for scale reasons. But as an example, the cost units obtained for 100Tb/s translucent networks using regenerators is 1057.6 in comparison to 1029.8 obtained in the regeneration using muxponders, because of the intermediate grooming that is searched by the algorithm.

Figure 4.11: Cost Distribution for OTU4 Capacity in Cost239 Network

Figure 4.12 shows, for the Cost239, the cost distribution per traffic and network. Looking at figure 4.5 it can be seen that almost 50% of services are blocked in the transparent architecture and have an impact in the cost distribution, should be “showing the solution is the cheapest, but having almost half of the services blocked is not a good solution. Again, the opaque architecture represents the most expensive solution but comparing to the translucent architectures, the most economic solution is the one using muxponders allowing regeneration and intermediate grooming. It can be noted that these are the first results where some muxponders were able to be replaced by regenerator cards by the implementation of algorithm 9.

Figure 4.12: Cost Distribution for OTUC-2 Capacity in Cost Network
The solution reached using OTUC-2 capacity in Finland network was added in appendix D in figure D.6. The UBN results were not added because, as shown before, almost 100% of the services are blocked.

Analysing figure 4.6 it can be seen that only Finland network has a solution using OTUC-3 signal capacity, as can be seen in figure 4.13. The opaque network is the most expensive architecture compared to the remaining ones. The transparent architecture gets inexpensive results just because almost 35% of the services were blocked by optical reach limitation. Comparison between the translucent networks, for low traffic the least costly solution is the translucent with intermediate grooming solutions, however, with the increase of traffic, the results get similar when compared to the end-to-end solution. As it is possible to see, the number of B2B muxponders which are possible to be replaced by regenerator cards also increase, achieving similar results. It is possible to conclude that intermediate grooming is not boosted by the increase of traffic.

![Cost Distribution for OTUC-3 Capacity in Finland Network](image)

Figure 4.13: Cost Distribution for OTUC-3 Capacity in Finland Network

Figure 4.14 shows the percentage of free muxponder ports. Having low percentage of used ports results in a good usage of elements in the network. Having free ports in the network result in an increase of the CapEx without being needed. The figures show a decrease of free ports with the increase of traffic, meaning the algorithms are working as they are supposed to, adding new services into previously added muxponders, saving costs. The low percentage of free ports in the opaque can be explained by the possibility of grooming services into one lightpath in each node. The translucent architecture using muxponders for regeneration, which gives the possibility for intermediate grooming, has the second best result compared to the source/destination grooming architectures.
The influence of the WSS was also studied and is now compared. For the previous results, the units of each equipment influences directly the impact in the network cost. WSS results can be seen in figure 4.15. The figures show a tendency graph having the results of the number of 1x2 WSS against the results using 1x5, 1x9 and 1x20 WSS using translucent architecture with regenerator. The tendency for the other architectures is similar. As it is possible to see, as expected, the number of WSS needed increase with the traffic, but the number for inlets are determinant for the number of elements used. The WSS with 20 inlets, needs, for 100Tb/s traffic, almost less 70% of WSSs compared to the 1x2 WSS topology. But one interesting result is the variation of the WSS cost, where the use of less WSS with the increase of inlets does not mean cost savings. Figure 4.15 is divided into two graphics. In the left side of the figure, it shows the variation of WSS units, while in the right side shows the variation of cost the graphic of cost, in comparison with 1x2 WSS. The graphic cost shows that, for Finland network, the use of 1x20 WSS in the network never leads to a cheaper solution compared to 1x2 WSS. The 1x5 WSS is the less costly solution and the 1x9 WSS only gets better results with the increase of traffic.

Figure 4.14: Free Ports Percentage for Mixed Capacities

Figure 4.15: Variation of WSS accounting and cost, in comparison with 1x2 WSS, for Mixed capacities in Finland network and Translucent with B2B muxponders

Figure 4.16 shows the number of units of each WSS architecture per traffic and tested architecture.
Similar to the previous analysis about the tendency result of the Finland network in figure 4.15, this result is shown for Cost239 network and using mixed capacity signals.

Figure 4.17 shows the cost distribution and as concluded for the previously analysed network, the decrease in the number of WSS units does not lead to a more cost effective solution. As it is possible to see, the solution using larger WSS lead to a solution using less elements but is not the most economic. The architectures which enable intermediate grooming typically have more WSS needed, since the addition of add/drop modules in the ROADM is common. As mentioned before, all these results were designed for a maximum of 3 contentionless degree ROADM.

The intermediate grooming, enabled by regeneration using B2B muxponders, has a higher number of WSS compared to the solution which uses only source grooming. This can be explained by the increase of add/drop modules in the ROADM's by the increase of wavelengths being added in each node.

In appendix D, the number and cost of WSS for mixed capacities in Finland and UBN are added. The same conclusions can be taken as in Cost239 network for Finland network.

In appendix D, the number of elements referring to the cost distribution of the previously shown results was also added.

Figure 4.18 shows for mixed capacities in the Finland Network, the cost solution using mixed cards versus SBVT cards. Two results were taken for SBVT, as explained in section 4.1.2, where the cost
input parameters were detailed. On the other hand, figure 4.19 shows the same results for the UBN network.

As explained, the algorithms search among the three first shortest paths, minimizing the global solution cost and number of wavelengths. All the algorithms were run just searching with the shortest path. As shown in section 4.5, considering only the shortest path does not necessarily lead to the best solution. Solutions searching only the first shortest will be referred to as Unbalanced, and the one searching between the three shortest paths is the balanced. Figure 4.20 shows the comparison in Cost239, for a balanced vs an unbalanced solution. It is possible to see similar results between the
balanced and unbalanced solution.

Figure 4.20: Balanced vs Unbalanced cost in Cost239 for Mixed Capacities

Also the comparison of number of wavelengths used, where the most advantages can be seen between unbalanced and balanced solution. Figure 4.21 shows the number of wavelengths, in the most loaded link, saved by the use of the balanced solution vs the unbalanced. As it is possible to see, with the Translucent network using intermediate grooming, in Cost239 almost 50% of wavelengths are saved by searching between the three first shortest paths.

Figure 4.21: Percentage of Saved Wavelengths Balanced vs Unbalanced for Mixed Capacities

4.5.3.A Computation Time comparison

The computation time was calculated for each script, and it is shown in figure 4.22. Each script calculates the solution for each architecture and using different capacity solutions. In general, the mixed capacity gets higher computation time, since it needs to calculate more possibilities using different capacities and optical reaches and compares the cheapest cost solution for choosing the best solution. The Translucent using muxponders for regeneration and opaque get higher computation times because in this algorithm the services are added one by one, against the source grooming algorithm which considers a set of services each time one iteration is done.
4.5.3.B Overview

The previous results show interesting data to compare the differences between architectures. The opaque, on the one hand, gets the best results in number of wavelengths needed, never reaching the limit of 80 wavelengths of the fibres, and also originates the solution with less percentage of blocked services. On the other hand, the solutions are always the most expensive since the O/E/O conversion in all the nodes increases the CapEx substantially. Also, in the analysis of WSS cost, the opaque architecture leads to the most expensive solutions.

The transparent approach, cannot be a good solution since even for OTU4 signal capacities and small networks, it results in high a percentage of blocked services. It can be concluded that for almost every network, regeneration is going to be needed for a significant part of the lightpath connections, and even with the increase of the optical reach, the network planning considering full transparent architectures are still not a viable solution assuming the limitations considered.

This leaves the translucent architectures to analyse. Here the solution of intermediate grooming leads to the least costly solutions for most of the tests, using different capacities and traffic but as the traffic grows the solution using source/destination grooming must be taken into account. Here, most of the tests lead to the conclusion that WSS cost is higher for the solution which enables intermediate grooming. But one big advantage for intermediate grooming is the use of substantially less wavelengths, and the source grooming solution will probably start blocking services sooner. Because of that efficiency, the percentage of free ports is lower for the nodes which enable intermediate grooming and that is a plus, since the added hardware is used in a more efficient way.

Also the analysis between a balanced solution and an unbalanced solution is made, where the amount of wavelength saved by using the balanced solution is well visible.

The analysis of WSS count and cost show that the use of big sized WSS does not mean a cost efficient solution and each case has to be tested separately.
5

Conclusions and Future Work

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5.1 Conclusion

With the constant increase of traffic and constant necessity to improve efficiency, it is important to study the implementation of optical capacities beyond 100G and considering different network architectures.

In chapter 2, some basic concepts were detailed, as well as considerations on OTN and the important network elements for this work. Some considerations on previous works are also done. Additionally, routing, balancing and wavelength assignment heuristic algorithms were presented. Chapter 3 outlines the system architecture, presenting the implemented frameworks and algorithms in this work. Frameworks which enable the study of Routing paths, heuristic algorithms and the balancing implemented algorithm are presented. Algorithms which enable cost reduction for source and intermediate grooming architectures were also detailed in this chapter. The results of this work are presented in chapter 4.

First, the impact of routing the traffic using different routing algorithms is studied. Then, balancing methods are studied and as a conclusion, when the routing uses only the shortest path algorithm, it leads to unbalanced networks. The use of different metrics can lead to better results. Even in the balancing algorithm results, it can be seen that the use of different routing algorithms, by exploring paths that normally are not considered, is a good strategy in order to minimize the number of wavelengths used throughout the network.

The cost optimization and main results of this work are explained in 3.5. This subsection presented different algorithms to minimize the cost solution for Transparent, Opaque and two Translucent architectures. The big difference, between the two translucent architectures, consists in the regeneration strategy. The first uses regenerator cards without the possibility of intermediate grooming. However, with the use of B2B muxponder for regeneration, intermediate grooming is allowed.

Different results, for different signal capacities, and node architectures are evaluated. With these results, the importance of intermediate grooming is taken into account. Different results for balanced and unbalanced networks were taken and the influence is recorded.

As a conclusion, the Opaque network achieved better results in wavelength usage, but the CapEx needed is prohibitive. The use of the transparent architecture, with an increase in the network link distances, is not a good implementation strategy since most of the services do not get to the destination, due to optical reach limitations. This leaves the Translucent architectures to compare. One, using regenerators, and the other Back-to-Back muxponders allowing regeneration and intermediate grooming. Generally, it is shown that the use of intermediate grooming leads to better results, which decreases the needed CapEx compared to the source/destination grooming solution. But the use of regenerators can get acceptable results with the increase of the traffic, where the difference comparing to translucent using B2B regeneration is almost unnoticeable. The number of wavelengths used and the possibility of adding new services into a previously added lightpath leads to better results using B2B regeneration.

Different optical signal capacities were also considered and some conclusions can be made. The
use of high capacity, as OTUC-2 and OTUC-3, is a necessary improvement for the future of optical telecommunications, but nowadays they are not good solutions for large networks. As was shown in this work, due to optical reach limitation, almost no services can be served using optical capacities beyond OTU4 in networks as Cost239 and UBN. On the other hand, these capacities are good solutions for small sized networks, like Finland, leading to cost effective solutions. For the same reasons, the SBVT muxponder can be considered for small sized networks. For medium and large sized networks, the difference in investment between the typical muxponder and the SBVT muxponder shows that the latter does not lead to a good solution.

The cost of WSS in the network is also taken into account and a particular conclusion can be made. The increase of inlets in the WSS, as expected, decreases the number of elements in the network. However, by observation of various cost results, the increase of WSS inlets are not related to the decrease of cost.

In order to prove the importance of balancing, the presented algorithms were implemented using only the shortest path. This lead to a poor usage of bandwidth and did not generate a lower cost for the implementation of the solution. This work shows the importance of techniques like grooming and balancing, and shows that a good network planning leads to better service, and cost saving. Multiple figures are shown in chapter 4 to ease the comprehension of the results.

As a final conclusion it is easy to see that Translucent architecture using B2B muxponders, allowing intermediate grooming, lead to the best global solution when combining good cost results and good bandwidth usage.

5.2 Future Work

As future work, the implementation of algorithms taking into account different client rates is proposed. Additionally, the design of an ILP model would be interesting to compare with the presented results.

The application of the proposed algorithms, especially the cost optimization for intermediate grooming, can use a traffic matrix variable in time, e.g., multi-period planning. The proposed algorithms are easily adaptable to these scenarios.

For an in-depth study of the number and cost influence of WSS, results should be taken using different ROADM architectures.

The implementation of the proposed algorithms, taking into consideration protection paths is also suggested.
Bibliography


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Multiplexing and Mapping structures for OTN
Figure A.1: OTN multiplexing and mapping structures - extracted from [7]
B.1 Finland

The optical network of Finland was chosen because of the particularly small dimensions of the optical fibres.

<table>
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<th>Edges</th>
<th>Max. Distance</th>
<th>Min. Distance</th>
<th>Average Node Degree</th>
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<td>19</td>
<td>183</td>
<td>16</td>
<td>3.2</td>
</tr>
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</table>

![Figure B.1: Physical Topology of Finland](image)

B.2 Cost239

One of the networks used is COST 239, run by the European Commission to promote pre-competitive research and development cooperation between industry, universities and national research centres. COST 239, "Ultra-high Capacity Optical Transmission Networks", is studying the feasibility of a transparent optical overlay network capable of carrying all the international traffic between the main centres of Europe [55].

<table>
<thead>
<tr>
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<th>Max. Distance</th>
<th>Min. Distance</th>
<th>Average Node Degree</th>
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<td>26</td>
<td>953</td>
<td>171</td>
<td>4.7</td>
</tr>
</tbody>
</table>
B.3 NSFNET

The National Science Foundation Network (NSFNET) is the second network used in our tests. Sponsored by the National Science Foundation, it was the cross-country backbone of the Internet in the United States of America connecting the whole country with thousands of campi and access networks that connect to regional networks spread across the country [56].

| Table B.3: NSFNET Characteristics |
|---------------------|-----------------|-----------------|-----------------|-----------------|
|                     | Nodes | Edges | Max. Distance | Min. Distance | Average Node Degree |
| NSFNET              | 14    | 21    | 2838           | 246            | 3                |

B.4 UBN

The US backbone network (UBN) was chosen because of its characteristics since it has long edges, and is the largest that has been analysed.
Table B.4: UBN Characteristics

<table>
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<th>Edges</th>
<th>Max. Distance</th>
<th>Min. Distance</th>
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<td>2600</td>
<td>250</td>
<td>3.58</td>
</tr>
</tbody>
</table>

Figure B.4: Physical Topology of UBN
Cost Function Flowchart

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Figure D.2: Number of Wavelengths used for OTUC-2 Capacity

Figure D.3: Number of Wavelengths used for OTUC-3 Capacity
Figure D.4: Elements Distribution for OTU4 Capacity in Finland Network

Figure D.5: Cost Distribution for OTU4 Capacity in Finland Network

Figure D.6: Elements Distribution for OTUC-2 Capacity in Finland Network
Figure D.7: Cost Distribution for OTUC-2 Capacity in Finland Network

Figure D.8: Elements Distribution for OTUC-3 Capacity in Finland Network

Figure D.9: Elements Distribution for Mixed Capacity in Finland Network
Figure D.10: Elements Distribution for OTU4 Capacity in Cost Network

Figure D.11: Elements Distribution for OTUC-2 Capacity in Cost Network

Figure D.12: Elements Distribution for Mixed Capacity in Cost Network
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Figure D.17: Cost of WSS in Finland Network for Mixed Capacities

Figure D.18: Number of WSS in UBN Network for Mixed Capacities
Figure D.19: Cost of WSS in UBN Network for Mixed Capacities

Figure D.20: Cost of SBVT cards vs Mixed Cards in Cost network