Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática,
2016

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Dimensionamento e Optimização da Arquitetura dos Nós em Redes de Trasporte Óticas

Dimensioning and Optimization of Node Architecture in Optical Networks

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"Anyone who has never made a mistake has never tried anything new."

— Albert Einstein

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Dimensioning and Optimization of Node Architecture in Optical Networks

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Dr. Armando Humberto Moreira Nolasco Pinto, Professor Associado do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro, coorientação empresarial do Dr. Rui Manuel Dias Morais, doutorado em Engenharia Eletrotécnica pela Universidade de Aveiro, coordenador de atividades de investigação em optimização de redes na Coriant Portugal.

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	GHI Professor associado da Universidade J (co-orientador)
	KLM Professor Catedrático da Universidade N

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Resumo

Nesta dissertao é apresentada uma introdução às redes de transporte óticas multicamada. Foram caracterizados os dois elementos principais da rede: nós e ligações. Ao nível das ligações foi feita uma abordagem menos profunda, baseada nos seus elementos físicos principais. Ao nível dos nós foi tido em consideração o tráfego de cliente (baixo débito) e o tráfego de linha (alto débito), bem como os componentes necessários para os transportar. A forma como o tráfego de cliente agregado e o encaminhamento do mesmo na rede, levam à necessidade de construo de uma arquitetura usando o mínimo de recursos necessários. A necessidade de otimizar este processo de projeção da rede levou construção e validação de métodos de agregao de tráfego e encaminhamento baseado em topologias lógicas da rede. Assim, proponho nesta dissertação algoritmos de agregação e encaminhamento aplicados a um software livre, previamente validados por modelos de programação linear baseados em restrições e funções objectivo adequadas topologia pretendida. A apresentação detalhada dos resultados considerando o CAPEX, bem como a sua análise nção foram descuidadas. Por fim, foram apresentadas conclusções e sugerido o trabalho científico que ainda pode ser realizado neste âmbito.

Abstract

In this thesis an introduction is presented to the multilayer optical transport networks. nodes and links: the two main elements of the network were characterized. In terms of connections it was made a shallower approach based on its key physical elements. In terms of nodes it has been taken into account client traffic (low output) and the line traffic (high speed) as well as the components necessary to carry. The way the client traffic is aggregated and forwarding the same network, leading to the need to build an architecture using minimal resources required. The need to optimize this network design process led to the construction and validation of traffic aggregation methods and routing based on logical network topologies. I therefore propose in this dissertation algorithms and aggregation routing applied to free software, previously validated by linear programming models based on constraints and objective functions suitable to the desired topology. A detailed presentation of the results considering the CAPEX and its analysis were not careless. Finally, conclusions were presented and suggested the scientific work that can still be done in this area.

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List of Acronyms

ROI	return on investment
OTN	optical transport network
AWG	arrayed waveguide grating
CapEx	capital expenditures
C-band	conventional band
CFP	C form-factor pluggable
EDFA	erbium doped fiber amplifier
ESM	electrical switch module
EXC	electrical cross connect
API	aplication user interface
IDE	integrated development interface
GA	genetic algorithm
GFP	generic framing procedure
IETF	Internet engineering task force
ILP	integer linear programming
IP	Internet protocol
ITU-T	international telecommunication union - telecommunication standardization sector
LC	liquid crystal
LR	long-reach
MEMS	micro electro mechanical system
MPLS-TP	multi protocol label switching - transport profile
NP-hard	non deterministic polynomial time hard
NPS	network planning system

Chapter 1

Introduction

Systems based on Machine-to-Machine (M2M) communication, Voice over Internet Protocol (VOIP) services, online gaming and data storage are considered penetration services. These services have led to an, more and more, overhead on existing networks caused by a huge number of users~~.~~ .[2][3][4]. As it increases the amount of traffic and the transmission rates required, telecommunication agents involved are undergoing a pressure to develop the network technology in their processes, in order to increase the bandwidth.[1]

Technological development has allowed lower prices for network components, however, these prices are similar to the major operators. The costs with the setup of the infrastructure, CAPEX, compromises physical network components and buildings where they are installed and software needed for network operation and management. Currently, almost all traffic is transported through optical networks, so the operators are very interested in reducing the cost per transported bit as much as possible without compromise the quality of service. At the same time, there are entities heedful with the ecological footprint because of the uncontrolled increase in energy reserved for telecommunications. Therefore, is inevitable to create or enhance methods and equipment compatible with networks already realized.So, to lead the market competition, those operators are making an effort to optimize their networks, using the minimum resources with the minimum power consumption. Hence, the outcome of reducing power consumption is the diminish of operational costs (OPEX) and a crucial step to save the planet. The result of summing capital expenditures and operational expenditures is the total cost of ownership (TCO).[5]

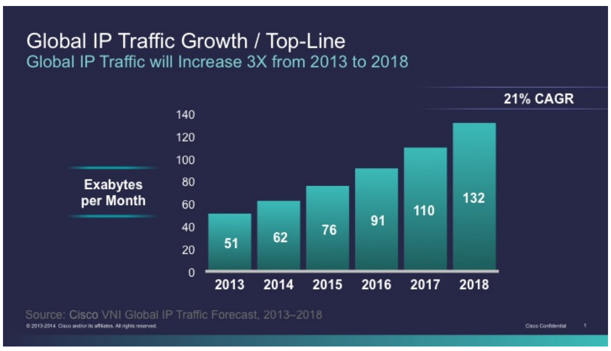


Figure 1.1: Cisco forecast for ip traffic growth

1.1 Motivation and objectives

Scientific researchers in the academic and business scope are joining efforts to improve network planning processes. In an optical network there are inevitable problems that occur such as, excessive traffic in one certain node or link and physical damage that may happen in the components of the network, this type of problems can block the flow of traffic and cause a huge loss of information if the network is not properly designed. The consequences of a failure of a single fiber can be catastrophic and may affect the medical emergency number, banking operations, or many other important services, that's why the study of protection and survivability methods are so crucial. In this context the operators are obliged to invest in more equipment and new strategies that ensure the protection and survivability of the network.

Nonetheless, it would be extremely difficult to make a fast and scalable planning to an optical network by hand, so it is used a network planning tool which is purposeful for systems vendors and network operators. It is used in the various stages of the telecommunications business, in the budgeting stage a planning tool offers a cost-efficient solution has a enormous benefit in a competing environment. However, the needs of people in terms of telecommunications are constantly changing, so in the operation stage, the planning tool can be used to re-optimize the available resources, making possible additional cost savings to network operators. Many companies as Coriant, Cisco and Ericson operating in the telecommunications area, developed their own optical network planners. However, it is evident that these tools are not publicly available to perform comparative studies of the obtained solutions for corporative reasons.

Therefore, in this dissertation, it is used an open source software (Net2Plan) as a platform to achieve a heuristic solution.Heuristic algorithms tend to be relatively fast, scalable, and suitable for huge networks[6]. The optimal solutions can be obtained through ILP models. However, scalability limitations may arise depending on the computational resources available and the network scale. Nevertheless, the type of solutions obtained and the models themselves can give an insight in key and structural aspects of the problem and are crucial to verify the quality of heuristic algorithms.These dimensioning tools, process input parameters and generate outputs regarding optical network constraints, in order to obtain a solution focused on cost efficiency.

In sum, this dissertation emerges from the collaboration between University of Aveiro, Instituto de Telecomunicaes Aveiro, and Coriant Portugal due to the interest of network operators ~~in saving some~~ resources inherent to the planning and operation of their networks and also contribute with knowledge to the scientific community of optical networks.

1. Develop ILP models for opaque and transparent networks using dedicated path protection.

2. Get a solution for optical networks with protection dimensioning through heuristic algorithms applied in Net2Plan (open source platform).

3. Compare and validate heuristics based results with the ILP based results.

4. Apply heuristic method to a realistic network.

1.2 Thesis outline

This dissertation is organized in 6 chapters. Chapter 2 is a state-of-art of optical networks topological design, dimensioning and dedicated protection. The basic concepts and fundamentals are defined as well as the physical and logical topology. In terms of physical topology, basic optical network elements are described in that chapter. The relation between logical topology and transport modes is presented in detail. Chapter 3 starts by a real network dimensioning problem analysis and a an integer linear programming approach. It begins with a problem definition, and the set of variables and inputs used. Hence, the remaining of the chapter is devoted to propose dimensioning models for optical networks based on opaque and transparent transport modes. In Chapter 4, a heuristic approach is suggested and described. Thus, an open source software was chosen to implement this solution to be accessible to students and modifiable for educational purposes. An overview of the software used to create the algorithms and on the platform used (Net2Plan). The pseudo code behind the routing and grooming is also contained in this chapter. The results of this two approaches are in Chapter **??**, the solution obtained through integer linear programming is considered the optimal solution and served to evaluate the quality of the solution based on heuristics. The optical channels needed for a specified client traffic matrix as a function of the algorithms runtime or as a function of different client traffic type are some of the results presented on the results chapter. The last step is the conclusions 6 and suggestions for future research directions.

Chapter 2

Topological Network Design and Network Protection

Internet is becoming one of the most powerful platforms allowing entertainment and productivity. Some services, as cloud storage or online social networks, have been implemented over Internet and they require a suitable network design for huge traffic requirements and able to deal, efficiently, with time-varying traffic. Thus, is mandatory to realize the best arrangement for physical resources, in order to simplify future improvements and ensure a reliable and efficient network. So, it is necessary to consider an overview of this chapter, starting from the optical reference network approach and the definition of main elements (links and nodes). As described on section 2.2.1, node mapping and links connecting them are considered physical topology. Optical links establish the connection between two adjacent nodes, ensuring the transmission of optical signals between them. Nodes can perform six main functions: encapsulation; electrical switching; deterministic or statistical multiplexing (grooming); wavelength assignment; optical switching; and optical multiplexing. This chapter is more focused on grooming tasks. Up to now, the majority of the functions performed at the nodes are only capable of being carried out in the electrical domain. However, an optical signal may suffer optical-electrical-optical (OEO) conversions in intermediate nodes. The consequence of this clear optical channels inside a wide area network(WAN) is a virtual topology as known as optical or logical topology 2.2.2. According to all-optical fragments in a single lightpath, three transport modes will emerge: opaque, transparent and translucent. In section 2.2, each transport mode is detailed, clarified and exemplified. An efficient topological network design makes optical networks more and more robust and reliable, but not infallible. An alternative for network working paths should be considered, regarding the limit of failure recovery time established by standardized protocols. Throughout the dissertation, only dedicated protection implementation strategies are considered 2.3. Thus, considering protection schemes and working paths for each traffic demand, it is possible to suggest an approach for node dimensioning, including optical and electrical components and support structures. The consequence of a well designed network is the minimization of node components and,as a result, lower capital expenditures (CapEx).

2.1 Optical Networks

Optical technologies are widely used in telecommunication networks, and currently they constitute the central physical network elements in most parts of the world, thanks to their high speed, large capacity, and other attractive characteristics. Optical networks can be classified as core, metro and access networks. The backbone infrastructure of telecommunication networks are core networks, which interconnects large cities (as network nodes), and spans nationwide, continental, and even intercontinental distances connected by links.

2.1.1 Links Arquitecture

Links are basically the connection between two adjacent nodes. In transport networks links are physical point-to-point connections ensured by transmission systems. The transmission system starts and ends in adjacent nodes, i.e. in directly connected nodes. Signals are transmitted through a pair of fibers, required bidirectional communication.

Optical signal is sent through optical fiber and this propagation cause signal deterioration and produce linear and non-linear effects. Loss coefficient imposed by optical fibers is a physical parameter described on each different fiber datasheet. In order to compensate attenuation, transmission systems contains optical amplifiers spaced by an expected distance (span) enough to increase signal power to allow a reliable signal detection at the receivers.

In figure 2.1 each colored line corresponds to an optical channel which is associated a wavelength. The WDM signal requires WDM transmission systems in the ends of the link.

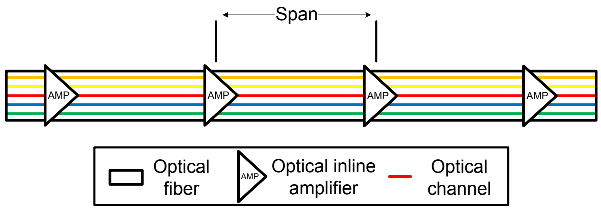


Figure 2.1: Bidirectional transmission system architecture: optical fiber and inline optical amplifiers.

Depending on the bandwidth used, WDM signals suffer different attenuation. Although, all channels are simultaneously amplified. An amplifier acts over the band selected, for example, EDFA (Erbium Doped Fiber Amplifier) is the most deployed fiber amplifier as its amplification window coincides with the third transmission window (1530nm –1570nm) of silica-based optical fiber.

2.1.2 Nodes Arquitecture

The more significant operations that the optical signal goes through in the network occur in nodes. Node operations require a lot of hardware (e.g. processors, modules, control modules, short-reach and long-reach transceivers), therefore nodes are generally considered the most expensive element of an optical transport network. In optical networks, nodes are composed of three essential structures : modules, shelves and rack. The modules can contain multiple ports. Shelves are the place where different modules are assembled and this shelves are contained within a larger structure, capable to provide sufficient power for each shelf. In high-capacity multilayer transport nodes, depending on network operation requirements in optical and electrical layer, different type of modules are used. Modules comprise electrical and optical components in order to perform well-defined functionalities as encapsulation, grooming and wavelength assignment. Connection between modules are established through front panel and backplane. Usually, front panel connections are mainly ensured by transceivers located in the ports. Depending on the optical signal travel distance, long-reach or short-reach transmitters must be used.

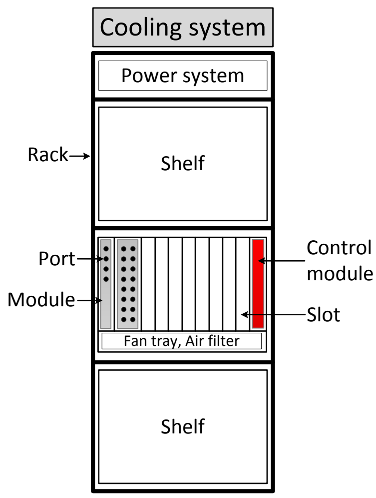


Figure 2.2: Node schematic: port, module, slot, shelf and rack.

2.1.2.1 Grooming

Traffic grooming refers to techniques used to combine low-speed traffic streams onto high-speed wavelengths in order to minimize the networkwide cost in terms of line terminating equipment and/or electronic switching. Network planners need to define which mixture of client signals should be aggregated as well as in which node will be grooming capable components, in order to improve the dimensioning of a multilayer node. Dimensioning models are closely related to the grooming operation as it determines the number of ports and wavelengths required. These models rely on ILP or heuristics, which require complete information about the network topology and traffic demands. In order to minimize the number of wavelengths used and, consequently, power consumption, network planners started with the aggregation of SDH/SONET traffic. The optimization of multi-layer networks has been focused on the two layer IP-over-WDM, or the three layer IP-over-OTN-over-WDM architectures. All optimization models of this dissertation are focus on OTN technology defined in ITU-T recommendation G.709 however the approaches and models are flexible to support other technologies such as SDH/SONET or Ethernet. The set of all client bit rates is denoted by C = $\{c : c \in \{1.25, 2.5, 10, 40, 100\}\}$ corresponding to an ODU1, ODU2, ODU3 and ODU4, these lower bit rate client signals, defined in Gbps, are then groomed to form a higher bit rate line signal, l. The set of line bit rates, defined in Gbps, will be denoted by L = $\{l : l \in \{2.5, 10, 40, 100\}\}$, corresponding to an OTU1, OTU2, OTU3 and OTU4, respectively. According to the ITU-T recommendation G.709, a single higher bit rate signal can be composed by a mix of different lower bit rate signals, then various lower bit rate signals, with different bit rates can be groomed into a single higher bit rate signal.

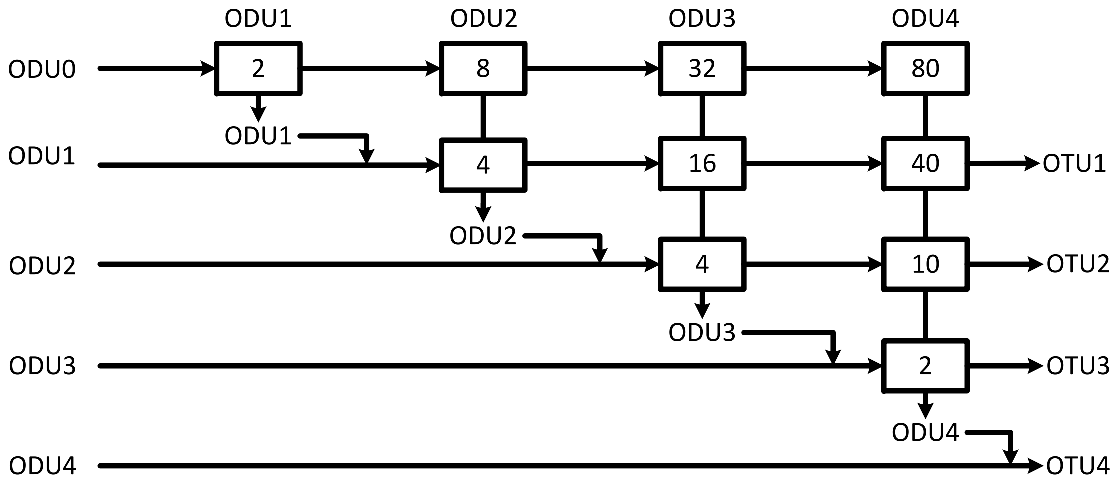


Figure 2.3: Grooming of OTN Signals

As depicted on figure 2.3, the grooming of eight ODU0 client signals results in an OTU2 line signal. However, two ODU0 client signals mixed with three ODU1 is another possibility form an OTU2 signal. The same reasoning is extensible to 100 Gbps line signals (OTU4) which are the line signals used in optimization models proposed in the next chapters.

2.1.2.2 Switching

In transport networks, currently, encapsulation, electrical switching and electrical grooming are usually realized using OTN. Regarding the original protocol, client traffic is encapsulated into ODU (optical data units) to be groomed and switched. The OTN technology is defined as circuit switching and depending on the layer where the switching occurs, two main types of switching were defined: electrical and optical.

2.1.2.2.1 Electrical Switching The use of circuit switched networks can introduce a waste of bandwidth due to the constant bit rate imposed by the OTN technology when the network becomes more and more packet dominated. Then, the Internet Engineering Task Force (IETF) defined the multi-protocol label switching - transport profile (MPLS-TP) as a customization of MPLS, in order to allow the possibility of packet switching transport networks. The MPLS-TP technology distinguishes the units of data through labels which are manipulated to provide an efficient bandwidth utilization. Then, there are different configurations for an electrical switch, but in general electrical switches are capable of receiving the traffic from an input interface,processing the traffic and switch to the appropriate output interface. The transparent transport mode does not perform switching in electrical domain. Then, the figure 2.4 shows an electrical switching capable node.

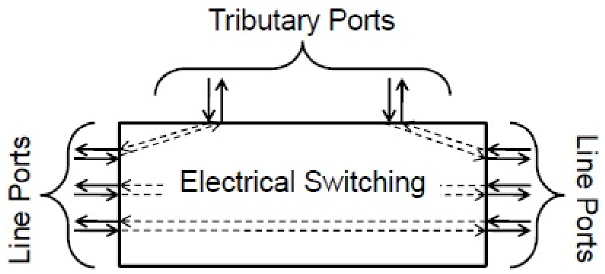


Figure 2.4: Scheme of a node for opaque transport mode network

Tributary ports are add/drop ports. Add ports are responsible for inserting traffic in the node from the access network and, inversely, the drop ports are used to extract traffic from the node. The line ports are used to make the connection between a node and the links of the core network through an higher bit rate signal (line signal).

2.1.2.2.2 Optical Switching In transparent and translucent networks, the optical layer has an important role in terms of switching. If a wavelength reaches a node in a transparent or translucent network, it can de switched to electrical domain to drop traffic information or can be correctly routed to the appropriate output port. In opaque networks there is no optical switching and the electrical layer is only used for wavelength multiplexing to perform WDM signals.

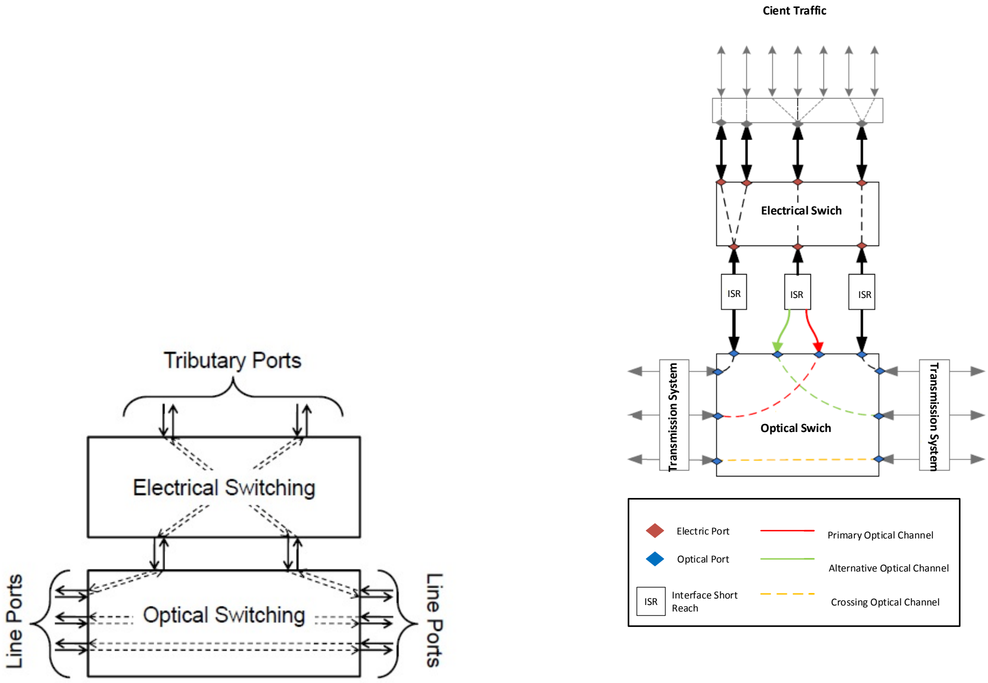


Figure 2.5: Translucent logical topologies

2.2 Transport modes

2.2.1 Physical Topology

Physical topology can be seen as a layout of a real optical network, the placement of an optical network components, i.e., nodes disposition and connection conceded by links. Hence, an optical network simulation can be advantageous to analyse this approach. Thus, can be helpful to consider a simple six node core optical network connected by links, so physical topology design:

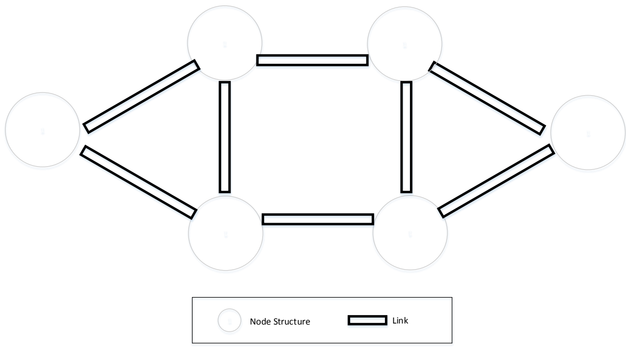


Figure 2.6: Nodes position and connection established by links located according to the real optical network.

As depicted in Figure 4.4, the main elements are nodes and links. In this specific case study the number of nodes (N) and the number of links (L) are 6 and 8 respectively. The degree of a node (δ_i) is given by the number of direct connection it has to other nodes.

2.2.2 Logical Topology

Optical or logical topology for networks is an approach that defines how components are connected. In the case of optical networks, logical topology is associated with the optical path segments in a single lightpath. Thus, each node may be optical directly connected to each other, or only optical connected to adjacent nodes or optical connected to suitable nodes. Therefore, these shorter optical paths along the route imposed by logical topology lead to a situation of three transport modes: Opaque, Transparent and Translucent. During this dissertation the focus will be opaque and transparent models.

2.2.3 Opaque

Opaque transport mode performs OEO(optical-electrical-optical) conversions at every intermediate node since origin to destination node. Thus, signal can be regenerated to provide signal quality conceded by electronic signal processing. In terms of topology, logical and physical topologies are the same, so each traffic route in logical topology corresponds to the link-by-link path imposed by optical fibers between each intermediate nodes until destination.

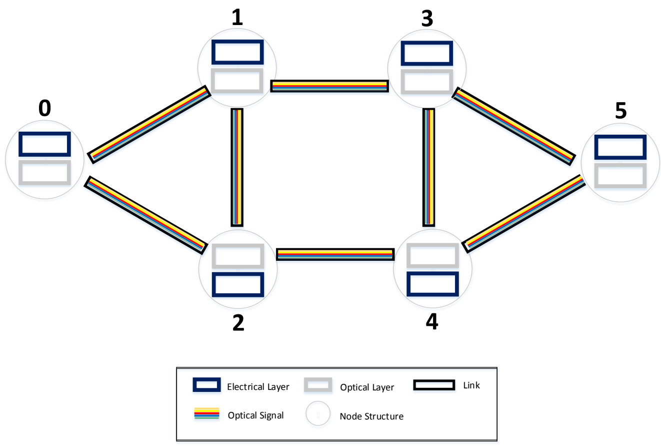


Figure 2.7: Opaque transport mode with a link-by-link grooming scheme.

As a deduction, at all consecutive nodes until egress node, line signal was subjected to OEO conversions. An advantage of this transport mode is that it eliminates accumulation of physical impairments and allows full flexibility in terms of switching and grooming. Thus, it can improve capacity utilization of optical channels by providing traffic grooming at every node.

2.2.4 Transparent

In transparent transport mode, the information travels in a defined route through optical channels between origin and destination nodes(i.e. lightpaths) always in optical domain, and consequently physical topology and logical topology are different 2.8. Generally this procedure includes the conservation of the same wavelength on all the links which compose the route, as known as, wavelength continuity constraint, as a consequence, grooming at intermediate nodes is not possible due to all-optical path applied end-to-end. Grooming scheme is single-hop because only client signals with the same destination and origin can be groomed in the same wavelength. Thus, figure 2.8 elucidate what is the optical topology for transparent transport mode from physical topology considered above.

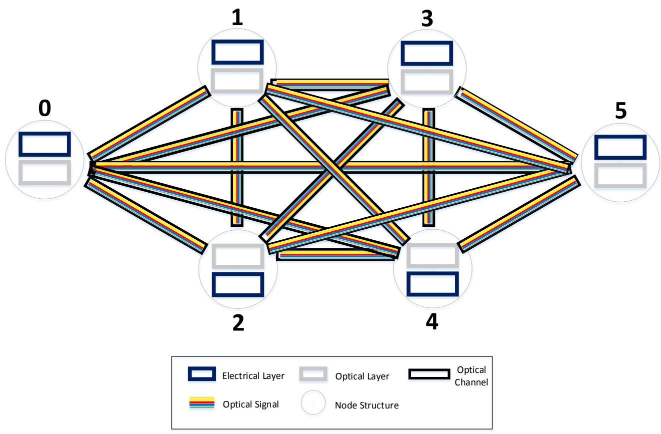


Figure 2.8: Logical topology for previous physical topology with each node connected to each other (Trnasparent Transport Mode).

Multicolor lines,obviously, assume the role of the optical signal. An advantage of this transport mode is the possibility for transportation of express traffic. Nevertheless, the quality of the optical signals degrade as they traverse the optical components along the route limiting the maximum optical reach of the signal. Another disadvantage is that the capacity utilization of optical channels is worse than in the opaque transport mode due to the grooming only in client signals with the same end-points.

2.2.5 Translucent

Translucent transport mode is a combination of previous transport modes. Thus, for the same physical topology there are several logical topologies. Within a single traffic route, the optical signal can cross some nodes regardless OEO conversions. However, to recover signal from all optical impairments and to optimize traffic grooming OEO conversions are needed. So, for a defined route there is some all-optical segments separated by regeneration, switching and grooming capable nodes. Then, using the same physical topology design as used in previous transport modes, figure 2.9 shows two possible examples of logical topologies.

In translucent transport mode a multi-hop grooming scheme is employed, so different source and destination nodes can share the same lightpath until reach some intermediate node common to both. Thus, in all network nodes, lightpaths carrying local or client traffic that need to be switched a different to a different lightpath are sent to electrical domain, while through traffic lightpaths are kept in optical domain.

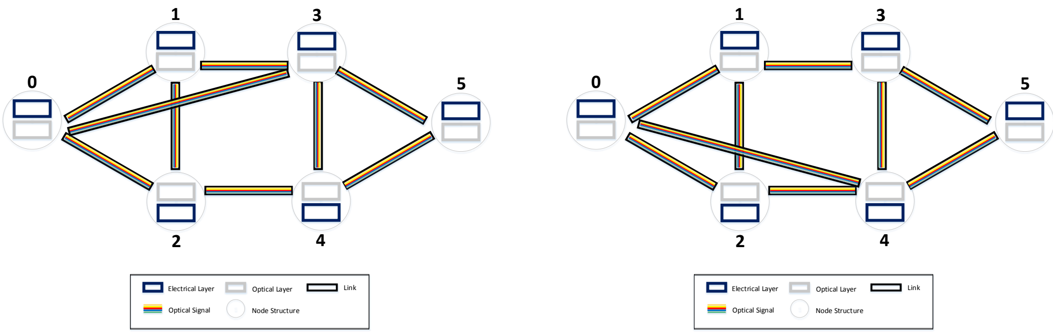


Figure 2.9: Translucent logical topologies

Transport mode	**Opaque**	**Transparent**	**Translucent**
Grooming			
Link-by-link	✓		
Single-Hop		✓	
Multi-Hop			✓
Intermediate nodes			
Electrical Switching	✓		✓
Optical switching		✓	✓
Grooming	✓		✓
Wavelength assignment	✓		✓
WDM multiplexing	✓	✓	✓
End nodes			
Encapsulation	✓	✓	✓
Electrical switching	✓	✓	✓
Grooming	✓	✓	✓
Wavelength assignment	✓	✓	✓
WDM multiplexing	✓	✓	✓

Table 2.1: Transport mode comparation

2.3 Network Survivability

Dedicated or shared protection are two main types of survivability applied for protection at any layer. Shared protection requires less spare capacity, employing protection reserved capacity for multiple working paths. A network planned for shared protection are feasible if the working paths that share the protection capacity have no links or intermediate nodes in common. This process is typically more vulnerable to multiple failures and slower to recover from a failure.

In dedicated protection backup resources are needed even before the failure occurrence. Depending on backup paths state, there will be two categories of dedicated path protection. In 1+1 mode, the backup path available is active, so both independent paths are transmitting at the same time and the choice of which is the best is the responsibility of the destination node. In opposition, the 1:1 dedicated protection activates the backup path, just in case of a failure on the primary path. After network restore, routes involved on previous failure may return to primary path (revertive mode) or proceed in backup path (non-revertive mode). In the following chapters will be proposed ways to implement dedicated path protection.

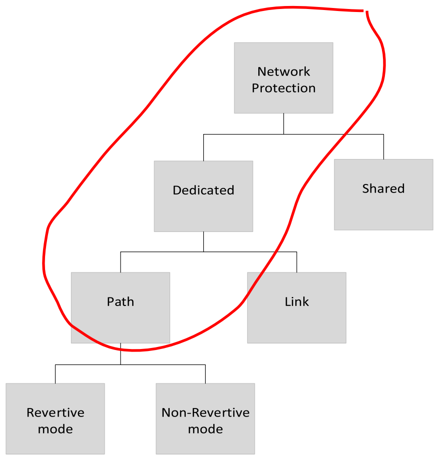


Figure 2.10: Network protection scheme.

2.4 Chapter summary

In terms of optical networking design, there are two basic concepts that are the physical topology and logical network.The physical topology is the physical components of the network and how they are arranged and the logical topology is how they work in terms of connection between the elements. Different types of logical topology in the same physical topology may have advantages or disadvantages desired by the network designer.[**?**] Thus, based on the characteristics necessary for the network, different logical topologies may be more useful.

Chapter 3

~~Integer Linear Programming~~ Models

Study of problems in which it is intended to minimize or maximize a cost function subject to a set of constraints is called optimization. The objective function is related to the set of constraints by the decision variables. Any decision variables values that satisfy the set of constraints are called admissible solution, in the cases that the solutions set is finite and the decision variables are restricted to integer values, it is called Integer Linear Programming (ILP). The problem optimal solution will be the values of an admissible solution(s) that obtains the higher or lower objective function value. The main goal is then to determine the non-negative values of the decision variables, such that all the linear equations or inequations are satisfied and the value of the objective function is maximized or minimized. Therefore, in order to solve the optimization models there are optimization software packages such as IBM ILOG CPLEX Optimization Studio, GLPK or Gurobi Optimizer. In this dissertation, lpsolve was the package used to solve optimization problems. The optimization models proposed in this chapter have a large number of variables and constraints dependent on the network topology and traffic. Then, it is required a software package as MATLAB to simplify the optimization problem description and effect a solution. The focus of current chapter is to describe two optimization models, based on opaque transport mode with protection. In section3.1, is described a real network protection topological design problem, and in the following two sections 3.2.1 and 3.2.2 are the proposals of optimization models.

3.1 Network protection topological design problem

First of all, let's consider a network consisting of a set of nodes, $V = \{1,\dots ,n\}$, and a set of bidirectional links, L = $\{\{i,j\} : i, j \in V, i < j\}$. The network in the form of an adjacency matrix called $G_{i,j}$. The communication between nodes is a demand, $D_{od} = \{[o, d] : o, d \in V, o < d\}$. For each type of client traffic, it must be created a bidirectional demand matrix. The result of the sum of this matrices is a 3-dimensional matrix D_{cod},depending on client traffic type in Gb/s, $c = \{1.25, 2.5, 10, 40, 100\}$. Thereby, it will be considered the reference network below as an example of a smaller network where ILP approach will be tested.

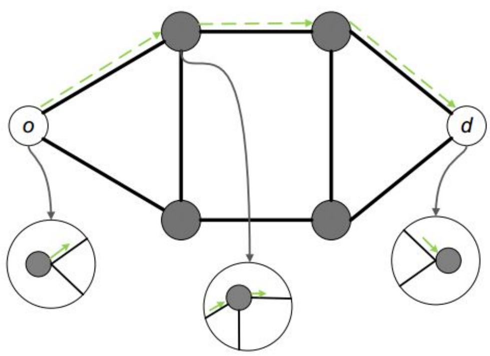


Figure 3.1: Nodes position and connection established by links located according to the real optical network.

The traffic demands go through one or more links to reach their destination and it is assumed that the path between the node o and d is the same as the path between the node d and o. Therefore, considering dedicated path protection, the integer variable f_{ij}^{od} indicates how many flows starting at o and ending in d cross the link (i, j). Thus, to be consistent, f_{ji}^{od} indicates if the link (i, j) is used in the protection path between nodes (o, d). A demand of traffic requires a reserved capacity in each transmission system depending on the type of client traffic (c).For instance, if there are four traffic demands at 40 Gb/s, so a bandwidth of 160 Gb/s will have to be reserved. Otherwise, in this dissertation will be considered line ports capable of transmitting at 100Gb/s. Each optical signal is composed by several optical channels and each optical channel has a corresponding wavelength. Then, variable W_{ij} is an integer variable indicating the number of 100 Gb/s optical channels between nodes i and j. Consequently, almost the same model may be applied for transparent transport mode, but this time using optical channels (W_{od}) between end nodes instead of using optical channels link-by-link along the path.

	Opaque	**Transparent**
Inputs	$G_{i,j}$ D_{cod}	G_{ij} d
Variables	f_{ij}^{od} W_{ij}	t_{ij}^{od} W_{od}

Table 3.1: Inputs and variables of opaque and transparent transport modes

The network depicted in figure 4.4 has the following information:

3.2 ILP models

Computational results obtained by ILP model are used to benchmark the heuristic results. Integer linear program proposed below, follow the standard form. The objective function is introduced by the keyword *"minimize"* or *"maximize"*, and the set of the constraints are introduced by the expression *"subject to"*. All ILP models proposed along this dissertation will be described using this structure.

3.2.1 Opaque with 1+1 Protection

The objective function of following ILP is a minimization of the sum of three variables: total number of links (i, j) in demand path for all demand pairs (o, d),total number of links (i, j) in demand protection path between each for all demand pairs (o, d), and still total number of optical channels in all links (i, j).

$$
\begin{aligned}
& \mathit{minimize} \quad \sum_{(i,j)} \sum_{(o,d)} f_{ij}^{od} + \sum_{(i,j)} W_{ij} && && (3.1) \\
& \mathit{subject\ to} \\
& \sum_{j \backslash \{o\}} f_{ij}^{od} = 2 && \forall (o,d) : o < d \ , \forall i : i = o && (3.2) \\
& \sum_{j \backslash \{o\}} f_{ij}^{od} = \sum_{j \backslash \{d\}} f_{ji}^{od} && \forall (o,d) : o < d \ , \forall i : i \neq o, d && (3.3) \\
& \sum_{j \backslash \{d\}} f_{ji}^{od} = 2 && \forall (o,d) : o < d \ , \forall i : i = d && (3.4) \\
& \sum_{(o,d):o<d} (f_{ij}^{od} + f_{ji}^{od}) + \sum_{c \in C} (B(c) D_{cod} \leq 100 W_{ij} G_{ij} && \forall (i,j) : i < j && (3.5) \\
& W_{ij} \leq 80 && \forall (i,j) : i < j && (3.6) \\
& f_{ij}^{od}, f_{ji}^{od} \in \{0,1\} && \forall (i,j) : i < j, \forall (o,d) : o < d && (3.7) \\
& W_{ij} \in \mathbb{N} && \forall (i,j) : i < j && (3.8)
\end{aligned}
$$

The objective function, to be minimized, is the expression(3.1). The flow conservation constraints are (3.2), (3.3) and (3.4) and ensures that, for each (o,d) pair, it routes one flow of traffic for all bidirectional links (i,j) of the demand path. The three following constraints have the same effect but are applied to the protection path. The constraint (3.8) guarantees the use of different links to the working path and the protection path.

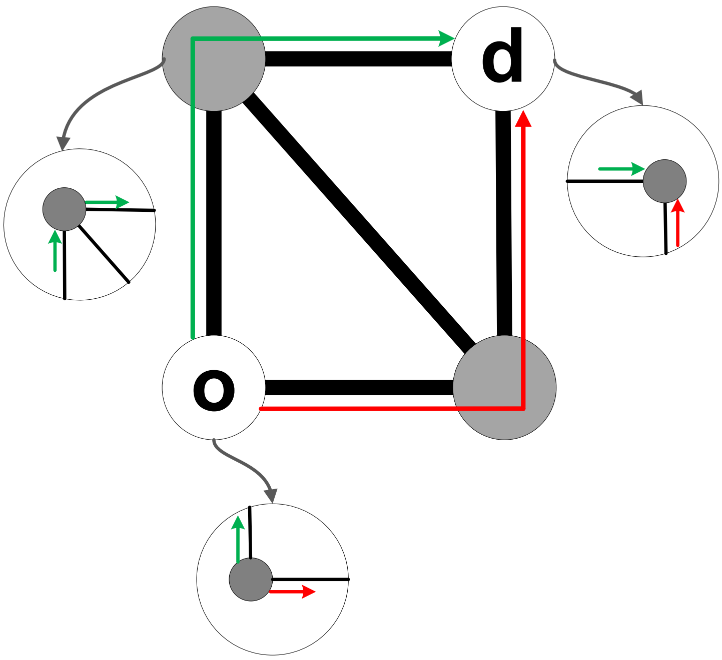


Figure 3.2: Example of two nodes in a network sent through disjoint links.

The constraint (3.9) ensures that the links used for protection and working path, times the demand traffic to these same links, can not be greater than the capacity of optical channels in the existing links. The constraint (3.10) ensures that the number of optical channel between node i and j does not exceed 80. Remaining constraints define the type of model variables.

3.2.2 Transparent with 1+1 Protection

The optimization model suggested for transparent transport mode with dedicated path protection intend to minimize the total number of optical channels between (o, d) that crosses link (i, j), total number of optical channel between (o, d) used for working traffic and total number of optical channel between (o, d) used for protection traffic. The main difference to the previous model is the grooming only in origin node instead of link-by-link grooming.

$$minimize \quad \sum_{(i,j)} \sum_{(o,d)} t_{ij}^{od} + \sum_{(o,d)} W_{od} \tag{3.9}$$

$$subject\ to$$

$$\sum_{j \backslash \{o\}} t_{ij}^{od} = 2 \qquad \forall (o,d) : o < d, \forall i : i = o \tag{3.10}$$

$$\sum_{j \backslash \{o\}} t_{ij}^{od} = \sum_{j \backslash \{d\}} t_{ji}^{od} \qquad \forall (o,d) : o < d\ , \forall i : i \neq o, d \tag{3.11}$$

$$\sum_{j \backslash \{d\}} t_{ji}^{od} = 2 \qquad \forall (o,d) : o < d, \forall i : i = d \tag{3.12}$$

$$\sum_{(o,d):o<d} (t_{ij}^{od} + t_{ji}^{od}) + xW_{od} \leq 80G_{ij} \qquad \forall (i,j) : i < j \tag{3.13}$$

$$t_{ij}^{od}, t_{ji}^{od} \in \mathbb{N} \qquad \forall (i,j) : i < j, \forall (o,d) : o < d \tag{3.14}$$

$$W_{od} \in \mathbb{N} \qquad \forall (o,d) : o < d \tag{3.15}$$

The objective function, to be minimized, is the expression(3.13). The constraint (3.14) and (3.15) ensures that the total number of optical channels between nodes o and d times the bit rate limit per channel, is greater or equal to the total client traffic between same nodes. Constraints (3.16), (3.17) and (3.18) are applied to match the number of optical channels which cross links (i, j) that comprise the path of (o, d) and the number of optical channels needed to satisfy all client traffic demands between o and d. Following three constraints (3.19), (3.20) and (3.21) have the same purpose but ,at this case, they are applied for protection. Optical channels between (i, j) for working path must be different than the optical channels for protection (3.22). Moreover, for all demands optical channels used for protection and for working traffic cannot be shared (3.23). In order to disallow network overload, the maximum network bandwidth need to be greater than the bandwidth needed for all used links (3.25). Last three constraints (3.25), (3.26) and (3.27) are related to the definition of the type of variables as positive integers.

3.3 LPSolve and Matlab implementation

MATLAB is ideally suited to handle linear programming problems. This powerful software can call lpsolve through an external interface or MEX-function. The control of lpsolve is provided by mxlpsolve driver and to simplify the user interface there is a LPSolve IDE [].

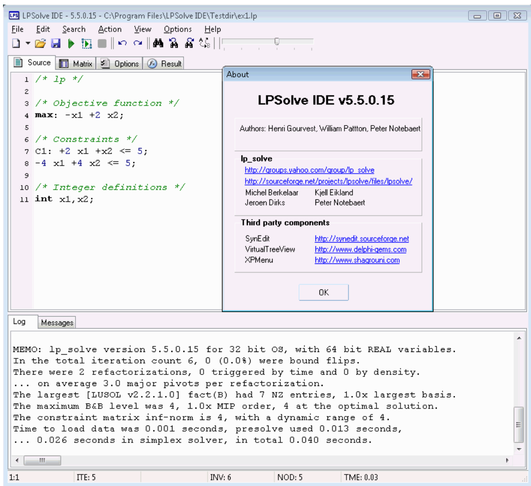


Figure 3.3: LPSolve integrated development interface [REF]

Optimization models presented in section 3.2.1 and 3.2.2 can be written on this format and to perform this code on MATLAB is necessary to follow the steps enumerated below, imposed by mxlpsolve driver:

1. Create and initialize of a new model with total number of variables.
2. Set the coefficients of the objective function.
3. Add the constraint vector with the coefficients and independent terms.
4. Set variable types.
5. Create ilp to an lp file
6. Solve the model
7. Returns the value of the objective function
8. Returns the value of the variables

3.4 ILP results

3.4.1 Opaque transport mode

Using homogeneous traffic:

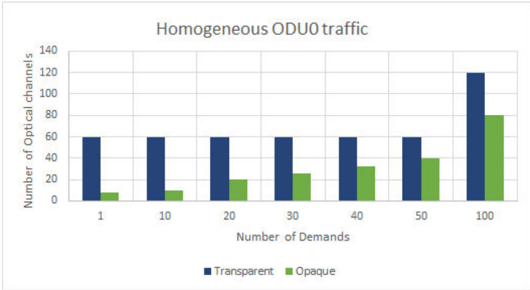


Figure 3.4: LPSolve integrated development interface [REF]

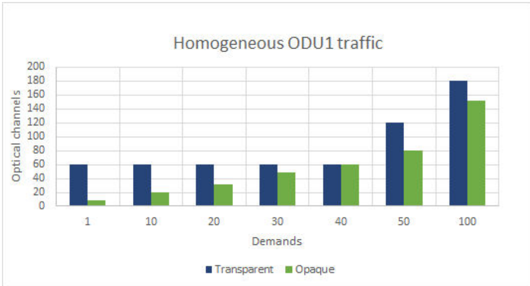


Figure 3.5: LPSolve integrated development interface [REF]

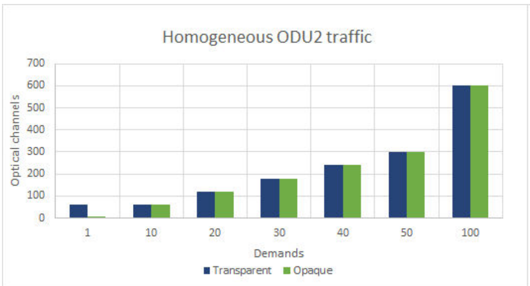


Figure 3.6: LPSolve integrated development interface [REF]

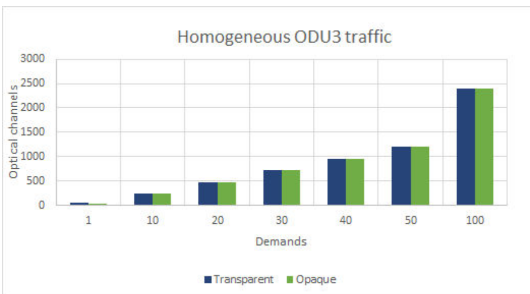


Figure 3.7: LPSolve integrated development interface [REF]

Heterogeneous traffic 10 demands:

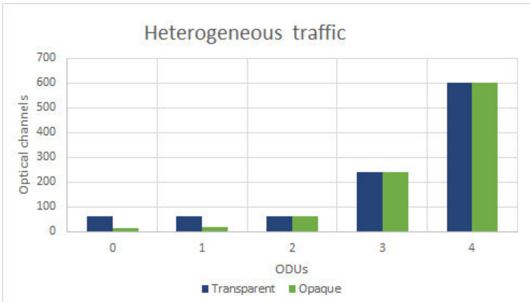


Figure 3.8: LPSolve integrated development interface [REF]

3.5 Chapter Summary

Chapter 4

Heuristics

Heuristic approaches are techniques for solving a problem, faster than optimal methods and able to find an acceptable solution. When networks are too large the ILP models can be very slow to obtain the solution. In this chapter , algorithms are proposed based on heuristics and their implementation in networks design software. The software was chosen, because it is open source and, consequently, easy to employ in academic projects. There are some commonly used heuristics such as genetic algorithm or simulated annealing. The grooming and routing algorithms presented in this chapter involve a graphical user interface developed for Net2Plan tool. Thus, the first section is an overview of the Net2Plan tool , focusing all the steps for an offline simulation and how people can contribute to the Net2Plan code repository. In section 4.3 there is a description of how the program works, the developers involved in the program and a brief approach to the interface from creating traffic matrices and network topology (inputs) until obtain the number of necessary transmission systems and the cost of the designed network. The real case study is the same as proposed in Chapter 3 (NSFNET) and the six-node reference network was used to prove the algorithms quality. In section 4.3.2, a succinct explanation about the logical topology algorithm implementation in Net2Plan, starting with the input parameters to the resulting interface. Grooming alghoritm is discussed in the next section 4.3.3 and the network state in terms of grooming and routing information after its execution. Concerning publication of the results, a specification of link and node features or components and network cost based on the price of most expensive components defined by the network design user as depicted on chapter4.3.4. The last section is a brief summary of the principal terms to retain.

4.1 Heuristic routing

Regarding the heuristic approach, an algorithm for routing and grooming was implemented, which will be explained in three steps. The pseudo code will be shown in a flowchart using rounded rectangle shapes to symbolize the beginning and the end of the program, the parallelogram shape indicates a point where there is input to or output from the program, the diamond shape symbolizing a decision point, the rectangle shape indicating the assignment of a value to a variable, constant or parameter, and the hexagon shows the beginning of a repetition.

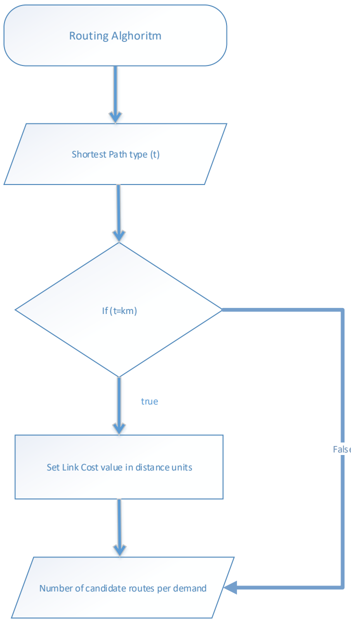


Figure 4.1: Net2Plan user interface for traffic matrices creation

Routing algorithm begins with the definition of the input parameter. The variable "t" is an input variable, which is defined by the user. The previous variable can assume two possible values: "hops" or "km". If the units of distance are the number kilometres, then it is necessary to assign a virtual cost to the links that will be used to decrease the computing time of the algorithm used to find the shortest path. Through the Dijkstra algorithm the paths sorted by distance units are added to a list and ordered by node pair. The number of candidate routes per node pair depends on the user, and can be defined through graphical interface setting the correspondent variable. The performance of the algorithm can be compromised if the number of routes or the network topology is too large.

Once the list of candidate routes has been filled, it is necessary to find the primary and protection paths for each demand. So, for each demand will run the code below.

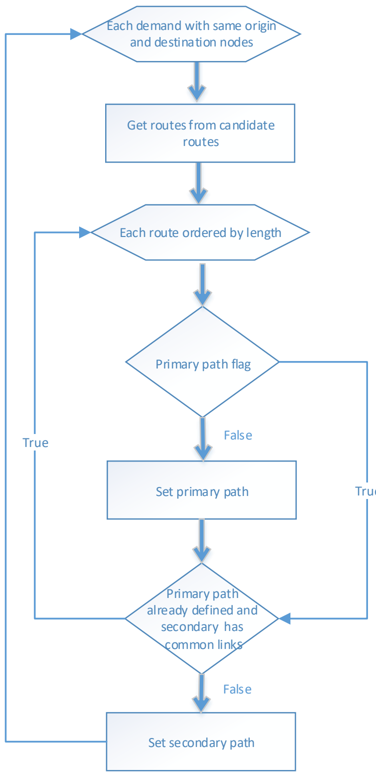


Figure 4.2: Net2Plan user interface for traffic matrices creation

The second step of routing algorithm begins with the search of candidate routes for the demand. The routes are analysed one by one, starting from the smallest to the largest. Then, the first (shortest) is the primary path and this must be set if the flag is disable. If the primary path flag is enabled, the program flow jumps to the decision point to verify if the route does not have links in common with the first path. Then, if it is verified, the protection path is the current route. On the other hand, if the route has at least a common link, the next step is try another route. The routing ends when the protection path of the last demand was found.

4.2 Heuristic grooming

After traffic routing decision, the consequent step is traffic aggregation. The algorithm begins by getting the routes (primary and protection path) already saved for each node pair. The input parameter of this algorithm is the type of grooming desired, which is represented in the flowchart as "g".

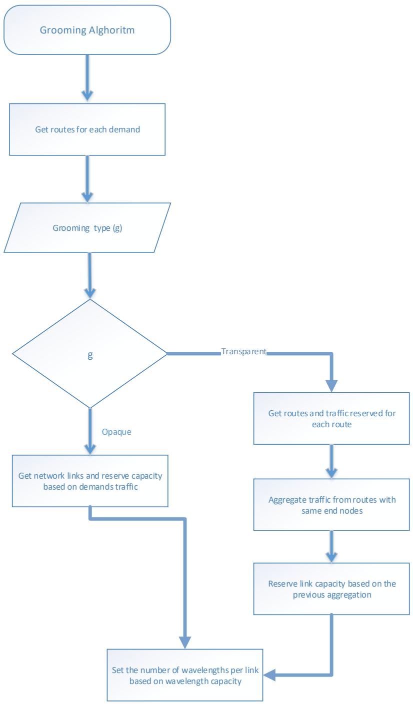


Figure 4.3: Net2Plan user interface for traffic matrices creation

The consequence of the proposed type of grooming is the branch of flowchart. In Opaque form, the procedure starts by obtaining all links and the capacity based on traffic per demand. The sum of traffic that crosses the same link give the information of carried traffic. After traffic aggregation, dividing the total carried traffic by the wavelength capacity it is possible to get the number of wavelengths (line transmission systems) in each link. Although, if logical topology is Transparent the plan of action is different. The branch starts by getting reserved traffic capacity in each path. Then, using routes from different demands with common end nodes it aggregates the traffic of these routes. After this step, knowing the links that constitute the path, it is reserved the capacity required in each link. In order to know the number of wavelengths, the reserved traffic capacity in each link need to be divided by wavelength capacity as in the previous grooming type. Obviously, this flowcharts are simplified schemes which express as much as possible the complexity of hundreds of lines of code.

4.3 Net2Plan Aproach

The Net2Plan tool began in 2011, with the aim of being used as a material for educational in Universidad Politcnica de Cartagena. At this time, there are already many simulators available for network planning as,for example, SIMTON ,OPNET ,NIST Merlin or TONetS [REF]. Up to now, the lastest version of Net2Plan tool is version 0.4.0. All alghoritms were developed in JAVA language, and the specific alghoritms presented in this dissertation were developed using Eclipse for JAVA developers IDE. The first step to start the simulation is the creation of traffic matrices.

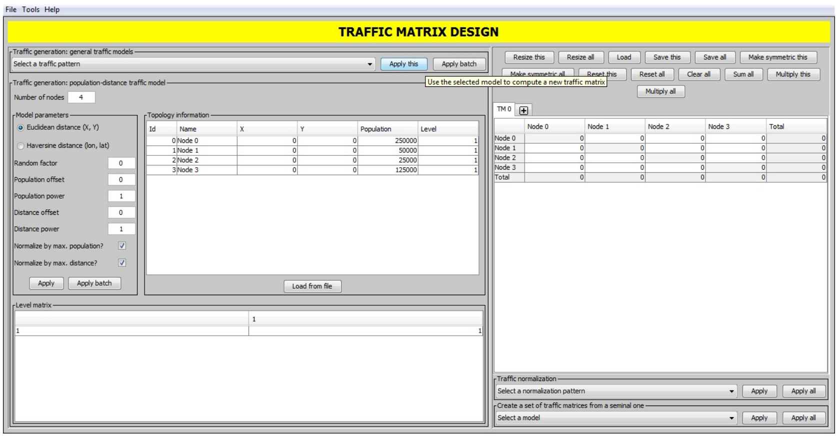


Figure 4.4: Net2Plan user interface for traffic matrices creation

The matrices created can be defined as a matrix with constant traffic, so the amount of traffic between all node pair are the same. Another possibility is choose randomly the traffic for each demand and there is also an option to choose automatically the number of nodes and the traffic amount or define manually all parameters. The results presented in this dissertation are obtained defining matrices manually to ensure that the ILPS and heuristics have the same inputs. After the matrices creation for each tipe of client bit rate (ODU0, ODU1...) is needed a network topological design.

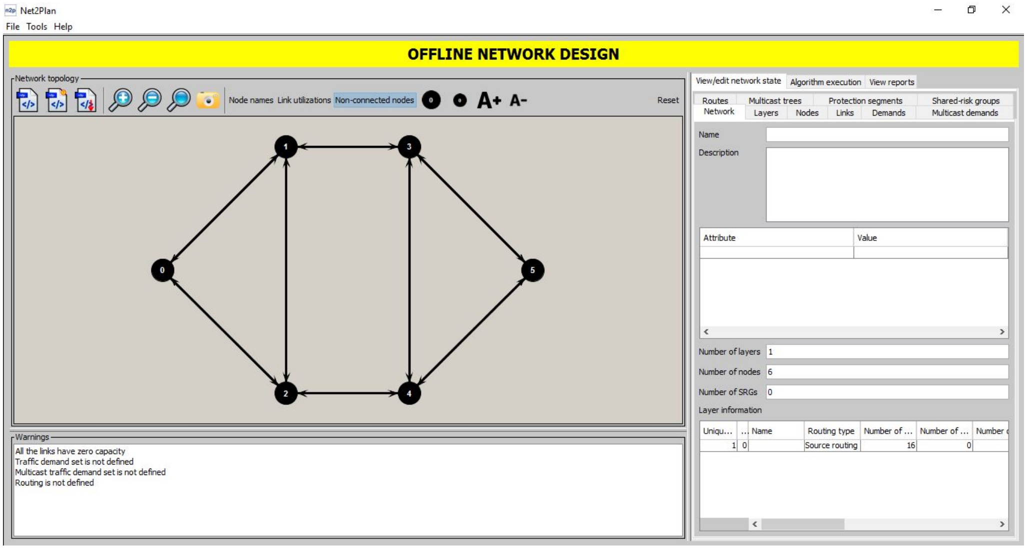


Figure 4.5: Net2Plan user interface for reference network topological design

In figure 5.2 is shown how the real network suggested in chapter 3 is designed in Net2Plan. Each black narrow symbolizes a bidirectional link. Once created the design of the network and the traffic matrices defined all inputs are set. Thus, the network is ready for routing and grooming.

4.3.1 Join Traffic Matrices Alghoritm

Having the basic physical topology created, the next step is to load the demand set into the network. In the case where there are multiple traffic matrices an algorithm was developed to aggregate these in order for it to be possible to load all demands. In order to deal with different client traffic in OTN units, it was developed the *"joinTrafficMatrices"* algorithm to convert all traffic matrices to ODU0. Besides converting the different ones to ODU0 it also creates an attribute in each demand indicating the type of signal before converting.

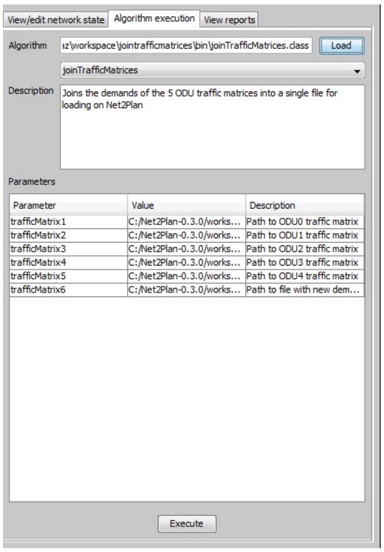


Figure 4.6: Net2Plan join traffic matrices alghoritm input parameters

As shown in figure 4.6 above, using five different paths for the client traffic matrices in ODU0, ODU1, ODU2, ODU3 and ODU4 as inputs and the last path to save the resultant demand set, is possible to create a matrix with total traffic regarding the original client traffic type. Thus, to set all network design inputs is just needed to load the demand traffic set to the network topology previously designed.

4.3.2 Logical Topology Alghoritm

The *"logicalTopology"* algorithm accepts only one input parameter and it creates a new layer depending on the transport mode chosen. This step is needed before network routing and grooming, because these two operations depend on the logical topology of the network. Besides creating this new Layer, the algorithm also copies the demands to that layer and defines the logical links based on the length of the physical ones.

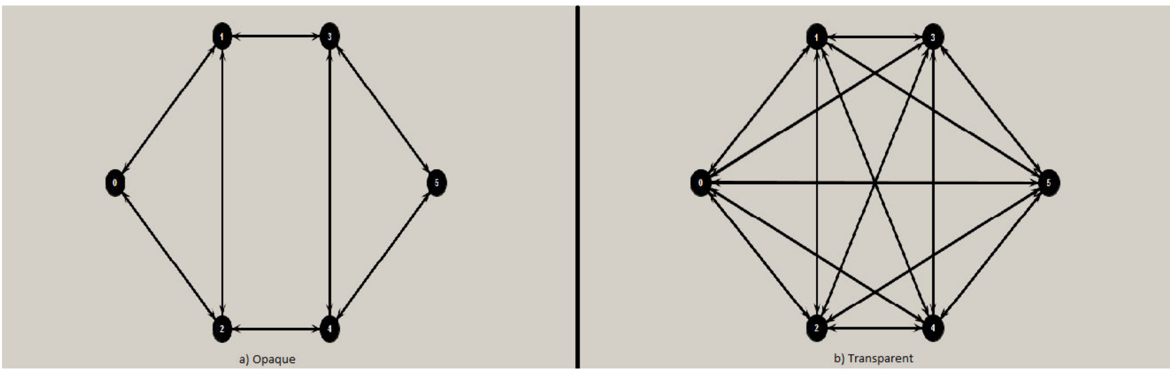


Figure 4.7: Net2Plan logical topology for reference network physical topology based on a) Opaque transport mode b)Transparent transport mode

As depicted in figure 5.3, an Opaque transport mode the traffic goes through an OEO conversion at every node and as such the logical topology is the same as the physical one. In the Transparent mode, there are no regeneration in intermediate nodes, so the logical topology shows that the traffic between nodes flows directly without grooming with signals from another source. Thus, in optical layer, for opaque transport mode the topology of the network are equal to the physic one and for transparent transport mode is a full mesh network topology.

4.3.3 Grooming and Routing Alghoritm

In this section, it is presented an algorithm to perform grooming an routing with dedicated path protection scheme. This algorithms are based on reducing the number of wavelengths needed for the network to carry all traffic. One way to minimize the number of wavelengths is minimizing the number of links for each path between all node pairs. The consequence of the reduction of the number of links is to decrease the number of necessary transmission systems leading to a lower cost of nodes.

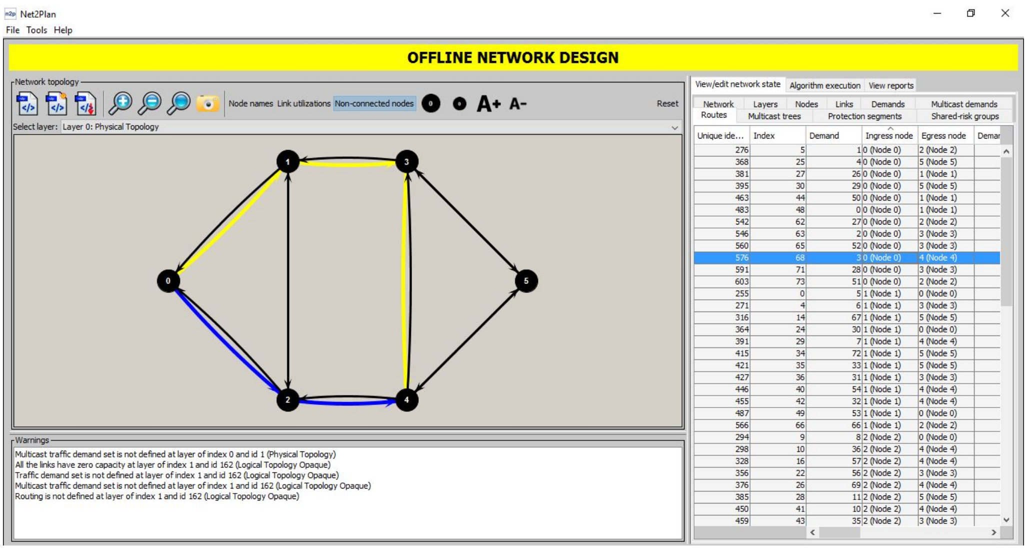


Figure 4.8: Net2Plan route using *grooming dedicated* alghoritm

Thus, this approach is done based on a shortest path algorithm where the routes for each demand are created based on the shortest number of hops needed to reach the destination node.The protection path for each demand, as shown in figure 4.8, is created using the same methodology, so the protection path is the second shortest loop disjoint path. The routes are made through the use of existing classes in Net2Plan, and the shortest path is computed using Dijkstra algorithm. The blue lines symbolize the working path and the protection segments are depicted in yellow. Grooming is different for the modes described above. Although, it is implemented in the same physical topology , i.e. the first layer in the program. The inputs, defined by network designer, of this algorithm are the number of routes computed per demand in order to find two disjoint shortest loopless paths and the wavelength capacity for each transmission system in ODU0.

4.3.4 Reports

The display of results was also a concern in the development of algorithms, a report was created in HTML language that can be written to a file or open through web browsers. The *networkCost* algorithm, which has as inputs the elements with higher cost. The most expensive elements are optical ports and equipments (OLT, OXC and OXC ports, Transponders and amplifiers) and electrical ports and equipments (EXCs, EXC ports).

The number of optical channels is already calculated for each link in subsection 4.3.3 and, consequently, the number of transmission systems. Thus, in order to make a characterization of the links is required the number of optical amplifiers. The result of this link information in Net2Plan report for the reference network is:

Node Pair	Wavelengths forward	Wavelengths backward	Amplifiers forward	Amplifiers backward
Node 0 -» Node 1	2	2	5	5
Node 1 -» Node 0	2	2	5	5
Node 0 -» Node 2	2	2	5	5
Node 2 -» Node 0	2	2	5	5
Node 1 -» Node 2	4	4	3	3
Node 2 -» Node 1	4	4	3	3
Node 1 -» Node 3	3	3	3	3
Node 3 -» Node 1	3	3	3	3
Node 2 -» Node 4	3	3	3	3
Node 4 -» Node 2	3	3	3	3
Node 3 -» Node 4	3	3	3	3
Node 4 -» Node 3	3	3	3	3
Node 3 -» Node 5	3	3	5	5
Node 5 -» Node 3	3	3	5	5
Node 4 -» Node 5	3	3	5	5
Node 5 -» Node 4	3	3	5	5

Figure 4.9: Reference network link information using random traffic matrices

4.4 Heuristic results validation

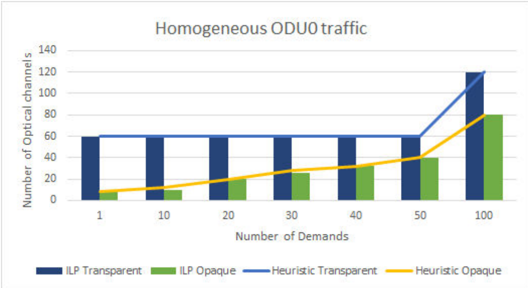


Figure 4.10: Reference network link information using random traffic matrices

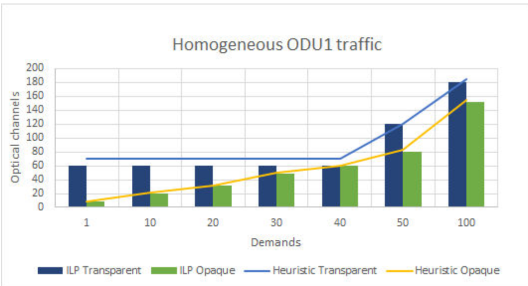


Figure 4.11: Reference network link information using random traffic matrices

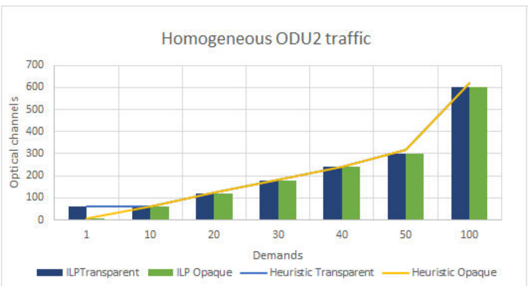


Figure 4.12: Reference network link information using random traffic matrices

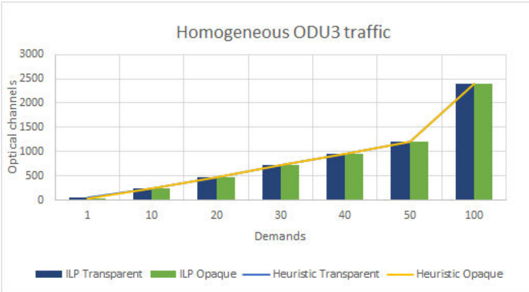


Figure 4.13: Reference network link information using random traffic matrices

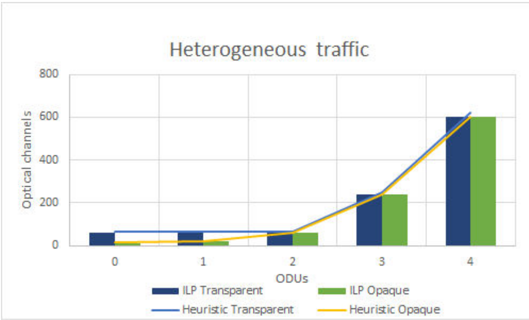


Figure 4.14: Reference network link information using random traffic matrices

Chapter 5

Case Study

After validating the quality of the algorithms implemented in Net2Plan, let's consider a realistic network. NSFNET refers to a program sponsored by National Science Foundation to support and foment advanced networking among United States research and education institutions. The way the nodes are geographically arranged can be seen from the figure 5.1.

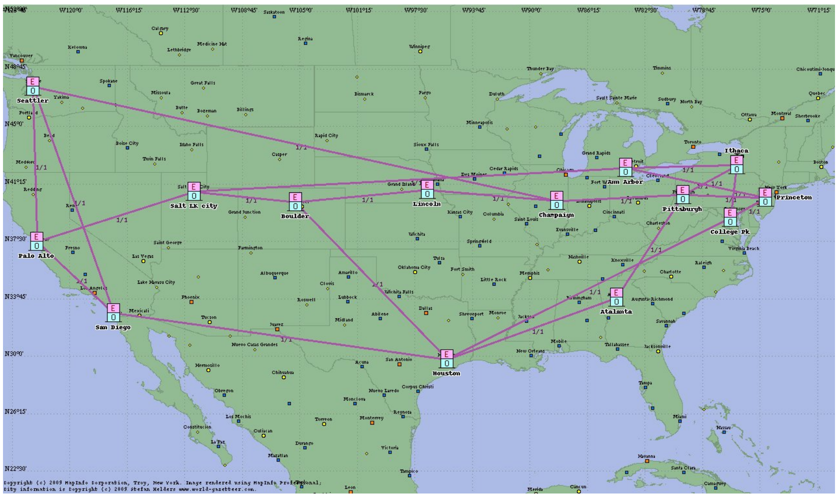


Figure 5.1: NSF Network topology. [REF]

The network represented above is composed of fourteen nodes and twenty one bidirectional links. The result of dividing the number of links per node by the number of nodes is the average degree of the nodes in this network. All nodes have less than four and more than two links, so major nodal degree is 4 and minor is 2. Then, there are no isolated nodes (node with only one connection) and it's important because the dedicated path protections requires disjoint paths, so each node must have at least two links. The maximum number of connections per node is also important because the larger it is, the fewer will be the number of hops suffered by each demand from the origin to the destination. Obviously, the number of links per node could be higher, but it would compromise the price to be paid for the network.

Constant	**Description**	**Value**
N	Number of,Nodes	14
E	Number of Bidirectional Links	21
$<\delta >$	Node out-degree (max,min, avg)	4,2,3.0
$<h >$	Mean Number of Hops,for Working Paths	2.14
$<h'>$	Mean Number of Hops,for Backup Paths	3.60
$<s >$	Mean Link Length (km)	1086

To begin the analysis of traffic routing and aggregation it is necessary to consider the matrix of demands (D):

$$D = \begin{bmatrix} 0 & 12 & 34 & 15 & 12 & 54 & 12 & 12 & 43 & 12 & 12 & 23 & 12 & 11 \\ 12 & 0 & 60 & 12 & 35 & 12 & 23 & 20 & 12 & 36 & 12 & 23 & 33 & 13 \\ 34 & 60 & 0 & 15 & 12 & 12 & 12 & 18 & 14 & 12 & 21 & 23 & 12 & 12 \\ 15 & 12 & 15 & 0 & 21 & 18 & 12 & 12 & 43 & 12 & 12 & 23 & 12 & 11 \\ 12 & 35 & 12 & 21 & 0 & 12 & 12 & 12 & 29 & 12 & 12 & 26 & 12 & 15 \\ 54 & 12 & 12 & 18 & 12 & 0 & 42 & 30 & 12 & 12 & 21 & 12 & 30 & 84 \\ 12 & 23 & 12 & 12 & 12 & 42 & 0 & 30 & 48 & 12 & 12 & 14 & 9 & 54 \\ 12 & 20 & 18 & 30 & 12 & 30 & 30 & 0 & 12 & 48 & 12 & 60 & 30 & 72 \\ 43 & 12 & 14 & 25 & 29 & 12 & 48 & 12 & 0 & 12 & 12 & 54 & 12 & 66 \\ 12 & 12 & 21 & 12 & 12 & 21 & 12 & 12 & 12 & 12 & 0 & 12 & 12 & 12 \\ 23 & 23 & 24 & 12 & 26 & 12 & 14 & 60 & 54 & 12 & 12 & 0 & 12 & 12 \\ 12 & 33 & 12 & 19 & 12 & 30 & 9 & 30 & 12 & 36 & 12 & 12 & 0 & 11 \\ 11 & 13 & 12 & 11 & 15 & 84 & 54 & 72 & 66 & 12 & 12 & 12 & 11 & 0 \end{bmatrix}$$

This traffic matrix was generated randomly through Net2Plan. The total amount of traffic in the NFSNET network considering this demands matrix is 5Tb/s. It should be noted that the total number of columns and rows is equal to the number of nodes and the main diagonal of the matrix is composed of zeros since it does not make sense for a node to send traffic to itself. Once traffic has been defined, the next step is to upload the shape of the network to the dimensioning software.

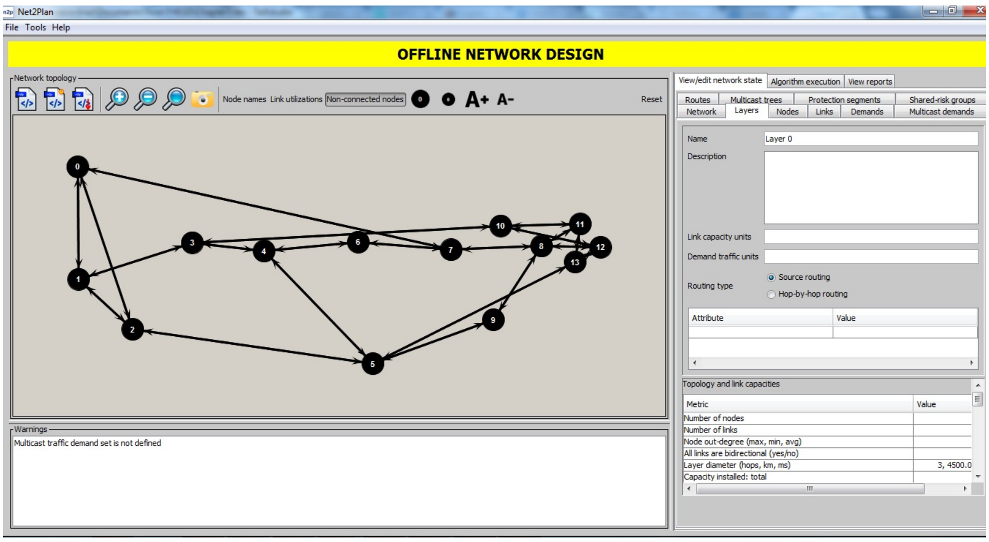
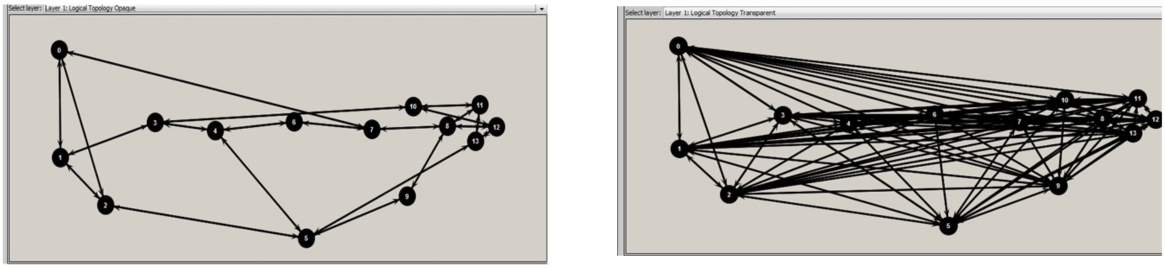


Figure 5.2: Net2Plan user interface for NSFNET topological network design

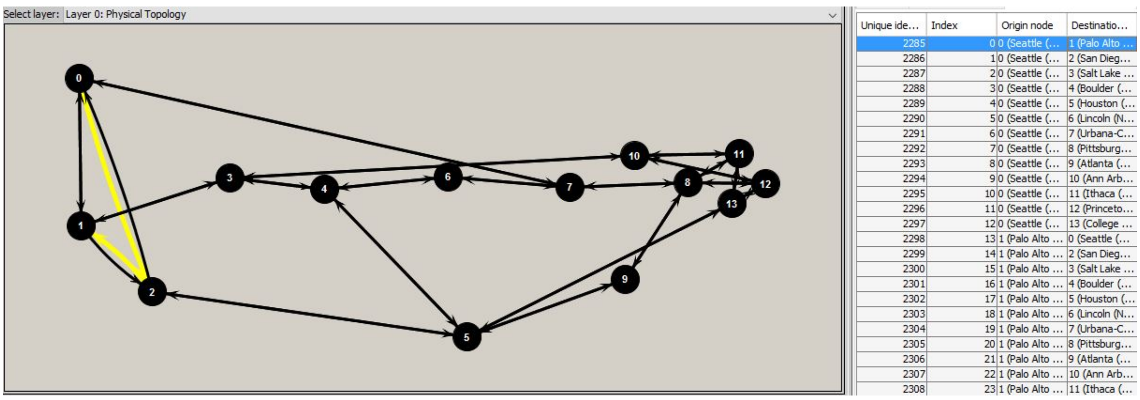
In the logical layer the network aspect for the Opaque and Transparent topology will be as follows:



a) Opaque b) Transparent

Figure 5.3: Net2Plan logical topology for NSFNET physical topology based on a) Opaque transport mode b)Transparent transport mode

All twenty one network links have the source and destination node attributes corresponding to the cities they belong, for instance, the link between node 0 and 2 has de attribute origin node equals to Seattle and destination San Diego. Obviously, to be consistent all nodes have the length attribute corresponding to the distance in kilometres they cross in the real context. Although there are 182 demands corresponding to traffic requests from each of the fourteen nodes to all the other thirteen, only 91 routes are needed because the path from "o" to "d" is assumed to be the same as "d" to". The computation of the routes obeys the same reasoning.



Unique ide...	Index	Origin node	Destinatio...
2285	0	0 (Seattle (...	1 (Palo Alto ...
2286	1	0 (Seattle (...	2 (San Dieg...
2287	2	0 (Seattle (...	3 (Salt Lake ...
2288	3	0 (Seattle (...	4 (Boulder (...
2289	4	0 (Seattle (...	5 (Houston (...
2290	5	0 (Seattle (...	6 (Lincoln (N...
2291	6	0 (Seattle (...	7 (Urbana-C...
2292	7	0 (Seattle (...	8 (Pittsburg...
2293	8	0 (Seattle (...	9 (Atlanta (...
2294	9	0 (Seattle (...	10 (Ann Arb...
2295	10	0 (Seattle (...	11 (Ithaca (...
2296	11	0 (Seattle (...	12 (Princeto...
2297	12	0 (Seattle (...	13 (College ...
2298	13	1 (Palo Alto ...	0 (Seattle (...
2299	14	1 (Palo Alto ...	2 (San Dieg...
2300	15	1 (Palo Alto ...	3 (Salt Lake ...
2301	16	1 (Palo Alto ...	4 (Boulder (...
2302	17	1 (Palo Alto ...	5 (Houston (...
2303	18	1 (Palo Alto ...	6 (Lincoln (N...
2304	19	1 (Palo Alto ...	7 (Urbana-C...
2305	20	1 (Palo Alto ...	8 (Pittsburg...
2306	21	1 (Palo Alto ...	9 (Atlanta (...
2307	22	1 (Palo Alto ...	10 (Ann Arb...
2308	23	1 (Palo Alto ...	11 (Ithaca (...

Figure 5.4: Protection traffic route between Seattle and Palo Alto

5.1 Opaque Topology

After presenting the network to be studied and its physical characteristics and geographic location it is important to apply the heuristics presented in the previous chapter. Running routing and grooming algorithm in Net2Plan, the following relevant information is obtained:

Description	**Value**
Number of demands	182
Total traffic in ODU0	4000
Average route length (km)	2351.350
Average link capacity reserved for protection in ODU0	79.264
Total unprotected traffic	0

The algorithm is able to protect the totality of the traffic by reserving an average of 80 ODU0 per link. It is essential not to forget that 80 ODU0 is equivalent to 100 Gb, approximately the capacity of each wavelength considered during this dissertation. The average distance per route is a little over 2000km. The value may seem great, but considering the size of the links (1086) reveals a low number of hops per route.

5.1.1 Network Cost

Regarding network cost, the approach will be based on three major factors: cost of the electrical part of the nodes, cost of the optical part of the nodes and cost of the links. Then, besides the equipment costs, this report also has the parameter *span*. The value of this variable is used to calculate the number of optical amplifiers needed in the network:

$$N^R = \sum_{l=1}^{L} \left(\left\lceil \frac{len_l}{span} \right\rceil - 1 \right) \tag{5.1}$$

- $N^R \rightarrow$ Total number of regenerators/amplifiers

- $len_l \rightarrow$ Length of link

- $span \rightarrow$ Distance between amplifiers

Thus, the number of regenerators or amplifiers is calculated based on the approximation (5.1). The equation means that the number of regenerators is given the division of the size of each link by the desired spacing between amplifiers minus one. The reason for the subtraction is to prevent the amplifier closer to the destination node from being unnecessary.

$$C_L = \left(\gamma_0^{OLT} \times L\right) + \left(\gamma_1^{OLT} \times \tau \times W\right) + \left(N^R \times c^R\right) \quad (5.2)$$

- C_L → Links Cost
- γ_0^{OLT} → OLT cost in Euros
- L → Number of unidirectional Links
- γ_1^{OLT} → Transponder cost in Euros
- τ → Traffic per port
- W → Total number of optical channels
- N^R → Total number of optical amplifiers
- c^R → Optical amplifiers cost in Euros

The cost of links includes the transmission systems (OLT - Optical line termination) for each link plus a parcel depending on the optical channels and bandwidth summing with the number of amplifiers and their cost. After analysing how to calculate the cost of links, will be considered the approximation to the cost of nodes, starting with the electrical layer.

$$C_{exc} = (\gamma_{e0} \times N) + (\gamma_{e1} \times \tau \times 2 \times P_{TRIB}) \quad (5.3)$$

- C_{exc} → Electrical Equipment Cost
- γ_{e0} → EXC cost in Euros
- N → Number of Nodes
- γ_{e1} → EXC port cost in Euros per Gb/s
- τ → Traffic supported by optical channel
- P_{TRIB} → Number of tributary ports

The equation (5.3) suggest the price of an electrical node based on the price of the electrical cross connect(electrical switching) for each node. In addition, there is a price that depends on the traffic that arrives at that node and consequently the number of ports. Then, the cost depends on the ports costs per Gb/s, the traffic per optical channel and 2 times the number of tributary ports because it's needed one for input client traffic and one for output at the node point of view. All of this equipment is used in opaque topology.

$$C_{oxc} = (\gamma_{o0} \times N) + \gamma_{o1} \times (P_{LINE} + P_{TRIB}) \tag{5.4}$$

- $C_{oxc} \rightarrow$ Optical Equipment Cost
- $\gamma_{o0} \rightarrow$ OXC cost in Euros
- $N \rightarrow$ Number of Nodes
- $\gamma_{o1} \rightarrow$ OXC port cost in Euros
- $P_{TRIB} \rightarrow$ Number of tributary ports
- $P_{LINE} \rightarrow$ Number of line ports

The equation (5.4) suggest the price of an optical node based on the price of the optical cross connect(optical switching) for each node. In addiction, there is a price depending on the cost of ports times the sum of tributary ports and the ports used to send an optical channel (line ports). Lastly, the price of node components and amplifiers span which will be the inputs of network cost are shown in the image below. It's difficult to know the real prices of network components, so the prices are just an approximation.

Parameter	Value	Description
EXC	10000	EXC cost in euros
EXCPort	1000	EXC port cost in euros pe...
OLT	15000	OLT cost in euros
OXC	20000	OXC cost in euros
OXCPort	2500	OXC port cost in euros
Transponder	5000	Transponder cost in euros
opticalAmplifier	4000	Optical amplifier cost in e...
span	100	Separation between rege...

Figure 5.5: Network cost inputs

5.1.2 Opaque topology results

Name	Trib ports in	Trib ports out	Line Ports in	Line Ports out	Total Ports in	Total Ports out
Seattle (WA)	13	13	66	66	79	79
Palo Alto (CA)	13	13	64	64	77	77
San Diego (CA)	13	13	63	63	76	76
Salt Lake City (UT)	13	13	88	88	101	101
Boulder (CO)	13	13	96	96	109	109
Houston (TX)	14	14	120	120	134	134
Lincoln (NE)	13	13	53	53	66	66
Urbana-Champaign (IL)	13	13	87	87	100	100
Pittsburgh (PA)	13	13	103	103	116	116
Atlanta (GA)	13	13	53	53	66	66
Ann Arbor (MI)	13	13	68	68	81	81
Ithaca (NY)	13	13	55	55	68	68
Princeton (NJ)	13	13	72	72	85	85
College Park (MD)	14	14	70	70	84	84
Total	184	184	1058	1058	1242	1242

Figure 5.6: Opaque ports per node

Category		Cost	Total
Link Cost	OLT	630,000	155,278,000
	Transponders	153,000,000	
	Amplifiers	1,648,000	
Node Cost	Electrical	37,840,000	37,840,000
	Optical	0	
Total Network Cost			193,118,000

Figure 5.7: Opaque cost given by Net2Plan

5.1.3 Transparent topology results

Name	Trib ports in	Trib ports out	Line Ports in	Line Ports out	Total Ports in	Total Ports out
Seattle (WA)	13	13	66	66	79	79
Palo Alto (CA)	13	13	64	64	77	77
San Diego (CA)	13	13	63	63	76	76
Salt Lake City (UT)	13	13	88	88	101	101
Boulder (CO)	13	13	96	96	109	109
Houston (TX)	14	14	120	120	134	134
Lincoln (NE)	13	13	53	53	66	66
Urbana-Champaign (IL)	13	13	87	87	100	100
Pittsburgh (PA)	13	13	103	103	116	116
Atlanta (GA)	13	13	53	53	66	66
Ann Arbor (MI)	13	13	68	68	81	81
Ithaca (NY)	13	13	55	55	68	68
Princeton (NJ)	13	13	72	72	85	85
College Park (MD)	14	14	70	70	84	84
Total	184	184	1058	1058	1242	1242

Figure 5.8: Transparent ports per node

Category		Cost	Total
Link Cost	OLT	630,000	531,278,000
	Transponders	529,000,000	
	Amplifiers	1,648,000	
Node Cost	Electrical	36,940,000	40,325,000
	Optical	3,385,000	
Total Network Cost			571,603,000

Figure 5.9: Transparent cost given by Net2Plan

5.2 Chapter Summary

Chapter 6

Conclusions and future directions

6.1 Conclusions

6.2 Future directions

References

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Appendices

NetPlanner

University of Aveiro

October 26, 2016

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1 Installing Net2Plan and its main options

This first section will describe how to install Net2Plan and some of the solvers usable by it as well as the main program preferences available.

1.1 Net2Plan download and installation

Before downloading Net2Plan, the first step is verifying if the computer has the necessary Java Runtime Environment, it is recommended the latest release (Version 8). This can be download from the java website at `https://java.com/en/download/`. The Java Runtime Environment is necessary as Net2Plan was coded in Java.

Having installed the Java Environment it is now possible to install Net2Plan. The download is available on its website at `http://net2plan.com/download.php`. The files just need to be extracted and the program can be run without an installation by just double clicking on the file "Net2Plan.jar". The latest Net2Plan version available at the time this report was revised is 0.4.2 from July 22nd, 2016

Figure 1: Net2Plan Opening Menu

1.2 Net2Plan Options and installing solvers

To access the main Net2Plan options click "File → Options". In this window the global parameters for simulations can be changed if needed. For example, an important option to note in this tab is the parameter "defaultRunnableCodePath", whose value should be the path to the jar file containing NetPlanner algorithms. As will be explained further on, Net2Plan is an open source tool and as such, new algorithms can be implemented and the default path can be changed to the path where those will be available instead of loading them manually each time Net2Plan is opened. The remaining parameters are related to solver options, which are the default external solvers used and also the path in which the "*.dll*", "*.so*", "*.dylib*" files of each solver are available. By default there is no path for each solver but in this case it was already changed to where the solvers were installed.

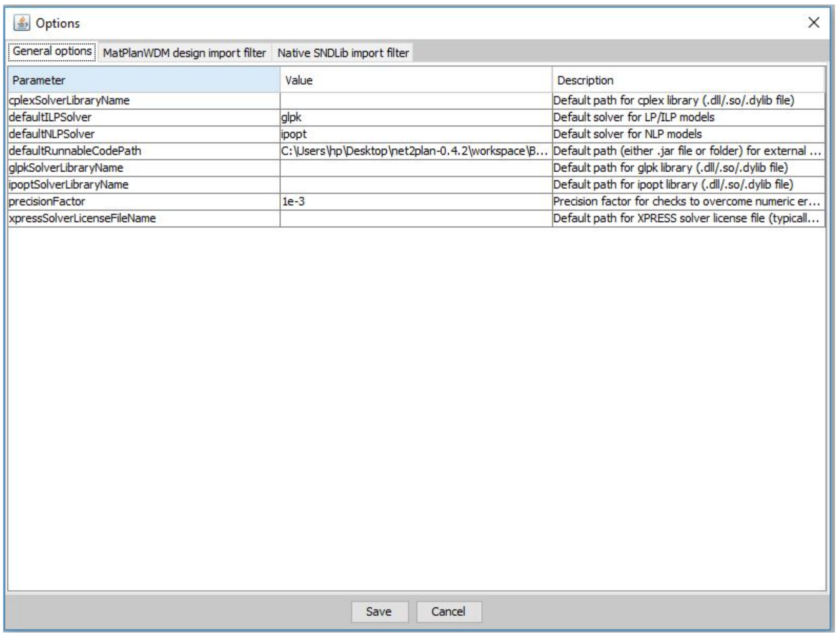


Figure 2: Net2Plan General Options

These external solvers are not extracted along with Net2Plan and as such, need to be downloaded if needed for the algorithms to be used. As "cplex" is a paid application, only the other two solvers will be shown as the process is similar.

The "IPOPT" solver can be downloaded from `http://www.coin-or.org/download/source/Ipopt/`. There are various choices available to download but for this case the *.dll* is the main file needed. An example of an algorithm which uses this solver is shown on Figure 3. Note that the "solverLibraryName" has the path shown earlier on the "Solver options" tab, this would have to be added manually if not introduced into the main options.

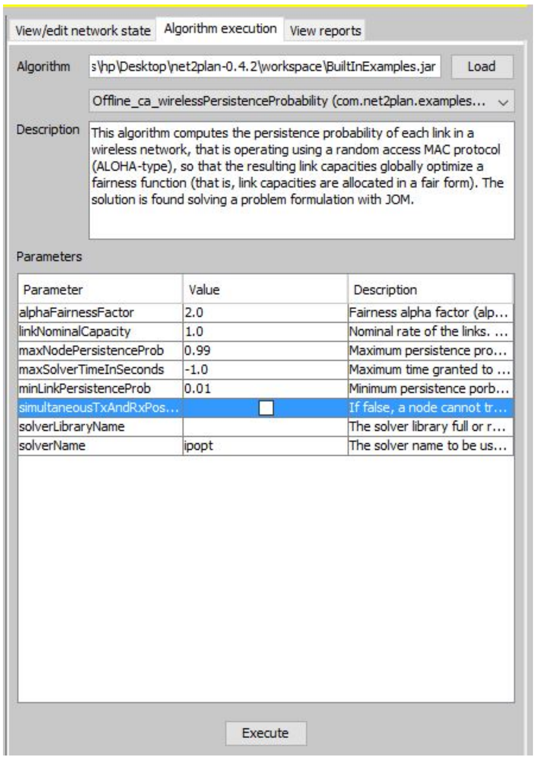


Figure 3: Net2Plan Algorithm with *ipopt* solver

The other free solver also used by some Net2Plan is "glpk", this one can be downloaded from http://sourceforge.net/projects/winglpk/?source=typ_redirect. An example is shown on Figure 4. Again note the path shows up as in the options.

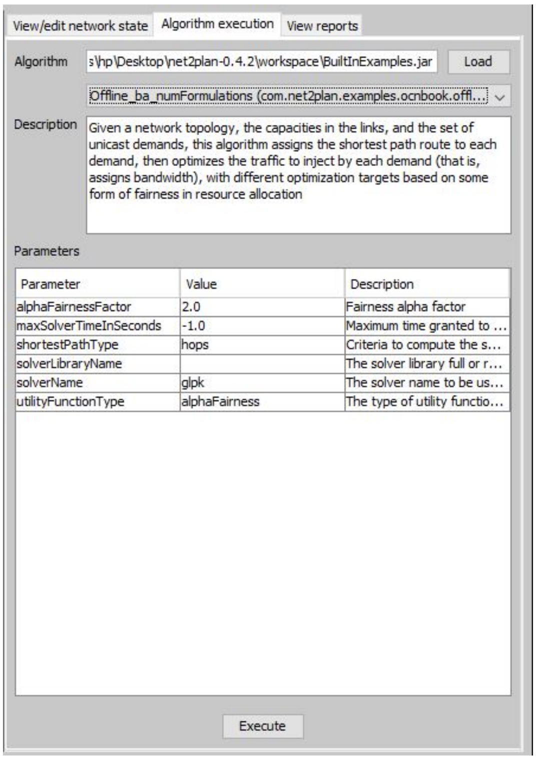


Figure 4: Net2Plan Algorithm with $glpk$ solver

2 Net2Plan Tools

This section will describe in some detail the tools presented in Net2Plan as a network planner, most notably how to created a traffic matrix, design a network and some of the simulation options available.

2.1 Creating Traffic Matrices

To start creating a traffic matrix in Net2Plan go to "Tools → Traffic matrix design" or press $Alt + 2$. The traffic matrix menu is shown on Figure 5.

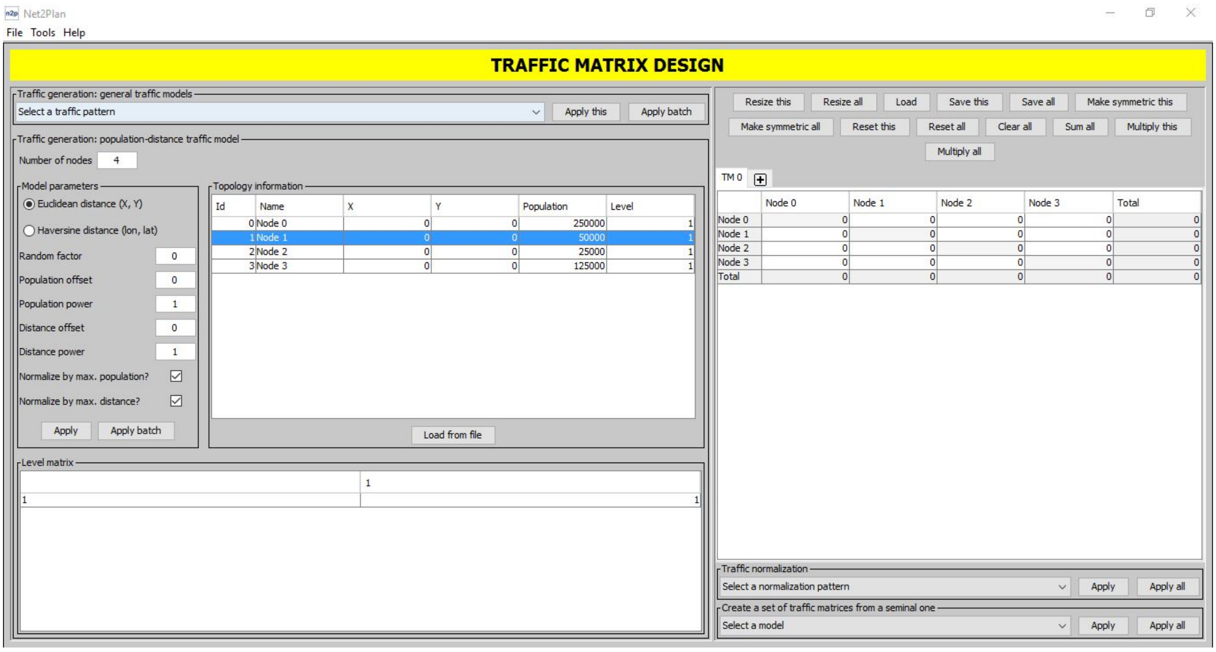


Figure 5: Net2Plan Traffic Matrix Design

On the top left side a traffic pattern can be chosen for one matrix or several if used the "Apply batch" option.

- "Constant" has two parameters the number of nodes and a constant value. This creates an uniform matrix with the number of nodes chosen and traffic equal to the value selected.
- "Uniform (0,10)" has the number of nodes and the option of being symmetric as the parameters. The matrix then has the number of nodes introduced and an amount of traffic chosen randomly between 0 and 10 which can be symmetric or not depending on the choice done.
- "Uniform (0,100)" is very similar to the other uniform option whereas in this case the traffic values are chosen randomly between 0 and 100.
- "50% Uniform (0,100) & 50% Uniform (0,10)" and "25% Uniform (0,100) & 75% Uniform (0,10)" are as expected a mixture of the previous two options.
- "Gravity model" in this option a number of nodes is chosen as well as the amount of traffic both generated and received by each node. The sum of the traffic generated by all the nodes needs to be equal to the sum of the traffic received by them.

Below the traffic pattern options, an existing model can be loaded and additional parameters defined such as Population and Node Level.

On the right side a traffic matrix can be created manually by defining the number of nodes on "resize this" and the amount of traffic can be typed on each demand. The other options above the matrix are self explanatory, for example, "multiply this" multiplies all the traffic by a constant number chosen. A point to note is that most options has an "all" choice as it is possible to have more then one matrix created.

Below the matrix part are two further options available for the matrices, the first one is the option to select a normalization pattern such as "Total normalization" where a total number of traffic can be chosen for the network and the demands are adapted to it accordingly. The other option is to create a set of matrices based on the designed one.

Figure 6 shows how to create batch of matrices with constant traffic.

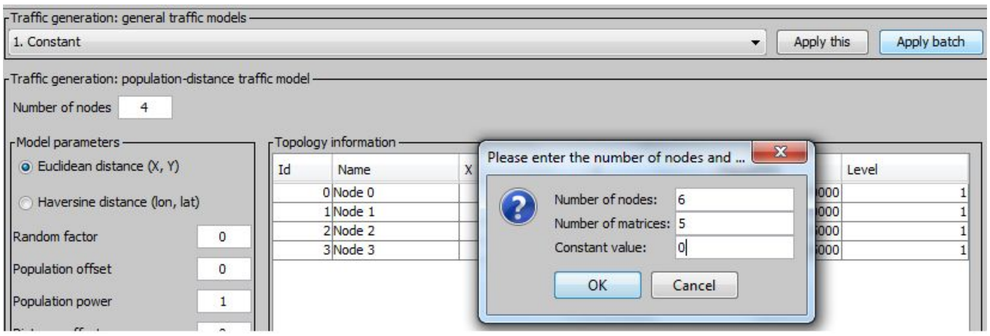
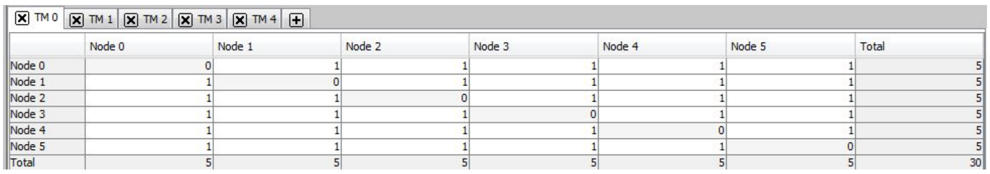


Figure 6: Net2Plan example on creating a batch of matrices

Using this option, 5 traffic matrices for a 6 node network were created all with a constant value of 1 as can be seen on figure 7 that shows the first matrix of the batch.



TM 0 | TM 1 | TM 2 | TM 3 | TM 4

	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Total
Node 0	0	1	1	1	1	1	5
Node 1	1	0	1	1	1	1	5
Node 2	1	1	0	1	1	1	5
Node 3	1	1	1	0	1	1	5
Node 4	1	1	1	1	0	1	5
Node 5	1	1	1	1	1	0	5
Total	5	5	5	5	5	5	30

Figure 7: Net2Plan Traffic Matrix Example

This example demonstrates how several different types of traffic can be introduced for a network by creating different matrices for each. These can then be saved individually and will further on be used as traffic matrices for ODU's 0 through 4.

2.2 Creating the Network topologies

To start with the Network creation tools in Net2Plan go to ”Tools → Offline network design” or press $Alt + 1$. The network design menu is shown on Figure 8.

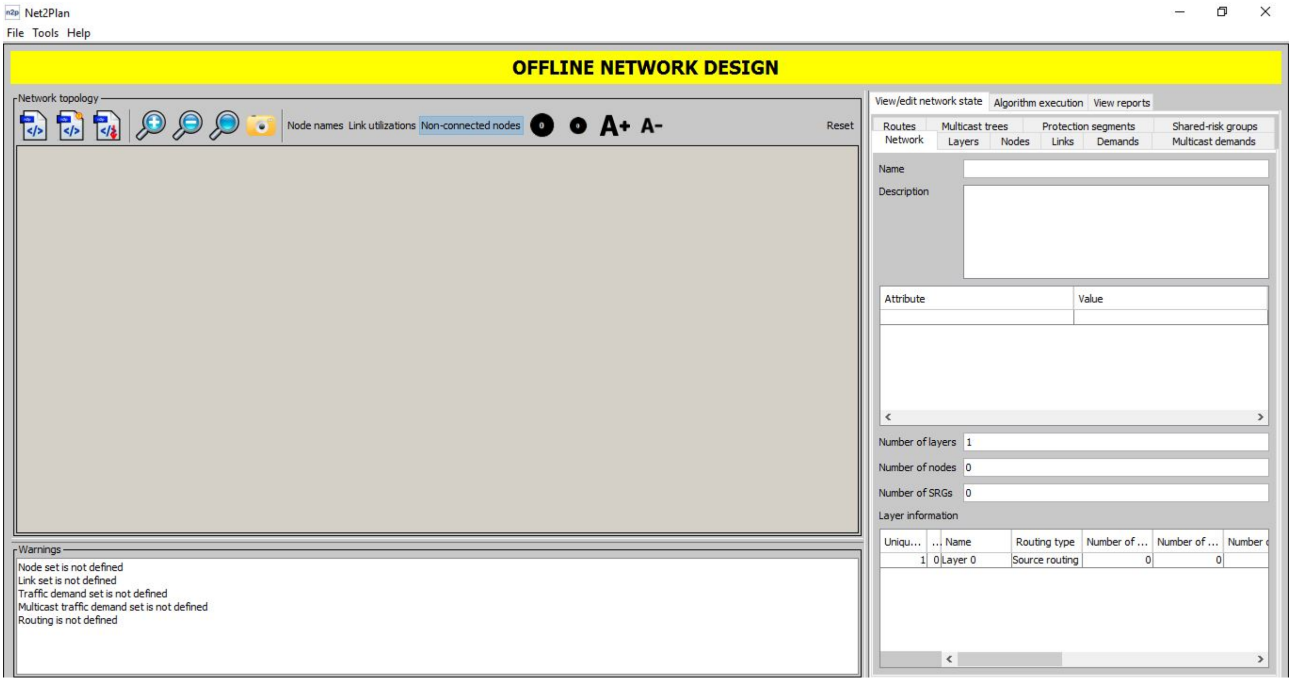


Figure 8: Net2Plan Offline Network Design

On the left side, the network topology part has the option to load an existing design and demand set or a new one can be created. To start creating a new network, first nodes have to be introduced by right clicking on the grey area and choosing ”Add node here”. Links between nodes are created by holding a click on the origin node and dragging until the destination node, holding shift before releasing the click creates 2 links, one in each direction. Another option to create links is to right click on an existing node and choosing the desired create a link option. Nodes can be moved by holding control and dragging them into the desired position.

Below the network topology is the ”Warnings” box where the parts missing from having a functional network are displayed. For example if the nodes and links where already created it should say ”traffic demand set is not defined” and ”Routing is not defined” as these were still not introduced.

The whole right side of the network design menu are the parameters separated into various tabs which will be explored further on in this document. Besides these tabs, there is also the tab for Algorithm execution where the network is modified based on built algorithms, for example a routing algorithm and the View reports tab where information on the network can be displayed from built in reports.

Figure 9 demonstrates an example of the 6 node and 16 links network created using the tools explained above. As can be seen on the image at the warning tab, this network sill has several steps left to become a fully functional network. The link capacity will be defined based on the routing algorithm chosen and the demand set will be loaded based on the matrices created.

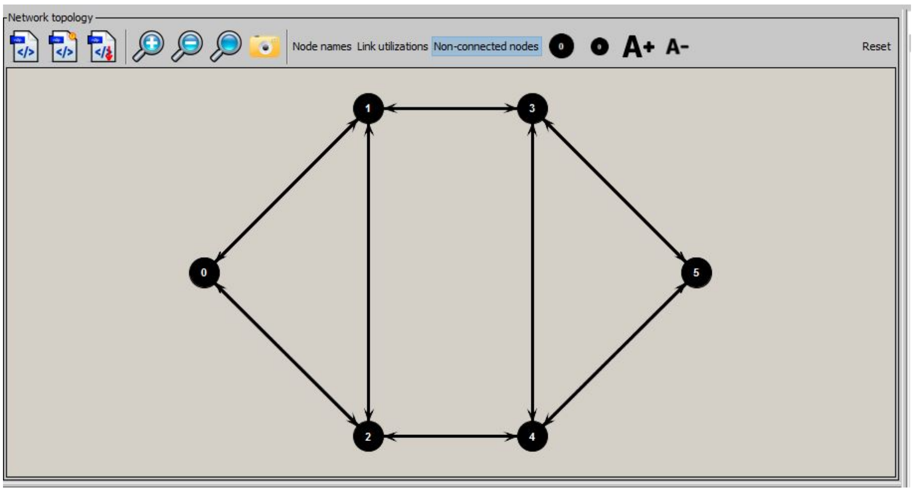
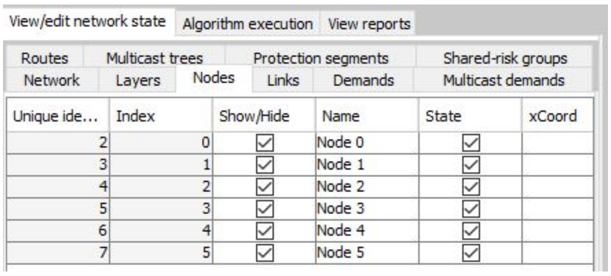


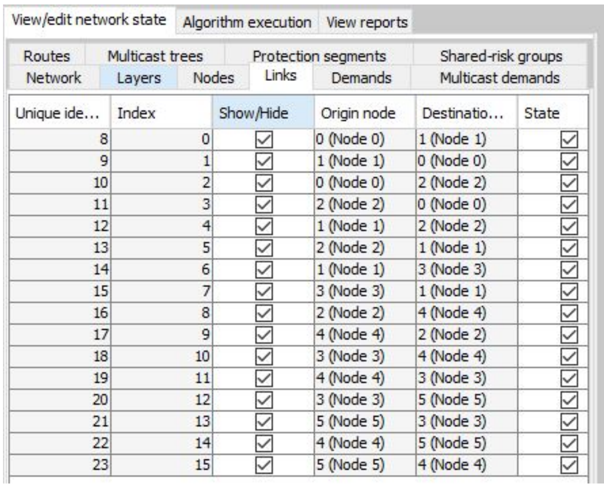
Figure 9: Net2Plan Network Example

The links and nodes parameters created for the network can be visualized and modified as seen on Figures 10(a) and 10(b) displaying the tabs for each case.



Unique ide...	Index	Show/Hide	Name	State	xCoord
2	0	☑	Node 0	☑	
3	1	☑	Node 1	☑	
4	2	☑	Node 2	☑	
5	3	☑	Node 3	☑	
6	4	☑	Node 4	☑	
7	5	☑	Node 5	☑	

(a)



Unique ide...	Index	Show/Hide	Origin node	Destinatio...	State
8	0	☑	0 (Node 0)	1 (Node 1)	☑
9	1	☑	1 (Node 1)	0 (Node 0)	☑
10	2	☑	0 (Node 0)	2 (Node 2)	☑
11	3	☑	2 (Node 2)	0 (Node 0)	☑
12	4	☑	1 (Node 1)	2 (Node 2)	☑
13	5	☑	2 (Node 2)	1 (Node 1)	☑
14	6	☑	1 (Node 1)	3 (Node 3)	☑
15	7	☑	3 (Node 3)	1 (Node 1)	☑
16	8	☑	2 (Node 2)	4 (Node 4)	☑
17	9	☑	4 (Node 4)	2 (Node 2)	☑
18	10	☑	3 (Node 3)	4 (Node 4)	☑
19	11	☑	4 (Node 4)	3 (Node 3)	☑
20	12	☑	3 (Node 3)	5 (Node 5)	☑
21	13	☑	5 (Node 5)	3 (Node 3)	☑
22	14	☑	4 (Node 4)	5 (Node 5)	☑
23	15	☑	5 (Node 5)	4 (Node 4)	☑

(b)

Figure 10: Network a) Nodes tab ; b) Links tab

On the Nodes tab most of the parameters are still 0 as there is no traffic on the network but there are three parameters that can be changed here. A node name can be set and both x and y coordinates can be defined as a more thorough alternative to define the node position.

On the links tab, again most is at 0 at this moment while the parameters that can be manually set are the link capacity, at 0 until defined and the link length which was set to the same value in every link.

Having the basic physical topology created, the next step is to load the demand set into the network. In the case where there are multiple traffic matrices an algorithm was developed to aggregate these in order for it to be possible to load all demands. For traffic matrices with ODU signals, an algorithm called ”joinTrafficMatrices” can aggregate the different ODUs and convert them to ODU0 in order to have all the traffic in the same units. Besides converting the different ones to ODU0 it also creates an attribute in each demand indicating the type of signal before converting. This attribute can be seen on the demands tab after loading the resulting demand list. Figure 11 shows the algorithm to be used.

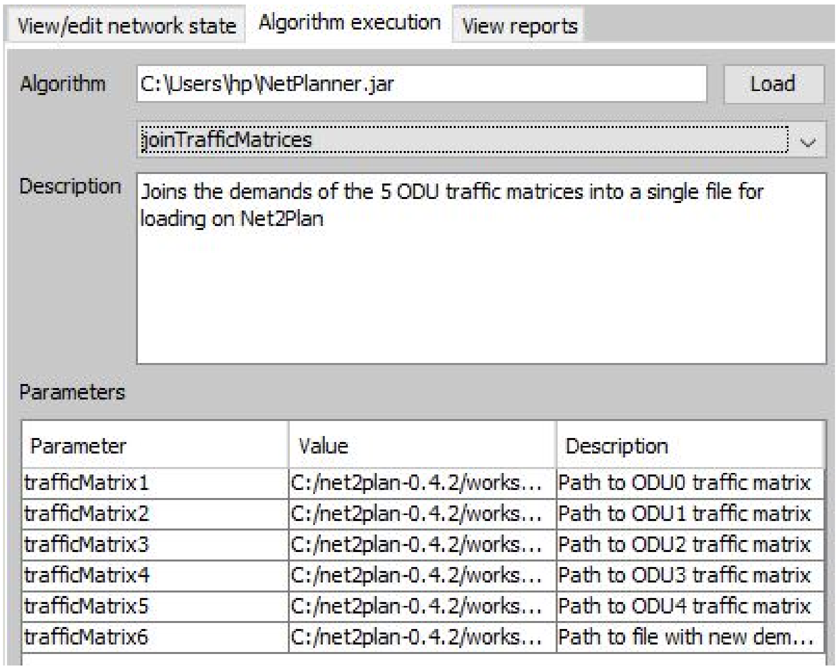


Figure 11: joinTrafficMatrices Algorithm

As can be seen on Figure 11 there are 6 user defined parameters, the first five are the paths for the traffic matrices to be aggregated in order, as said in the description. The last parameter is the resulting demand list that can then be loaded into the network.

The paths are by default defined considering Net2Plan is on C: and the matrices are in the default directory were they are saved. Lastly, the name of the files are in order ODU0.n2p through ODU4.n2p. All the path and file names can be changed to where the matrices are saved taking into account that just the order of the ODUs needs to be kept due to the conversion to ODU0 units.

To load the resulting demands into the created network the second icon on top of the network topology called ”Load a demand traffic set” is used. After this, the warning tab changes from ”Traffic demand set not defined” to ”Traffic losses: Not all the traffic is being carried”. This new warning indicates that the demand are in the network but as the routes have not yet been defined the traffic is not being transported.

In the demands tab, all the traffic that was created will be displayed in order of ODU type. For this case as all matrices were unitary and uniform, there are thirty demands with offered traffic 1 which is the ODU0 matrix and then consecutively groups of 30 demands (6 nodes) with offered traffic based on the ODU type (5 matrices). For example, an ODU1 is equivalent to two ODU0 so these demands have 2 in offered traffic and an attribute called ODU with value 1.

Before going into the network routing, the network transport mode needs to be defined by creating a logical topology. An algorithm was developed that creates a new layer consisting on this topology depending on the transport mode chosen. This algorithm can be seen on Figure 12.

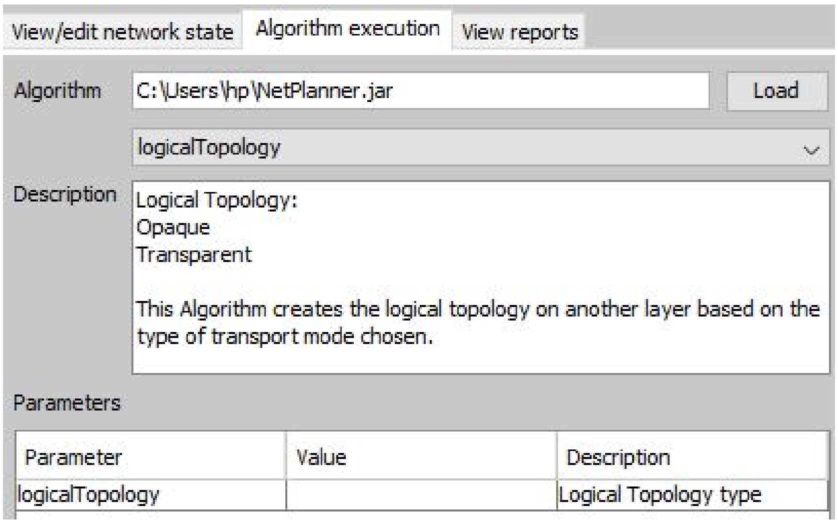
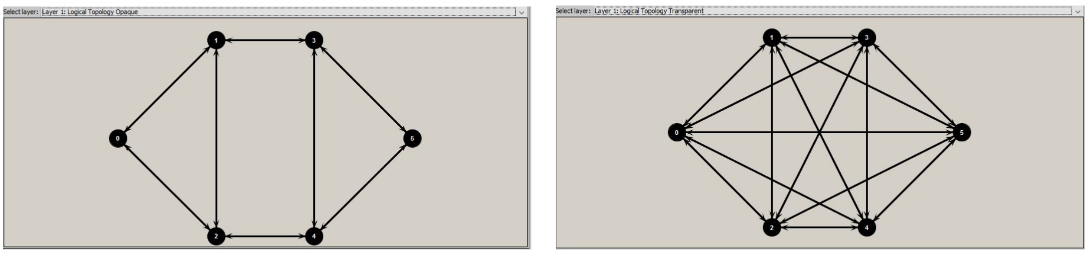


Figure 12: Net2Plan Logical Topology Algorithm

There are two user defined parameters on this algorithm. The ”logicalTopology” parameter defines the type of transport mode, Opaque or Transparent.

Besides creating this new Layer, the algorithm also copies the demands to that layer and defines the logical links based on the length of the physical ones. Figures 13(a), 13(b) demonstrate the resulting logical topologies for each transport mode.



(a) (b)

Figure 13: Logical Topology: a) Opaque; b) Transparent;

As can be seen on the logical topologies, for an Opaque transport mode the traffic goes through an OEO conversion at every node and as such the logical topology is the same as the physical one.

In the Transparent mode, there are no regeneration in intermediate nodes and as such the logical topology shows that the traffic between nodes flows directly without grooming with signals from another source.

2.3 Routing and Grooming

In this section, different routing and grooming options will be discussed for both a network without protection and using a 1+1 protection scheme (dedicated path protection).

The routing will be done based on a shortest path algorithm where the routes for each demand are are created based one either the shortest number of hops needed to reach the destination node or by shortest distance in km. The option can be chosen as a user defined parameter on the algorithm as can be seen on Figure 14. This algorithm does the routing in both the logical and physical topologies based on the transport mode chosen and makes sure routes are bidirectional meaning the route from node *o* to *d* should be the opposite direction of node *d* to *o* as there could be different routes with the shortest path that are not using the same path.

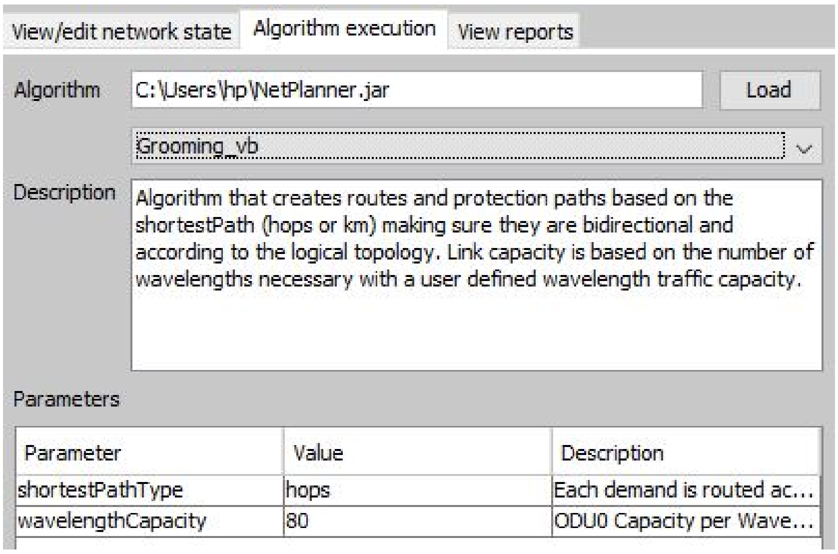


Figure 14: Net2Plan Grooming shortest Path Algorithm

Besides the metric through which the shortest path is calculated, the other available parameter defines the amount of ODU0s each wavelength is capable of carrying. By default it is set for 80 ODU0s as it is equal to an ODU4 or 100 Gbit/s.

The protection segments similarly to the routes have their own tab where information on their path, route it protects and such can be observed.

2.4 Reports

As looking separately at each tab to obtain information for different parts of the network is a slow process and does not show some important metrics, Net2Plan allows for the creation of reports where in a similar way to algorithms they can be adjusted to display the information needed, these can also be seen in html format for an easier read. In this section, the report developed will be demonstrated.

A very important aspect in network planning that is not present natively in Net2Plan is a Network Cost report. To fulfil this gap, a report was created to obtain the network Capex based on user defined equipment costs present on Table 1.

Equipment	Costs
OLT	15000€
Transponder	5000€/GB
Optical Amplifier	4000€
EXC	10000€
OXC	20000€
EXC Port	1000€/GB/s
OXC Port	2500€/port

Table 1: Equipment Costs

These Equipment costs are introduced into a report as user defined parameters as can be seen on Figure 15.

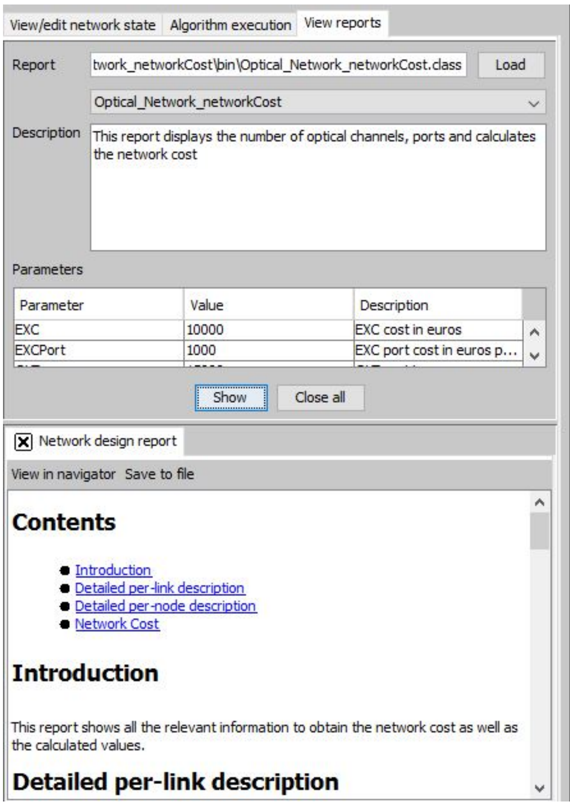


Figure 15: Network Cost Report

Besides the equipment costs, this report also has the parameter ”span”. The value of this variable is used to calculate the number of optical amplifiers needed in the network using Equation 1.

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

The other parameters of this equation being:

- $N^R \rightarrow$ Total number of regenerators/amplifiers
- $len_l \rightarrow$ Length of link l
- $span \rightarrow$ Distance between amplifiers

By running the report three main categories are presented to the user.

The first category displayed by the report is the Detailed per-link description. In here the number of optical channels or wavelengths is displayed for each link based on the grooming algorithm used. The numbers displayed are based on the physical topology and represent all the wavelengths that will be needed to transport the network traffic. Using this information it is possible to obtain the average and total number of optical channels on the network.

Besides the number of wavelengths, this section also indicates the amount of amplifiers necessary in each link.

The second category is the Detailed per-node description. This section displays a table indicating how many ports are needed of each type for every node. The number of tributary ports obtained in each node is the sum of all traffic originating from that node or ending on it depending if its the input or output ports divided by the amount of traffic each optical channel can carry. This number also depends on the links through which traffic will be routed, for example, if 40 ODU0s are transmitted into 2 separate links only one wavelengths could carry it but as they are going through different routes then 2 wavelengths will be used resulting in also a need for 2 tributary ports.

The number of line ports is obtained by adding the total amount of optical channels in the links that use that specific node as origin or destination.

Finally the total number of ports is as expected the sum of all the tributary ports with the line ones. With this information the average and the total number of ports in the network can be obtained which will later be used in calculating the network cost.

Having the node and link information available, the network cost can then be calculated as displayed on the third category of the report. The Node electrical cost is obtained with Equation 2 for a Transparent Network.

$$C_{exc} = (\gamma_{e0} \times N) + (\gamma_{e1} \times \tau \times 2 \times P_{TRIB}) \tag{2}$$

- $C_{exc} \rightarrow$ Electrical Ports Cost
- $\gamma_{e0} \rightarrow$ EXC cost in Euros
- $N \rightarrow$ Number of Nodes
- $\gamma_{e1} \rightarrow$ EXC port cost in Euros per GB/s
- $\tau \rightarrow$ Traffic supported by optical channel

- $P_{TRIB} \rightarrow$ Number of tributary ports

The cost values can be obtained from Table 1, the number of nodes is a known value when designing a network, the traffic supported by optical channel is defined by the grooming algorithm or by dividing the link capacity by its amount of optical channels and the number of tributary ports was obtained on the previous section of the report.

For an Opaque network, the electrical nodes cost is similar as displayed in Equation 3.

$$C_{exc} = (\gamma_{e0} \times N) + (\gamma_{e1} \times \tau (P_{LINE} + P_{TRIB})) \tag{3}$$

The node optical cost on the other hand, can be calculated for a Transparent network using Equation 4.

$$C_{oxc} = (\gamma_{o0} \times N) + \gamma_{o1} \times (P_{LINE} + P_{TRIB}) \tag{4}$$

- $C_{oxc} \rightarrow$ Optical Ports Cost
- $\gamma_{o0} \rightarrow$ OXC cost in Euros
- $N \rightarrow$ Number of Nodes
- $\gamma_{o1} \rightarrow$ OXC port cost in Euros
- $P_{TRIB} \rightarrow$ Number of tributary ports
- $P_{LINE} \rightarrow$ Number of line ports

As for the electrical ports, the cost values were previously defined in Table 1 and as such, only the number of ports is needed. These value were obtained on the second part of the report (Detailed per-Node description).

For an Opaque network, the node optical cost is 0 as the ports are all electrical.

The Node Total Cost is as expected the sum of both the optical and electrical node costs.

The rest of the network cost is from the links. This cost is obtained with Equation 5.

$$C_L = \left(\gamma_0^{OLT} \times L\right) + \left(\gamma_1^{OLT} \times \tau \times W\right) + \left(N^R \times c^R\right) \tag{5}$$

- $C_L \rightarrow$ Links Cost
- $\gamma_0^{OLT} \rightarrow$ OLT cost in Euros
- $L \rightarrow$ Number of unidirectional Links
- $\gamma_1^{OLT} \rightarrow$ Transponder cost in Euros
- $\tau \rightarrow$ Traffic per port
- $W \rightarrow$ Total number of optical channels

- $N^R \rightarrow$ Total number of optical amplifiers
- $c^R \rightarrow$ Optical amplifiers cost in Euros

As in previous equations, the costs are all available in Table 1. The total number of optical channels can be obtained by summing the wavelengths in each link on the Detailed per-Link description section. The number of optical amplifiers was calculated previously with Equation 1.

The middle part of the equation: $\gamma_1^{OLT} \times \tau \times W$ refers to the Transponders cost while the rest is the "Fiber" and the "OLT" cost. Lastly the total network cost can be obtained by adding the Links cost with the Nodes cost.

3 Results

This section will display the results obtained using the algorithms and reports previously explained for a network with an Opaque transport mode and for one with Transparent.

3.1 Opaque with 1+1 protection

The results will be displayed only in the logical topology as in an opaque network it is the same as the physical one. Using the algorithm presented on figure 14 the routes and protection segments are created as well as the grooming.

There is not a second algorithm type for wavelengths reduction due to the fact that, that algorithm chooses the best path based on the shortest or disjointed path which in this case both need to be used one for work and one for protection. As such, is difficult to reduce in any instance the shortest path because of the algorithm performance.

The traffic matrix for the reference 6 node network, used for demonstration is shown below.

$$\begin{bmatrix} 0 & 17 & 17 & 15 & 1 & 13 \\ 17 & 0 & 32 & 7 & 15 & 114 \\ 17 & 32 & 0 & 11 & 46 & 1 \\ 15 & 7 & 11 & 0 & 11 & 7 \\ 1 & 15 & 46 & 11 & 0 & 93 \\ 13 & 114 & 1 & 7 & 93 & 0 \end{bmatrix}$$

Figure 16:

The amount of traffic that needs to be reserved in each link is as was to be expected a lot higher due to the need to reserve double the amount and in more links. The same happens in terms of wavelengths.

The number of wavelengths can again be seen on the links section of the "networkCost" report as well as the amplifiers needed on Figure 17.

The conclusions to take from these results are the same as was previously discussed as the number of amplifiers does not change and the wavelengths are the ones shown on the line matrices.

As for the nodes in the network Figure 18 shows the ports needed.

Detailed per-link description

Node Pair	Wavelengths forward	Wavelengths backward	Amplifiers forward	Amplifiers backward
Node 0 «-» Node 1	10	10	1	1
Node 0 «-» Node 2	10	10	1	1
Node 1 «-» Node 2	14	14	1	1
Node 1 «-» Node 3	14	14	1	1
Node 2 «-» Node 4	14	14	1	1
Node 3 «-» Node 4	14	14	1	1
Node 3 «-» Node 5	10	10	1	1
Node 4 «-» Node 5	10	10	1	1

Figure 17: Links for Opaque Network with 1+1 Protection

Detailed per-node description

Name	Trib ports in	Trib ports out	Line Ports in	Line Ports out	Total Ports in	Total Ports out
Node 0	9	9	20	20	29	29
Node 1	9	9	38	38	47	47
Node 2	9	9	38	38	47	47
Node 3	10	10	38	38	48	48
Node 4	10	10	38	38	48	48
Node 5	9	9	20	20	29	29
Total	56	56	192	192	248	248

Figure 18: Nodes for Opaque Network with 1+1 Protection

Again, the difference for the case without protection is only on the number of line ports as this value is based on the number of wavelengths going in or out of that node.

Comparing the number of ports obtained here with the network with a transparent transport mode, the amount is lower for the opaque network due to the reduced number of wavelengths required to route the traffic.

Lastly the total network cost is on Figure 19.

Network Cost

Category		Cost	Total
Link Cost	OLT	240,000	96,304,000
	Transponders	96,000,000	
	Amplifiers	64,000	
Node Cost	Electrical	24,860,000	24,860,000
	Optical	0	
Total Network Cost			121,164,000

Figure 19: Network Cost for Opaque Network with 1+1 Protection

The increase in cost is as described on the transparent network just based on the additional number of wavelengths required which translates in also more trunk ports needed. As noted above in the amount of ports, the cost is also lower in this instance when compared to the transparent network due to the cheaper cost in transponders and optical ports.

3.2 Transparent with 1+1 protection

For a network with a transparent transport mode, the routing as was explained before, is done using a shortest path algorithm since there are no traffic grooming between different node pairs. For this instance as there is also a 1+1 protection scheme in place, the algorithm needs to not only create the routes but also a protection segment for each route. This segment is the shortest disjoint path of the route created.

Comparing the results obtained here with the previous example, it can be seen that the amount of traffic and wavelengths is significantly higher. It is in both cases, double the amount of before since the same quantity needs to be reserved for protection.

The conclusions that can be taken from the physical topology are as explained before, the huge number of wavelengths is related to the needed for double the amount of traffic where this extra will go through even more links.

For the logical topology the Average second shortest path number of hops is 1 since as for the shortest path, it is considered that there are always direct links between nodes in a transparent network. As for the physical topology, this value is not so obvious as it has to be calculated based on the second shortest path between each node pair.

These differences for the transparent network with protection segments can also be seen on the information provided in the "networkCost" report. Figure 20 shows the results for the links in the physical topology.

Detailed per-link description

Node Pair	Wavelengths forward	Wavelengths backward	Amplifiers forward	Amplifiers backward
Node 0 «-» Node 1	12	12	1	1
Node 0 «-» Node 2	12	12	1	1
Node 1 «-» Node 2	18	18	1	1
Node 1 «-» Node 3	18	18	1	1
Node 2 «-» Node 4	18	18	1	1
Node 3 «-» Node 4	18	18	1	1
Node 3 «-» Node 5	12	12	1	1
Node 4 «-» Node 5	12	12	1	1

Figure 20: Links for Transparent Network with 1+1 Protection

It can be seen that as expected the number of amplifiers is the same due to the link lengths remaining constant but the number of wavelengths are higher due to having a grooming scheme worst with this topology.

The results in terms of ports per node are shown below.

Detailed per-node description

Name	Trib ports in	Trib ports out	Line Ports in	Line Ports out	Total Ports in	Total Ports out
Node 0	10	10	24	24	34	34
Node 1	10	10	48	48	58	58
Node 2	10	10	48	48	58	58
Node 3	10	10	48	48	58	58
Node 4	10	10	48	48	58	58
Node 5	10	10	24	24	34	34
Total	60	60	240	240	300	300

Figure 21: Nodes for Transparent Network with 1+1 Protection

The number of tributary ports remain the same but the number of line ports increase based on the higher number of wavelengths needed in the network.

Lastly, the total network cost is shown on Figure 22.

Network Cost

Category		Cost	Total
Link Cost	OLT	240,000	120,304,000
	Transponders	120,000,000	
	Amplifiers	64,000	
Node Cost	Electrical	12,060,000	12,930,000
	Optical	870,000	
Total Network Cost			133,234,000

Figure 22: Network Cost for Transparent Network with 1+1 Protection

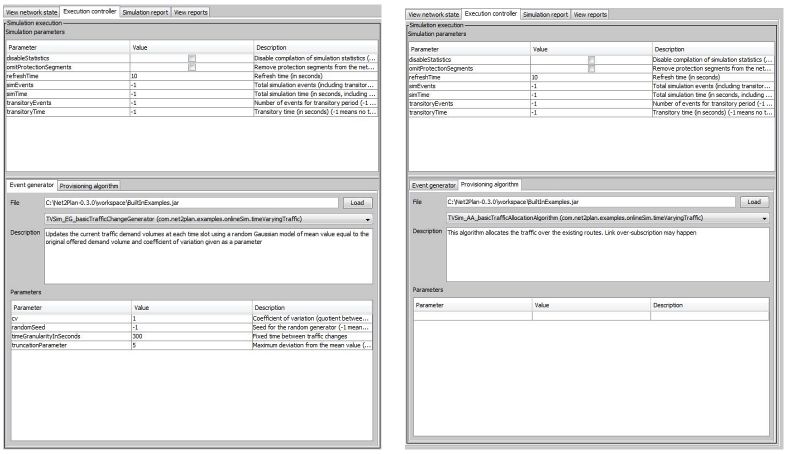
The results obtained for the network Cost confirm those obtained in the previous categories in this report. The OLT and amplifiers cost does not change as the number of links and amplifiers remains the same. Similarly, the electrical ports cost is also the same as the amount of ADD/DROP ports remains the same.

The differences are in the Transponders cost in the links and the Optical cost in the nodes. These as expected, cost more based on the increased number of them needed in the network to have a 1+1 protection scheme in a transparent transport mode network.

4 Simulations

To access the Simulations window go to ”Tools $\rightarrow$ Online Simulation” or press $Alt + 3$. The simulations menu is very similar to the one available for network design with the notable difference that in this instance the network needs to have already been saved with every definition done as all the tabs described earlier are only available here for viewing.

Using the already built network with the demand set introduced as well as routing and protection segments, an example of a Time-varying simulation is demonstrated. The main parameters to be chosen on this simulation are the ”Event generator” and the ”Provisioning algorithm”, displayed on Figures 23(a) and 23(b).



(a) (b)

Figure 23: a) Net2Plan Event generator ; b) Net2Plan Provisioning algorithm

The Event generator shown creates a time varying simulation by updating the network traffic based on the chosen parameters while the allocation algorithm in this case only allocates this traffic into the available routes. Besides these options it is also possible to change the main simulation parameters which are displayed on the top half.

Having defined all the simulation parameters and the other necessary options, the simulation can be started by just pressing ”run” below the network topology at the lower left side. The ”simulation controller” will update automatically based on the time defined at the simulation parameters or it can be paused for an update on the results.

5 Implementing new algorithms on Net2Plan

This section will demonstrate some of the possibilities provided by Net2Plan as an open source tool. By creating new algorithms or reports it is possible to adapt this program for most necessities in terms of network planning.

There are already several built-in algorithms present in Net2Plan but as it is impossible to have an algorithm built for every specific necessity it is possible for each user to build new ones or modify existing ones to fulfil what needs to be done.

As everything in Net2Plan was built in Java, the program ”Eclipse” that can be downloaded from https://eclipse.org/downloads/ was chosen as the best option for coding. All the .java files from the available algorithms in Net2Plan can be downloaded from its website and introduced into ”Eclipse” to create a class.

When opening Eclipse, the first choice is to define the work directory in which all the projects will be created. Having defined the workspace, Figure 24 demonstrates the window for creating new projects in Eclipse, this can be accessed by going into ”File → New → Java Project”. In this window, only the name needs to be defined and then finish.

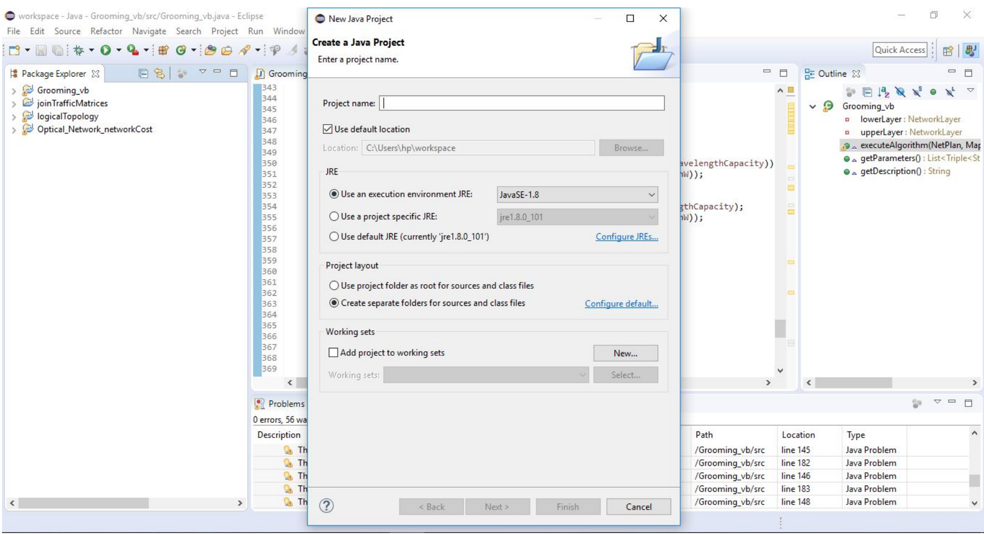


Figure 24: Eclipse new project

Having created a new project, a ”src” directory should be available where the .java should be located. As a starting point, an existing algorithm should be used as a template and then modified to do its necessary purpose. Figure 25 shows a newly created project called ”logicalTopology”.

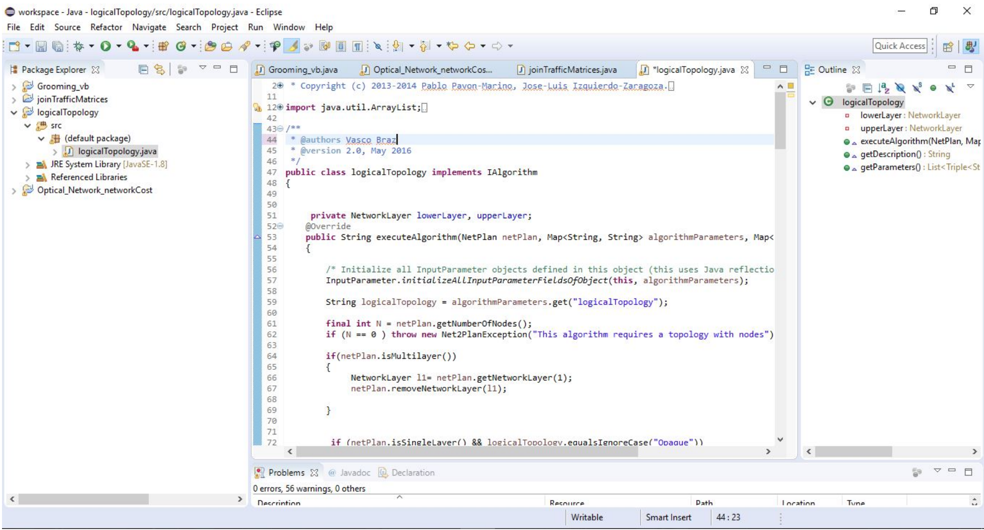
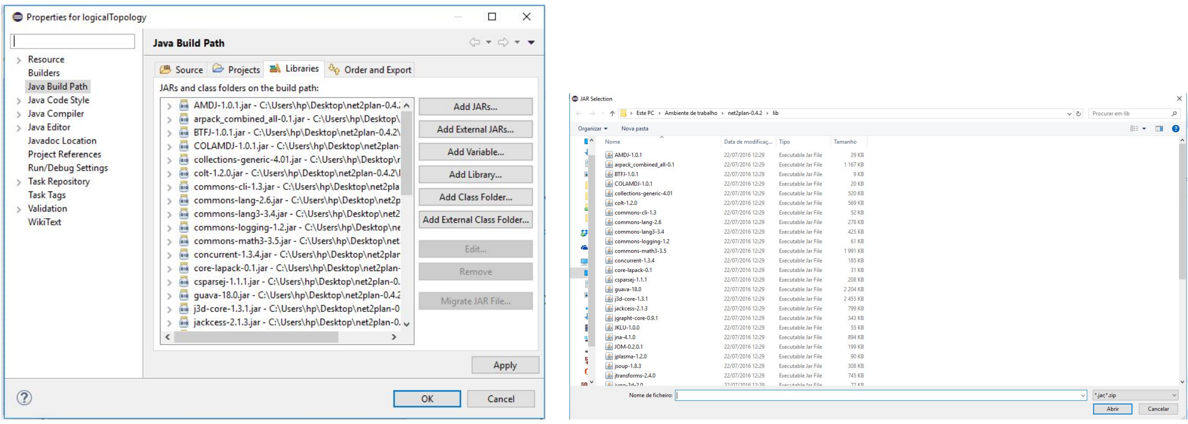


Figure 25: Eclipse new project with source file

To add the library files to a project, right click on it and choose ”Build Path → Configure Build Path ...” . On the window that appears, press ”Add External Jars...” and include all the files in the Net2Plan ”lib” directory as shown on Figures 26(a) and 26(b).



(a) (b)

Figure 26: a) Eclipse Java Configure Build Path ; b) Net2Plan library files

To further illustrate how these modifications to algorithms work, the project created above using an existing code as a template was modified to create a new algorithm which creates the logical topology of a network in another layer.

The code created is shown on Figure 24. By saving this project on Eclipse a .class file is created on the bin directory of the project which can be loaded on Net2Plan. On the ”Algorithm execution” tab at the ”Offline network design”, the ”BuiltInExamples.jar” is loaded as the default location for algorithms and as it is a .jar file all the available ones that came with Net2Plan are integrated into it. To get the newly created algorithm available, press ”Load” and find the .class file created in Eclipse as shown on Figure 27.

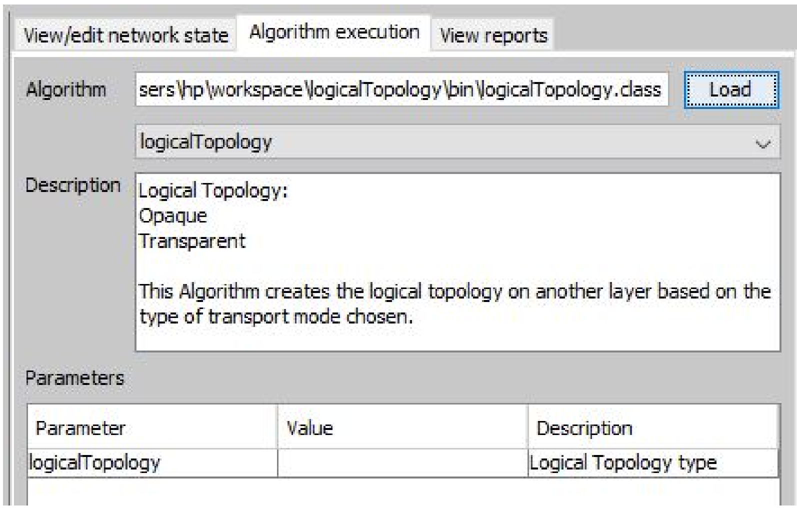
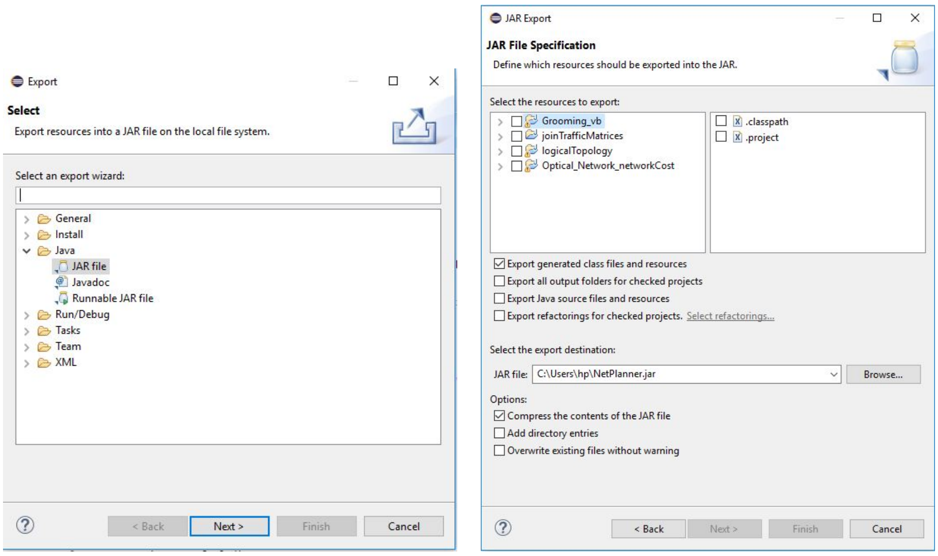


Figure 27: Net2Plan new algorithm

As was said before and can be seen on the ”Description”, this algorithm creates the network logical topology as was explained on section 2.2.

Algorithms developed on Eclipse can be exported into a .jar file so on Net2Plan this file can be loaded and all the algorithms developed are shown in a list in the same manner as the ones that came with the Net2Plan installation. The export option can be accessed by going into File → Export, and the menu are shown in Figures 28(a) and 28(b).



(a) (b)

Figure 28: a) Eclipse export ; b) Projects to export into a .jar file

By default only the .class files are exported along with the necessary libraries so that the algorithms can be loaded on Net2Plan. There is however an option to also export the .java files so that if needed the ones who will use the code also have access to it if they need to change it.

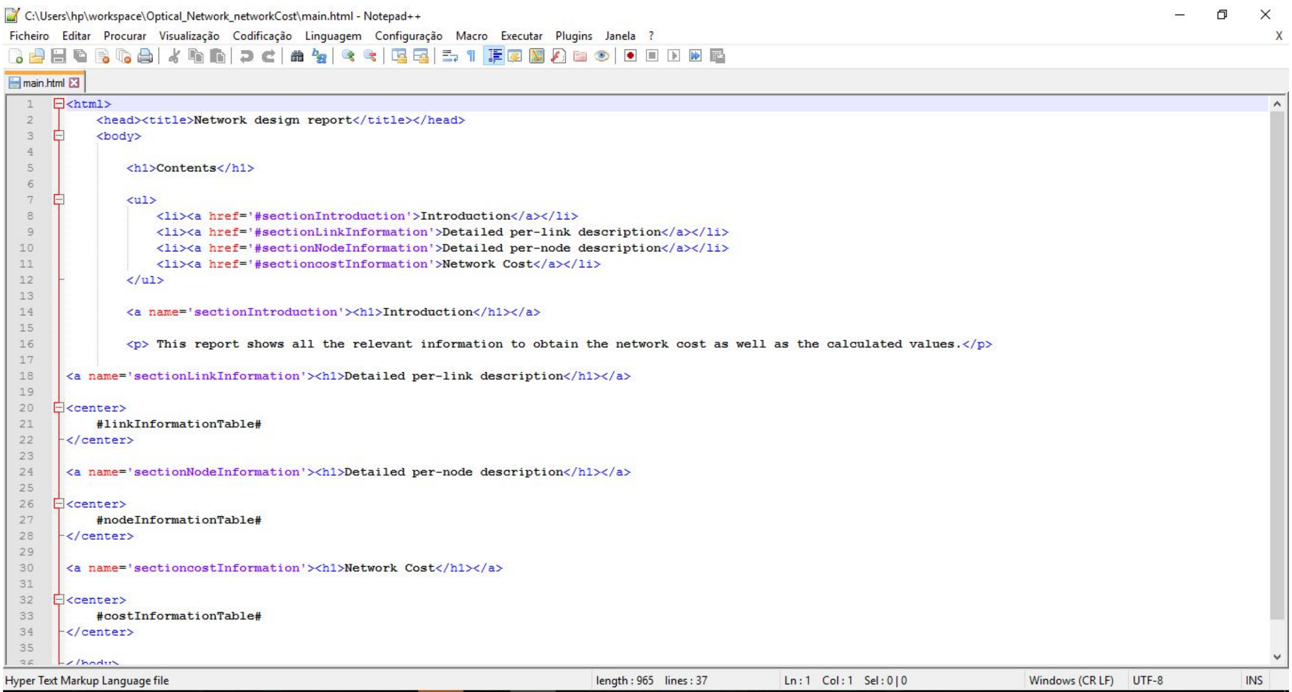
6 Developing new Reports

Similarly to the way algorithms can be modified or new ones created, also reports can be done using almost the same steps. For the following examples, the ”Optical_Network_networkcost” is being used as a basis for modifying or creating new reports.

An important point to note as the main difference as to when modifying algorithms, is that in this case not only are the Net2Plan libraries needed but also the extra files summoned by the report. These files can be found opening the ”BuiltInExamples.jar” file in the Net2Plan directory on the corresponding report.

For the report being used there is an .html file called ”main” which is where the information to be displayed in html form is described as well as several image files that are displayed in the report. As such, if the modifications to be done in the reports are to be shown in html format the ”main.html” file needs to be modified in order to adapt to these changes.

The tables themselves are created in eclipse as Java code but the html file needs to be opened for example with ”Notepadd++” to change some its code as the tables are being appended into the html. Figure 29 shows the modified html that is used in the Optical_Network_networkcost.



```
<html>
    <head><title>Network design report</title></head>
    <body>

        <h1>Contents</h1>

        <ul>
            <li><a href='#sectionIntroduction'>Introduction</a></li>
            <li><a href='#sectionLinkInformation'>Detailed per-link description</a></li>
            <li><a href='#sectionNodeInformation'>Detailed per-node description</a></li>
            <li><a href='#sectioncostInformation'>Network Cost</a></li>
        </ul>

        <a name='sectionIntroduction'><h1>Introduction</h1></a>

        <p> This report shows all the relevant information to obtain the network cost as well as the calculated values.</p>

<a name='sectionLinkInformation'><h1>Detailed per-link description</h1></a>

<center>
    #linkInformationTable#
</center>

<a name='sectionNodeInformation'><h1>Detailed per-node description</h1></a>

<center>
    #nodeInformationTable#
</center>

<a name='sectioncostInformation'><h1>Network Cost</h1></a>

<center>
    #costInformationTable#
</center>
```

Figure 29: html file for Network Cost report

As can be seen, this is a simple example of an html file since there are only hyper links created to link the contents index to the tables. Other options could be added as for example, hyper links to each of the network costs with the formula describing its calculations by adding the necessary information in this file. These extra options are present on more complex reports such as the ”Report_networkDesign” where the images used are equations showcasing how some of the calculations are done.