NetXPTO - NetPlanner

22 de Maio de 2018

Conteúdo

Capítulo 1

Introduction

LinkPlanner is devoted to the simulation of point-to-point links.

Capítulo 2

Simulator Structure

LinkPlanner is a signals open-source simulator.

The major entity is the system.

A system comprises a set of blocks.

The blocks interact with each other through signals.

2.1 System

2.2 Blocks

2.3 Signals

List of available signals:

- Signal

Capítulo 3

Development Cycle

The NetXPTO-LinkPlanner has been developed by several people using git as a version control system. The NetXPTO-LinkPlanner repository is located in the GitHub site http://github.com/netxpto/linkplanner. The more updated functional version of the software is in the branch master. Master should be considered a functional beta version of the software. Periodically new releases are delivered from the master branch under the branch name Release<Year><Month><Day>. The integration of the work of all people is performed by Armando Nolasco Pinto in the branch Develop. Each developer has is how branch with his/her name.

Capítulo 4

Reference Network Specification

The purpose of this chapter is to describe a reference network that will be used for the various types of dimensioning throughout this project. In addition to the reference network will also be described the various traffic models used in this network in question.
The organization of this chapter is done by creating two sub-chapters, the first to describe the physical topology of the network and a second to create the traffic matrix for the three existing traffic models (low, medium and high traffic).

4.1 Physical Topology

Student Name	:	Tiago Esteves (October 03, 2017 -)

In the following figure we can see that our reference network consists of 6 nodes and 8 bidirectional links. Besides this layout of links and nodes will also need to know the average length of the links. This value varies depending on the length of each link so it will be necessary to define all distances between the respective nodes. Finally, it is also necessary to indicate the total traffic used in this network so the ODU matrices will be created.

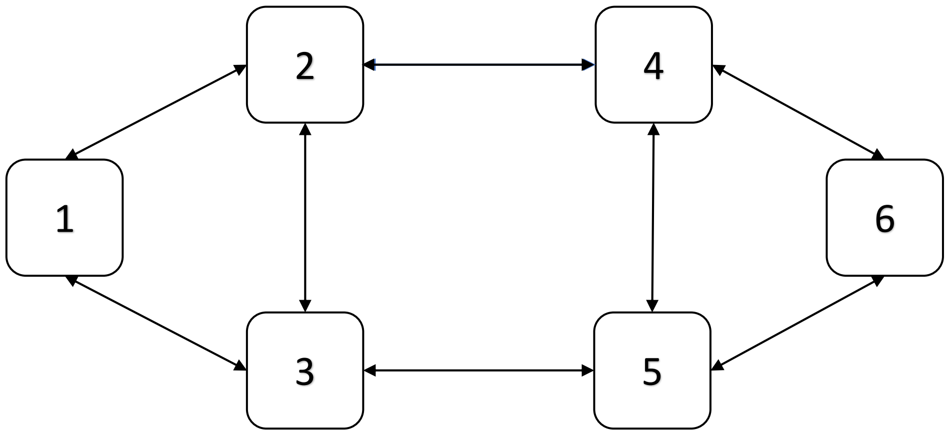

Figura 4.1: Physical topology of the reference network.

The distance matrix for this reference network is the same regardless of its associated traffic. The values indicated in the distance matrix, referred to below, are expressed in kilometers (Km) and, as it could not be otherwise, this matrix is symmetric because the distance from 1 to 2 must be the same as 2 to 1.

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

For this project has to take into consideration the table 4.1 because in it we can see the values of the variables associated with this network.

Constant	Description	Value
N	Number of nodes	6
L	Number of bidirectional links	8
<δ>	Node out-degree	2.667
<len>	Mean link length (km)	500
<h>	Mean number of hops for working paths	1.533
<h'>	Mean number of hops for backup paths	2.467

Tabela 4.1: Table of reference network values

4.2 Traffic Matrices

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For a better interpretation of the later results we will assume three traffic models for this network. Being the first model with a low traffic scenario, the second with a medium traffic scenario and a last one with a high traffic scenario. For each scenario it will be necessary to create different traffic matrices and to know the traffic of the network we will use five matrices of traffic. These traffic matrices are represented by ODU0, ODU1, ODU2, ODU3 and ODU4 where each one has a certain bit rate. The ODU0 corresponds to 1.25 Gbits/s, the ODU1 corresponds to 2.5 Gbits/s, the ODU2 corresponds to 10 Gbits/s, the ODU3 corresponds to 40 Gbits/s and finally the ODU4 corresponds to 100 Gbits/s. As we can see below, these arrays are bi-directional because they are symmetric arrays and as such, the traffic sent in a certain direction must be the same traffic sent in that opposite direction.

4.2.1 Low traffic scenario (0.5 Tbits/s)

The traffic matrices for this scenario are:

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

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

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

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

T_1^0 = 60x1.25 = 75 Gbits/s T_1^1 = 50x2.5 = 125 Gbits/s T_1^2 = 16x10 = 160 Gbits/s

T_1^3 = 6x40 = 240 Gbits/s T_1^4 = 4x100 = 400 Gbits/s

T_1 = 75 + 125 + 160 + 240 + 400 = 1000 Gbits/s T = 1000/2 = **0.5 Tbits/s**

Where the variable T_1^x represents the unidirectional traffic of the ODUx, for example, T_1^0 represents the unidirectional traffic of the ODU0 and T_1^1 represents the unidirectional traffic of the ODU1. The variable T_1 represents the total of unidirectional traffic that is injected into the network and finally the variable T represents the total of bidirectional traffic.

4.2.2 Medium traffic scenario (5 Tbits/s)

The traffic matrices for this scenario are:

$$ODU0 = \begin{bmatrix} 0 & 50 & 10 & 30 & 10 & 30 \\ 50 & 0 & 0 & 10 & 50 & 0 \\ 10 & 0 & 0 & 10 & 40 & 10 \\ 30 & 10 & 10 & 0 & 10 & 10 \\ 10 & 50 & 40 & 10 & 0 & 30 \\ 30 & 0 & 10 & 10 & 30 & 0 \end{bmatrix} \qquad ODU1 = \begin{bmatrix} 0 & 20 & 40 & 20 & 0 & 50 \\ 20 & 0 & 0 & 30 & 10 & 10 \\ 40 & 0 & 0 & 10 & 10 & 0 \\ 20 & 30 & 10 & 0 & 10 & 30 \\ 0 & 10 & 10 & 10 & 0 & 10 \\ 50 & 10 & 0 & 30 & 10 & 0 \end{bmatrix}$$

$$ODU2 = \begin{bmatrix} 0 & 10 & 10 & 10 & 0 & 0 \\ 10 & 0 & 0 & 0 & 10 & 0 \\ 10 & 0 & 0 & 10 & 10 & 0 \\ 10 & 0 & 10 & 0 & 10 & 0 \\ 0 & 10 & 10 & 10 & 0 & 10 \\ 0 & 0 & 0 & 0 & 10 & 0 \end{bmatrix} \quad ODU3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 10 \\ 0 & 10 & 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ODU4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \\ 0 & 10 & 0 & 0 & 10 & 0 \end{bmatrix}$$

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

T_1^0 = 600x1.25 = 750 Gbits/s T_1^1 = 500x2.5 = 1205 Gbits/s T_1^2 = 160x10 = 1600 Gbits/s

T_1^3 = 60x40 = 2400 Gbits/s T_1^4 = 40x100 = 4000 Gbits/s

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

4.2.3 High traffic scenario (10 Tbits/s)

The traffic matrices for this scenario are:

$$ODU0 = \begin{bmatrix} 0 & 100 & 20 & 60 & 20 & 60 \\ 100 & 0 & 0 & 20 & 100 & 0 \\ 20 & 0 & 0 & 20 & 80 & 20 \\ 60 & 20 & 20 & 0 & 20 & 20 \\ 20 & 100 & 80 & 20 & 0 & 60 \\ 60 & 0 & 20 & 20 & 60 & 0 \end{bmatrix} \quad ODU1 = \begin{bmatrix} 0 & 40 & 80 & 40 & 0 & 100 \\ 40 & 0 & 0 & 60 & 20 & 20 \\ 80 & 0 & 0 & 20 & 20 & 0 \\ 40 & 60 & 20 & 0 & 20 & 60 \\ 0 & 20 & 20 & 20 & 0 & 20 \\ 100 & 20 & 0 & 60 & 20 & 0 \end{bmatrix}$$

$$ODU2 = \begin{bmatrix} 0 & 20 & 20 & 20 & 0 & 0 \\ 20 & 0 & 0 & 0 & 20 & 0 \\ 20 & 0 & 0 & 20 & 20 & 0 \\ 20 & 0 & 20 & 0 & 20 & 0 \\ 0 & 20 & 20 & 20 & 0 & 20 \\ 0 & 0 & 0 & 0 & 20 & 0 \end{bmatrix} \quad ODU3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 20 & 0 & 0 & 20 \\ 0 & 20 & 0 & 0 & 20 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 20 & 0 & 0 & 0 \\ 0 & 20 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ODU4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20 \\ 0 & 20 & 0 & 0 & 20 & 0 \end{bmatrix}$$

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

T_1^0 = 1200x1.25 = 1500 Gbits/s T_1^1 = 1000x2.5 = 2500 Gbits/s

T_1^2 = 320x10 = 3200 Gbits/s T_1^3 = 120x40 = 4800 Gbits/s

T_1^4 = 80x100 = 8000 Gbits/s

T_1 = 1500 + 2500 + 3200 + 4800 + 8000 = 20000 Gbits/s

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

Capítulo 5

Integer Linear Programming (ILP)

ILP models are used to design networks that describe real components and their capabilities through a set of linear equations. Despite their quality, the solutions obtained through these models, depending on the number of variables and computational resources, can take days, months or even years.

The focus of the current chapter is to propose and describe an optimization model for calculating the CAPEX of the network, based on the three modes of transport (opaque, transparent and translucent) without survivability and protection.

In section 5.1, it is described how the network CAPEX is calculated as well as the objective function of the dimensioning problem. In the following subsections it is proposed in detail the restrictions of the three models previously mentioned, without survivability and with protection as well as a detailed report of the obtained results for each case.

5.1 CAPEX

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement of the ILP model to obtain the best possible CAPEX of a given network.

The cost of a telecommunications network can be divided into CAPEX and OPEX. CAPEX is the amount of money needed to set up and install a particular network. OPEX is the amount of money needed to run this network as well as its maintenance and operation over time. In this section we will only focus on CAPEX, that is, the costs of installing a particular network. As we know the telecommunications networks are made up of links and nodes, so it is possible to define the CAPEX as being the sum of the cost of links and cost of nodes. This can be said that the CAPEX cost in monetary units (e.g. euros, or dollars), C_C, is given by the equation 5.1

$$C_C = C_L + C_N \tag{5.1}$$

where

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

For this calculation first let's focus on the cost of the links and for this we have to take into account the figure 5.1 where we can see the design of a link. In this figure we can see that a link consists of two optical line terminals (one at each end), it also has several amplifiers (this number depends on the length of the link) placed at a certain distance (span) and finally it also consists of several optical channels each with a certain wavelength.

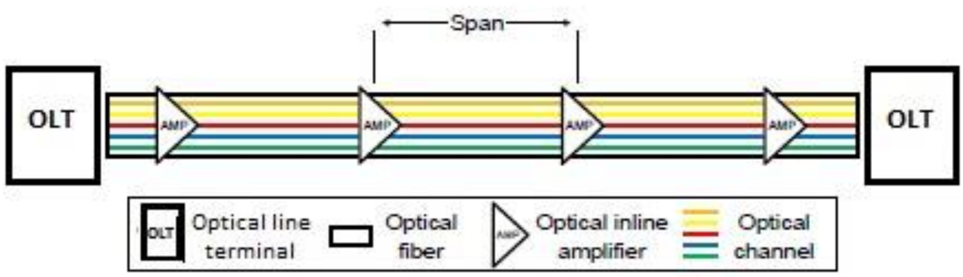


Figura 5.1: Design of a link.

Thus, through the previous image, we can conclude that the link cost in monetary units (e.g. euros, or dollars), C_L, is calculated by the equation 5.2

$$C_L = \sum_{i=1}^{N} \sum_{j=i+1}^{N} L_{ij} \left(2\gamma_0^{OLT} + 2\gamma_1^{OLT} \tau W_{ij} + 2N_{ij}^{R} c^{R} \right) \tag{5.2}$$

where

- $i \rightarrow$ Index for start node of a physical link
- $j \rightarrow$ Index for end node of a physical link
- $N \rightarrow$ Total number of nodes, N $\in \mathbb{N}$
- $L_{ij} \rightarrow$ Binary variable indicating if link between the nodes i and j is used, $L_{ij} \in 0, 1$
- $\gamma_0^{OLT} \rightarrow$ OLT cost in monetary units (e.g. euros, or dollars)
- $\gamma_1^{OLT} \rightarrow$ Transponder cost in monetary units (e.g. euros, or dollars)
- $\tau \rightarrow$ Line bit-rate
- $W_{ij} \rightarrow$ Number of optical channels in link i j
- $N_{ij}^{R} \rightarrow$ Number of optical amplifiers in link i j
- $c^{R} \rightarrow$ Optical amplifiers cost in monetary units (e.g. euros, or dollars)

The number of amplifiers for each link can be calculated by equation 5.3

$$N_{ij}^{R} = \sum_{i=1} \sum_{j=i+1} \left(\left\lceil \frac{len_{ij}}{span} \right\rceil - 1 \right) \tag{5.3}$$

where the variable len_{ij} is the length of link ij in kilometers and the $span$ is the distance between amplifiers also in kilometers. For all cases this distance is always 100 km.

The next step is to take into account the cost of the nodes, but for this we must first know how a node is constituted. The nodes have an electrical part, C_{EXC}, and an optical part, C_{OXC}, so we can conclude that the cost of the nodes, C_N, is given by the sum of these two parts thus obtaining the equation 5.4.

$$C_N = C_{EXC} + C_{OXC} \tag{5.4}$$

In relation to the electric part we can see the figure 5.2 where it shows its constitution.

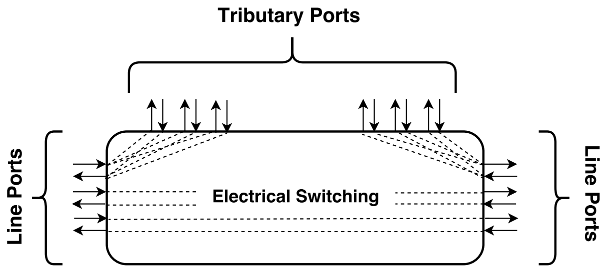


Figura 5.2: Design of a electrical switching.

Thus, through the previous image, we can conclude in a simple way that the electric cost is the sum of the fixed cost of the electrical connection with the total cost of all the electric ports. Therefore the electric cost in monetary units (e.g. euros, or dollars), C_{EXC}, is given by equation 5.5

$$C_{EXC} = \sum_{n=1}^{N} N_{exc,n} \left(\gamma_{e0} + \sum_{c=-1}^{B} \gamma_{e1,c} P_{exc,c,n} \right) \tag{5.5}$$

where

- $N \rightarrow$ Total number of nodes, N $\in \mathbb{N}$
- $N_{exc,n} \rightarrow$ Binary variable indicating if node n is used, $N_{exc,n} \in 0, 1$
- $\gamma_{e0} \rightarrow$ EXC cost in monetary units (e.g. euros, or dollars)
- $\gamma_{e1,c} \rightarrow$ EXC port cost in monetary units (e.g. euros, or dollars) with bit-rate B and with a given transceiver reach
- $P_{exc,c,n} \rightarrow$ Number of ports of the electrical switch
- $B \rightarrow$ A natural number corresponding to the maximum index of short-reach ports, see table below

Index	Bit rate
-1	100 Gbits/s line bit-rate (long-reach port)
0	1.25 Gbits/s tributary bit-rate (short-reach port)
1	2.5 Gbits/s tributary bit-rate (short-reach port)
2	10 Gbits/s tributary bit-rate (short-reach port)
3	40 Gbits/s tributary bit-rate (short-reach port)
4	100 Gbits/s tributary bit-rate (short-reach port)

Tabela 5.1: Table with index and your corresponding bit rate

In relation to the optical part we can see the figure 5.3 where it shows its constitution.

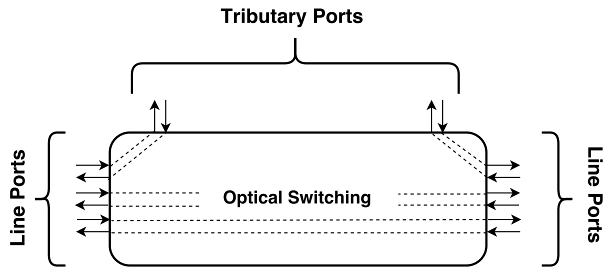


Figura 5.3: Design of a optical switching.

Thus, through the previous image, we can conclude in a simple way that the electric cost is the sum of the fixed cost of the optical connection with the total cost of all the optical ports. Therefore the optical cost in monetary units (e.g. euros, or dollars), C_{OXC}, is given by equation 5.6

$$C_{OXC} = \sum_{n=1}^{N} N_{oxc,n} \left(\gamma_{o0} + \gamma_{o1} P_{oxc,n} \right) \tag{5.6}$$

where

- $N \rightarrow$ Total number of nodes, N $\in \mathbb{N}$
- $N_{oxc,n} \rightarrow$ Binary variable indicating if node n is used, $N_{oxc,n} \in 0, 1$
- $\gamma_{o0} \rightarrow$ OXC cost in monetary units (e.g. euros, or dollars)
- $\gamma_{o1} \rightarrow$ OXC port cost in monetary units (e.g. euros, or dollars)
- $P_{oxc,n} \rightarrow$ Number of ports of the optical switch

We have to take into account that the calculated value for the variable $P_{exc,c,n}$ and $P_{oxc,n}$ will depend on the mode of transport used (opaque, transparent or translucent) but later on it will be explained how these values are calculated for each specific transport mode.

To obtain the best possible value, it will be necessary to minimize the cost of the capex mentioned above so that we can obtain the objective function 5.7.

$$minimize \quad \left\{ \ C_C \ \right\} \tag{5.7}$$

Subject to the following restrictions where these restrictions are the flow conservation constraints.

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = Z \qquad \forall(o,d): o<d, \forall i: i=o \tag{5.8}$$

This constraint ensures that, for all demand pairs (o, d), it routes Z flow of traffic for all bidirectional links (i, j) when j is not equal to the origin of the demand. The variable Z depends of the transport mode and survivability mechanism.

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = \sum_{j\backslash\{d\}} f_{ji}^{od} \qquad \forall(o,d): o<d, \forall i: i\neq o,d \tag{5.9}$$

In this constraint, assuming bidirectional traffic, so the number of flows in both directions of the link is the same.

$$\sum_{j\backslash\{d\}} f_{ji}^{od} = Z \qquad \forall(o,d): o<d, \forall i: i=d \tag{5.10}$$

This constraint ensures that, for all demand pairs (o, d), it routes Z flow of traffic for all bidirectional links (j, i) when i is not equal to the destination of the demand. The variable Z depends of the transport mode and survivability mechanism.

Finally, one aspect to be taken into account is the cost of the equipment used in the network. Through the table 5.2 we can see the cost in euros of the equipment.

Equipment	Symbol	Cost
OLT without transponders	γ_0^{OLT}	15 000 €
Transponder	γ_1^{OLT}	5 000 €/Gb
Unidirectional Optical Amplifier	c^R	4 000 €
EXC	γ_{e0}	10 000 €
OXC	γ_{o0}	20 000 €
EXC Port for line ports	$\gamma_{e1,-1}$	100 000 €/port
EXC Port for ODU0	$\gamma_{e1,0}$	10 €/port
EXC Port for ODU1	$\gamma_{e1,1}$	15 €/port
EXC Port for ODU2	$\gamma_{e1,2}$	30 €/port
EXC Port for ODU3	$\gamma_{e1,3}$	60 €/port
EXC Port for ODU4	$\gamma_{e1,4}$	100 €/port
OXC Port	γ_{o1}	2 500 €/port

Tabela 5.2: Table with costs

5.1.1 Opaque without Survivability

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the ILP model for the opaque transport mode without survivability.

Model description

First, for a better understanding of the functions and variables used in the ILP, a table 5.3 will be created with all indexes, inputs and variables and with their respective description.

Description of notation used in the objective function	
i	index for start node of a physical link
j	index for end node of a physical link
o	index for node that is origin of a demand
d	index for node that is destination of a demand
c	index for bit rate of the client signal
(i,j)	physical link between the nodes i and j
(o,d)	demand between the nodes o and d
C	set of the client signal
f_{ij}^{od}	binary variable indicating if link between the nodes i and j is used in the path between nodes o and d
L_{ij}	binary variable indicating if link between the nodes i and j is used
W_{ij}	number of optical channels between the nodes i and j
B_c	client signals granularities (1.25, 2.5, 10, 40, 100)
D_{odc}	client demands between nodes o and d with bit rate c
G_{ij}	network topology in form of adjacency matrix

Tabela 5.3: Table with description of variables used in opaque transport mode.

Before carrying out the description of the objective function we must take into account the following particularity of this mode of transport:

- $N_{OXC,n} = 0, \quad \forall$ n
- $N_{EXC,n} = 1, \quad \forall$ n that process traffic

The objective function of following the ILP is a minimization of the CAPEX through the equation 5.1 where in this case for the cost of nodes we only have in consideration the electric cost 5.5 because of the particularity previously mentioned. In this case the value of $P_{exc,c,n}$ is obtained by equation 5.11 for long-reach and by the equation 5.12 for short-reach.

As previously mentioned, equation 5.11 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e. the number of line ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} w_{nj} \tag{5.11}$$

where w_{nj} is the number of optical channels between node n and node j.

As previously mentioned, equation 5.12 refers to the number of sort-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{5.12}$$

where $D_{nd,c}$ are the client demands between nodes n and d with bit rate c.

In this case there is the following particularity:

- When n=d the value of client demands is always zero, i.e, $D_{nn,c} = 0$

The objective function, to be minimized, is the expression 5.7, i.e.,

$$minimize \quad \left\{ \; C_C \; \right\}$$

$subject\ to$

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = 1 \qquad \forall(o,d) : o < d, \forall i : i = o \tag{5.13}$$

This constraint are equal to the constraint 5.8 assuming that Z variable has the value of 1.

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = \sum_{j\backslash\{d\}} f_{ji}^{od} \qquad \forall(o,d) : o < d, \forall i : i \neq o, d \tag{5.14}$$

This constraint are equal to the constraint 5.9.

$$\sum_{j\backslash\{d\}} f_{ji}^{od} = 1 \qquad \forall(o,d) : o < d, \forall i : i = d \tag{5.15}$$

This constraint are equal to the constraint 5.10 assuming that Z variable has the value of 1.

$$\sum_{o=1} \sum_{d=o+1} \left(f_{ij}^{od} + f_{ji}^{od} \right) \sum_{c \in C} (B\,(c)\, D_{odc} \leq \tau W_{ij} G_{ij} \qquad \forall (i,j) : i < j \qquad (5.16)$$

This restriction is considered grooming constraint, so it means the total client traffic flows can not be greater than the capacity of optical transmission system on all links where τ is always 100 Gbits/s.

$$W_{ij} \leq K_{ij} L_{ij} \qquad \forall (i,j) : i < j \qquad (5.17)$$

This restriction concerns the capacity of the optical channels which must be less or equal to the maximum number of optical channels. For any situation the maximum number of optical channels supported by each transmission system is 100, i.e., K_{ij} = 100.

$$f_{ij}^{od}, f_{ji}^{od} \in \{0, 1\} \qquad \forall (i,j) : i < j, \forall (o,d) : o < d \qquad (5.18)$$

The number of flows per demand in this case can be zero if there are no traffic demands or one if considering traffic.

$$W_{ij} \in \mathbb{N} \qquad \forall (i,j) : i < j \qquad (5.19)$$

The last constraint is just needed to ensure the number optical of channels is a positive integer values greater than zero.

Result description

To perform the calculations using the implementation of the models described previously it is necessary to use a mathematical software tool. For this we will use MATLAB which is ideal for dealing with linear programming problems and can call the LPsolve through an external interface. We already have all the necessary to obtain the CAPEX value for the reference network 10.1. As described in the subsection of network traffic 4.2, we have three values of network traffic (low, medium and high traffic) so we have to obtain three different CAPEX. The value of the CAPEX of the network will be calculated based on the costs of the equipment present in the table 5.2.

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.1. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topology, the second are the logical topology for all ODUs and finally the resulting physical and optical topology.

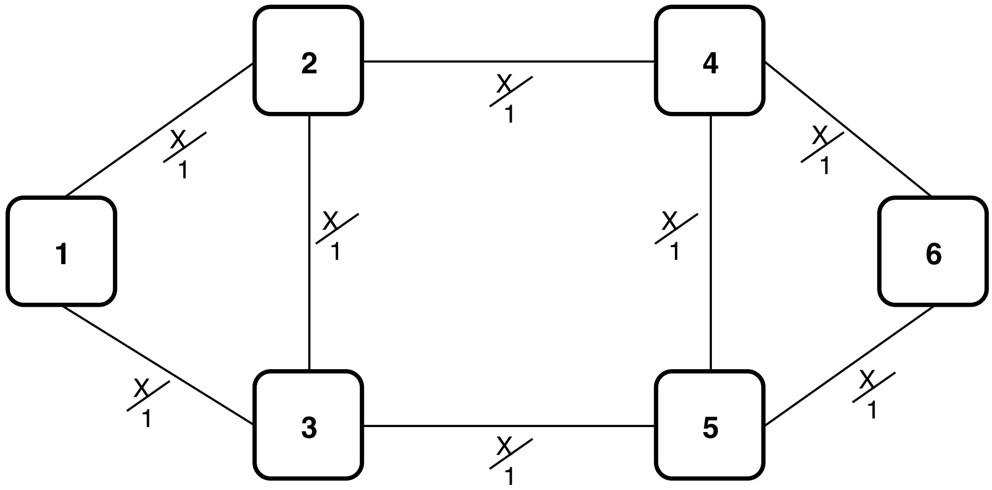


Figura 5.4: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

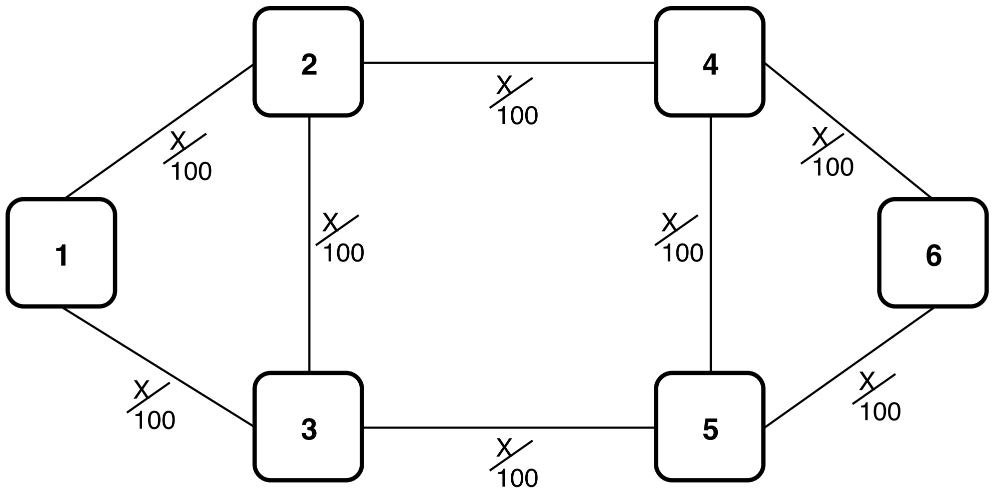


Figura 5.5: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

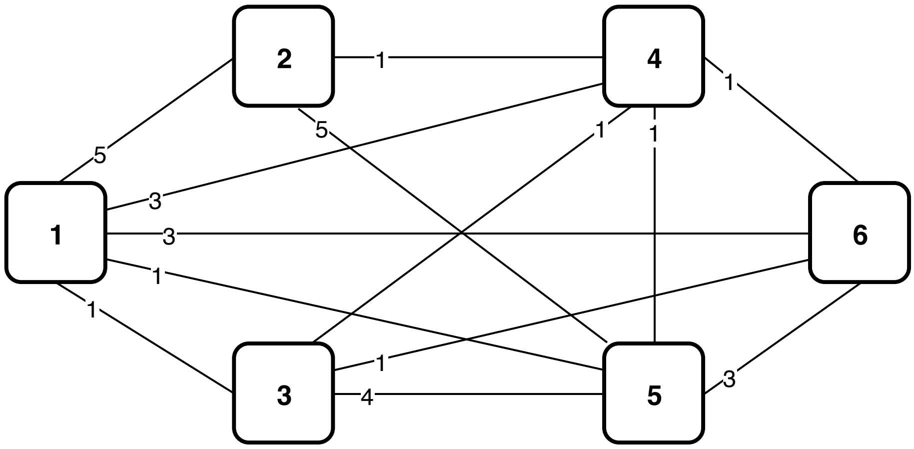


Figura 5.6: ODU0 logical topology defined by the ODU0 traffic matrix.

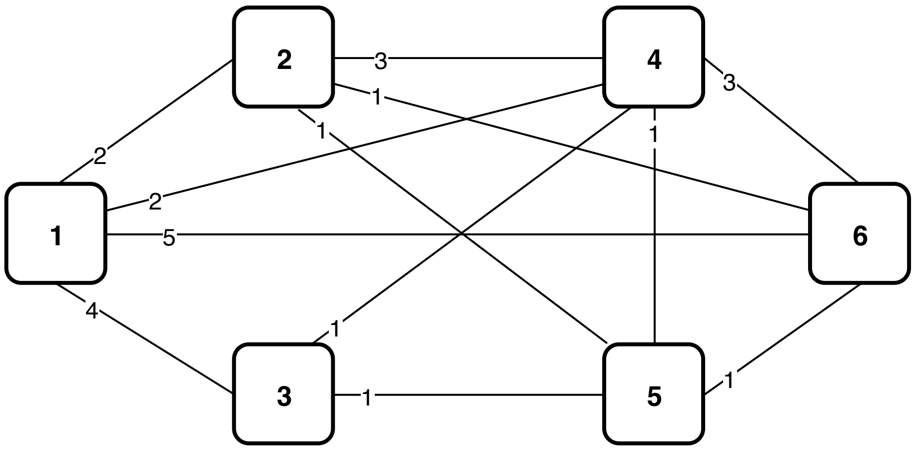


Figura 5.7: ODU1 logical topology defined by the ODU1 traffic matrix.

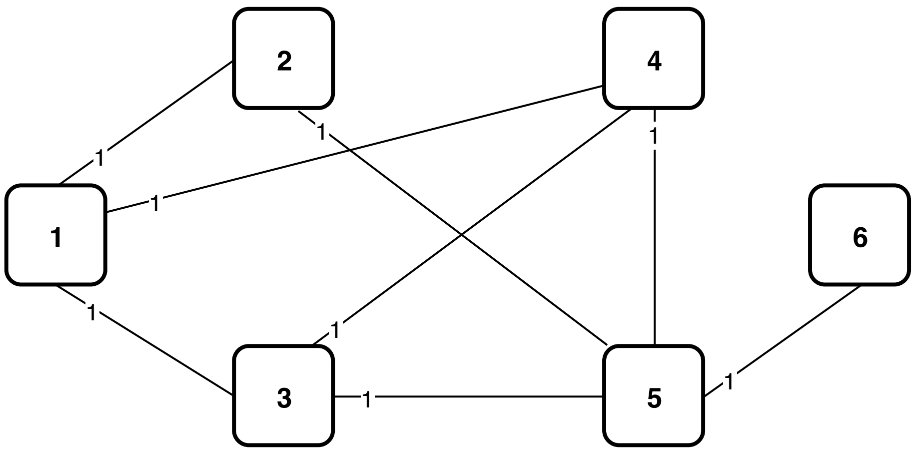


Figura 5.8: ODU2 logical topology defined by the ODU2 traffic matrix.

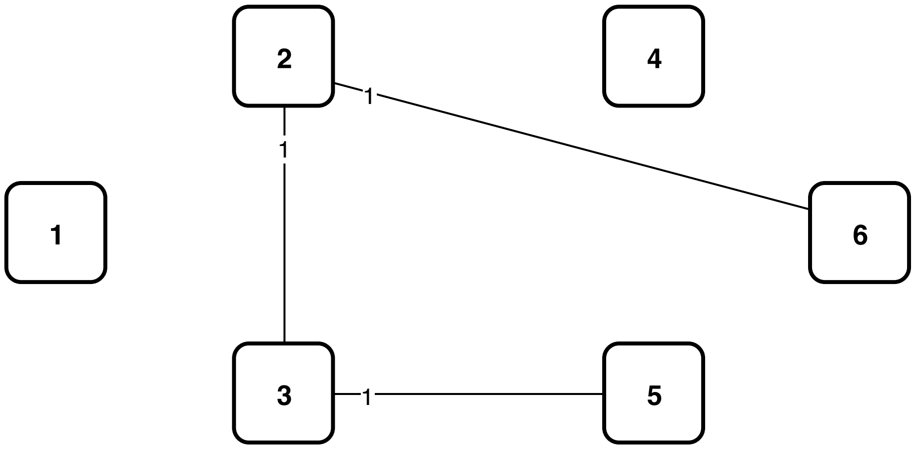


Figura 5.9: ODU3 logical topology defined by the ODU3 traffic matrix.

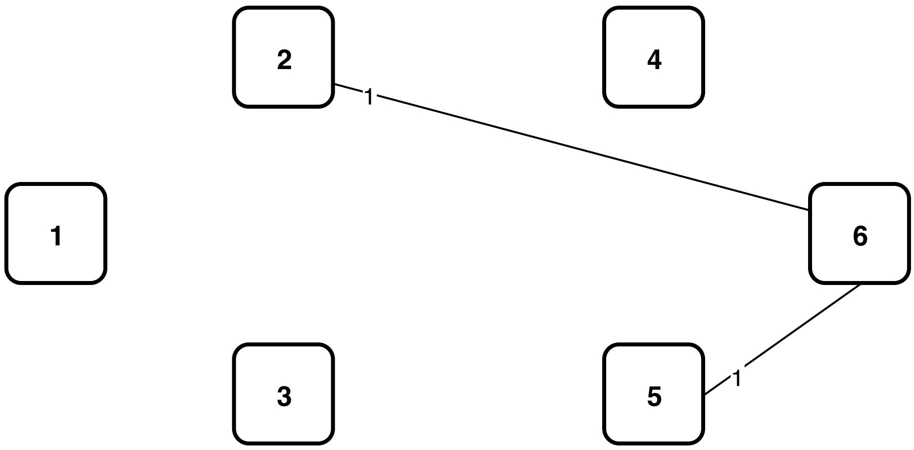


Figura 5.10: ODU4 logical topology defined by the ODU4 traffic matrix.

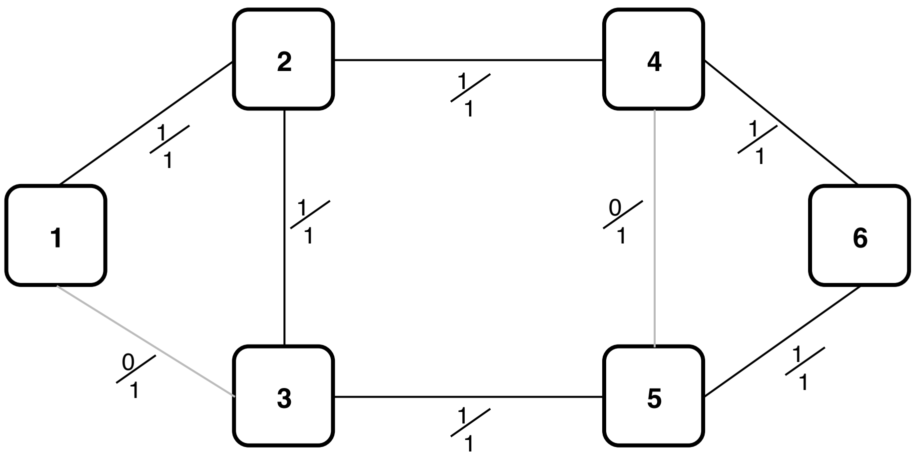


Figura 5.11: Physical topology after dimensioning.

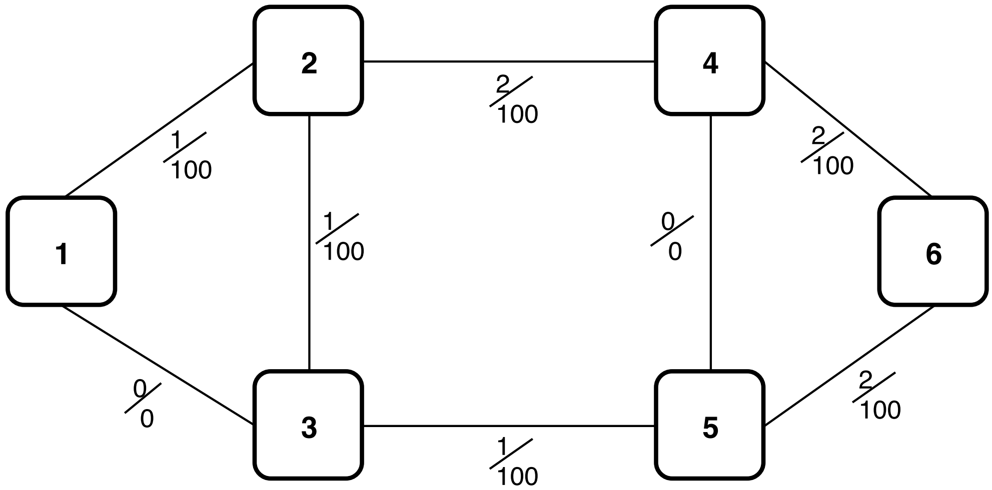


Figura 5.12: Optical topology after dimensioning.

In table 5.4 we can see the number of optical channels calculated using 5.2 and 5.7 and the number of amplifiers for each link calculated using 5.3. In the case where there are no optical channels we assume that the number of amplifiers is zero.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	1	4
Node 1 <-> Node 3	0	0
Node 2 <-> Node 3	1	0
Node 2 <-> Node 4	2	6
Node 3 <-> Node 5	1	8
Node 4 <-> Node 5	0	0
Node 4 <-> Node 6	2	7
Node 5 <-> Node 6	2	3

Tabela 5.4: Table with information regarding links for opaque mode without survivability.

In table 5.5 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports calculated using 5.11 and the number of tributary ports calculated using 5.12 for each node.

Information regarding nodes			
Node	Resulting Nodal Degree	Line Ports	Tributary Ports
1	1	1	29
2	3	4	23
3	2	2	18
4	2	4	20
5	2	3	24
6	2	4	22

Tabela 5.5: Table with information regarding nodes for opaque mode without survivability.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate (in relation to the line ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
	Number of total demands	Bit rate
29 tributary ports	13	ODU0
	13	ODU1
	3	ODU2
	Node<–Optical Channels–>Node	Bit rate
1 line ports	1 <—- 1 —-> 2	100 Gbits/s

Tabela 5.6: Table with detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1.

Detailed description of Node 2		
	Number of total demands	Bit rate
23 tributary ports	11	ODU0
	7	ODU1
	2	ODU2
	2	ODU3
	1	ODU4
	Node<–Optical Channels–>Node	Bit rate
4 line ports	2 <—- 1 —-> 1	100 Gbits/s
	2 <—- 1 —-> 3	
	2 <—- 2 —-> 4	

Tabela 5.7: Table with detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1.

Detailed description of Node 3		
	Number of total demands	Bit rate
18 tributary ports	7	ODU0
	6	ODU1
	3	ODU2
	2	ODU3
	Node<–Optical Channels–>Node	Bit rate
2 line ports	3 <—- 1 —-> 2	100 Gbits/s
	3 <—- 1 —-> 5	

Tabela 5.8: Table with detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1.

Detailed description of Node 4		
	Number of total demands	Bit rate
20 tributary ports	7	ODU0
	10	ODU1
	3	ODU2
	Node<–Optical Channels–>Node	Bit rate
4 line ports	4 <—- 2 —- > 2	100 Gbits/s
	4 <—- 2 —-> 6	

Tabela 5.9: Table with detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1.

Detailed description of Node 5		
	Number of total demands	Bit rate
24 tributary ports	14	ODU0
	4	ODU1
	4	ODU2
	1	ODU3
	1	ODU4
	Node<–Optical Channels–>Node	Bit rate
3 line ports	5 <—- 1 —-> 3	100 Gbits/s
	5 <—- 2 —-> 6	

Tabela 5.10: Table with detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1.

Detailed description of Node 6		
	Number of total demands	Bit rate
22 tributary ports	8	ODU0
	10	ODU1
	1	ODU2
	1	ODU3
	2	ODU4
	Node<–Optical Channels–>Node	Bit rate
4 line ports	6 <—- 2 —-> 4	100 Gbits/s
	6 <—- 2 —-> 5	

Tabela 5.11: Table with detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1.

In next step let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 5.12 we can see all the routing obtained for all nodes.

Routing							
o	d	Links	ODU0	ODU1	ODU2	ODU3	ODU4
1	2	{(1,2)}	5	2	1	0	0
1	3	{(1,2),(2,3)}	1	4	1	0	0
1	4	{(1,2),(2,4)}	3	2	1	0	0
1	5	{(1,2),(2,3),(3,5)}	1	0	0	0	0
1	6	{(1,2),(2,4),(4,6)}	3	5	0	0	0
2	3	{(2,3)}	0	0	0	1	0
2	4	{(2,4)}	1	3	0	0	0
2	5	{(2,3),(3,5)}	5	1	1	0	0
2	6	{(2,4),(4,6)}	0	1	0	1	1
3	4	{(3,2),(2,4)}	1	1	1	0	0
3	5	{(3,5)}	4	1	1	1	0
3	6	{(3,5),(5,6)}	1	0	0	0	0
4	5	{(4,6),(6,5)}	1	1	1	0	0
4	6	{(4,6)}	1	3	0	0	0
5	6	{(5,6)}	3	1	1	0	1

Tabela 5.12: Table with description of demands routing. We are assuming that between a pair of nodes all demands follow the same route.

Finally and most importantly through table 5.13 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above.

<table>
<tr><th colspan="7">CAPEX of the Network</th></tr>
<tr><th colspan="3"></th><th>Quantity</th><th>Unit Price</th><th>Cost</th><th>Total</th></tr>
<tr><td rowspan="3">Link Cost</td><td colspan="2">OLTs</td><td>12</td><td>15 000 €</td><td>180 000 €</td><td rowspan="3">9 404 000 €</td></tr>
<tr><td colspan="2">100 Gbits/s Transceivers</td><td>18</td><td>5 000 €/Gbit/s</td><td>9 000 000 €</td></tr>
<tr><td colspan="2">Amplifiers</td><td>56</td><td>4 000 €</td><td>224 000 €</td></tr>
<tr><td rowspan="9">Node Cost</td><td rowspan="7">Electrical</td><td>EXCs</td><td>6</td><td>10 000 €</td><td>60 000 €</td><td rowspan="9">1 862 590 €</td></tr>
<tr><td>ODU0 Ports</td><td>60</td><td>10 €/port</td><td>600 €</td></tr>
<tr><td>ODU1 Ports</td><td>50</td><td>15 €/port</td><td>750 €</td></tr>
<tr><td>ODU2 Ports</td><td>16</td><td>30 €/port</td><td>480 €</td></tr>
<tr><td>ODU3 Ports</td><td>6</td><td>60 €/port</td><td>360 €</td></tr>
<tr><td>ODU4 Ports</td><td>4</td><td>100 €/port</td><td>400 €</td></tr>
<tr><td>Line Ports</td><td>18</td><td>100 000 €/port</td><td>1 800 000 €</td></tr>
<tr><td rowspan="2">Optical</td><td>OXCs</td><td>0</td><td>20 000 €</td><td>0 €</td></tr>
<tr><td>Ports</td><td>0</td><td>2 500 €/port</td><td>0 €</td></tr>
<tr><td colspan="6">Total Network Cost</td><td>11 266 590 €</td></tr>
</table>

Tabela 5.13: Table with detailed description of CAPEX for this scenario.

All the values calculated in the previous table were obtained through the equations 5.2 and 5.4 referred to in section 5.1, but for a more detailed analysis we created table 5.14 where we can see how all the parameters are calculated individually.

	Equation used to calculate the cost
OLTs	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}\gamma_0^{OLT}$
Transceivers	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}w_{ij}\gamma_1^{OLT}\tau$
Amplifiers	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}N_{ij}^{R}c^{R}$
EXCs	$\sum_{n=1}^{N} N_{exc,n}\gamma_{e0}$
ODU0 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,0}\gamma_{e1,0}$
ODU1 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,1}\gamma_{e1,1}$
ODU2 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,2}\gamma_{e1,2}$
ODU3 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,3}\gamma_{e1,3}$
ODU4 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,4}\gamma_{e1,4}$
Line Port	$\sum_{n=1}^{N}\sum_{j=1}^{N} N_{exc,n}w_{nj}\gamma_{e1,-1}$
OXCs	For opaque transport mode this parameter is always zero.
P_{oxc}	For opaque transport mode this parameter is always zero.
CAPEX	The final cost is calculated by summing all previous results.

Tabela 5.14: Table with description of calculation

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.2. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topology, the second are the logical topology for all ODUs and finally the resulting physical and optical topology.

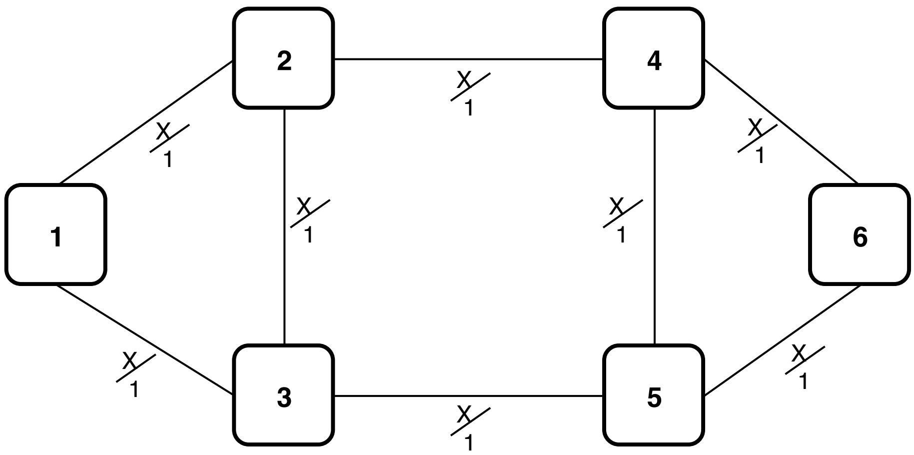


Figura 5.13: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

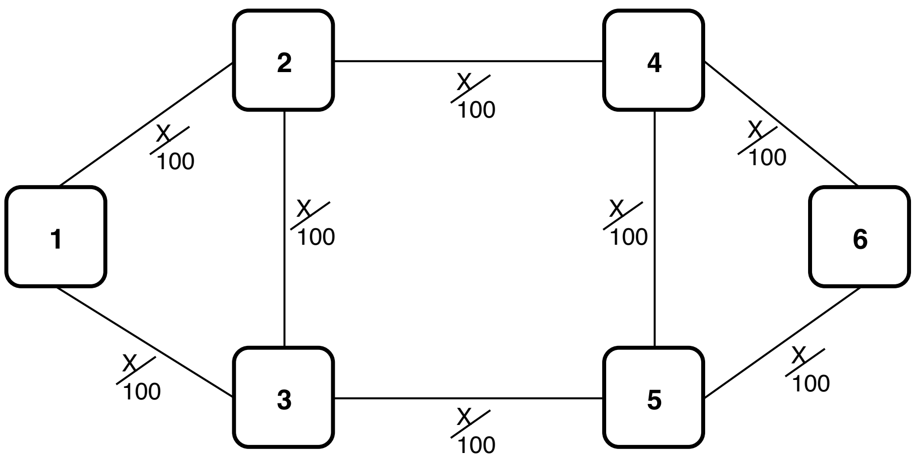


Figura 5.14: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

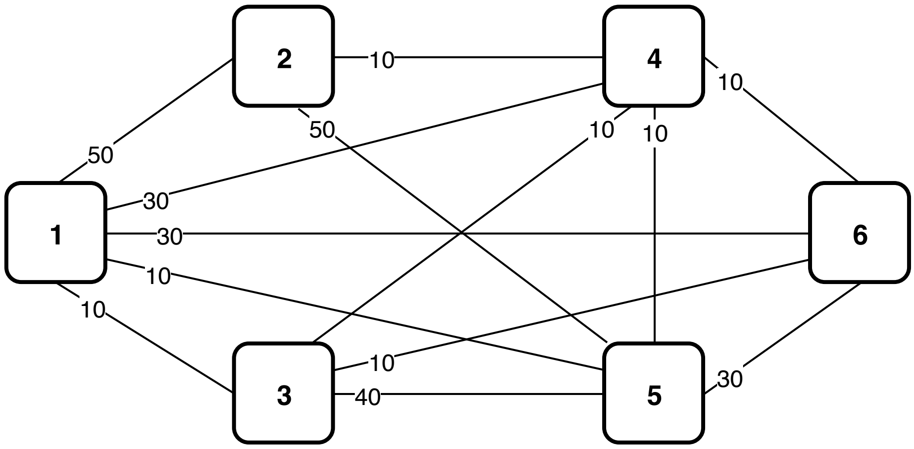


Figura 5.15: ODU0 logical topology defined by the ODU0 traffic matrix.

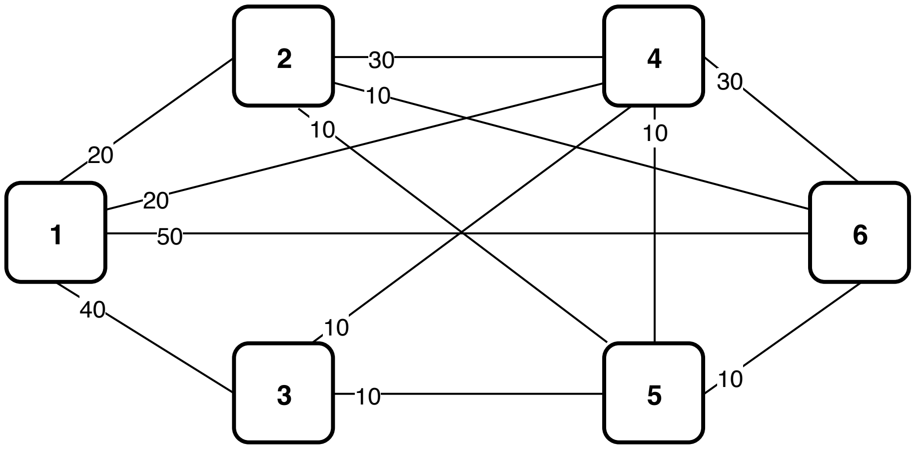


Figura 5.16: ODU1 logical topology defined by the ODU1 traffic matrix.

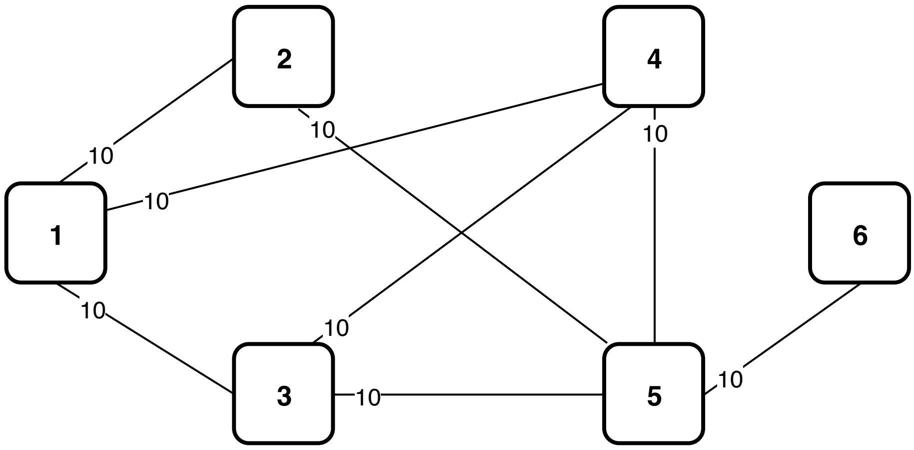


Figura 5.17: ODU2 logical topology defined by the ODU2 traffic matrix.

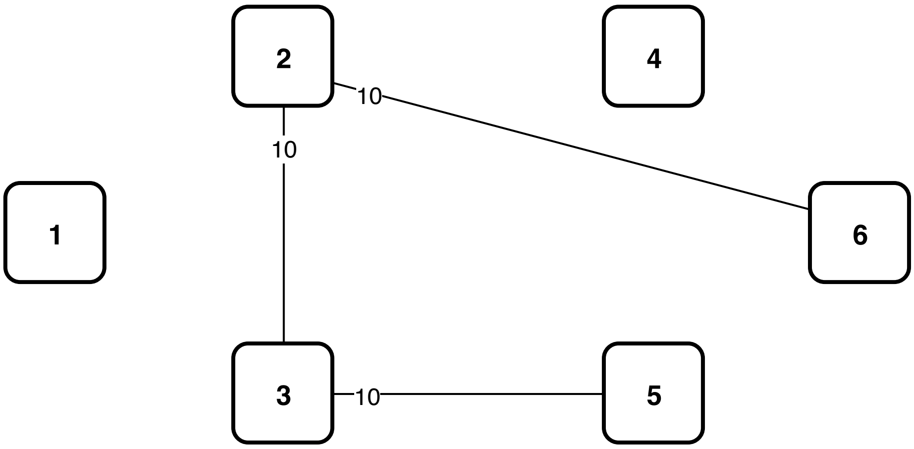


Figura 5.18: ODU3 logical topology defined by the ODU3 traffic matrix.

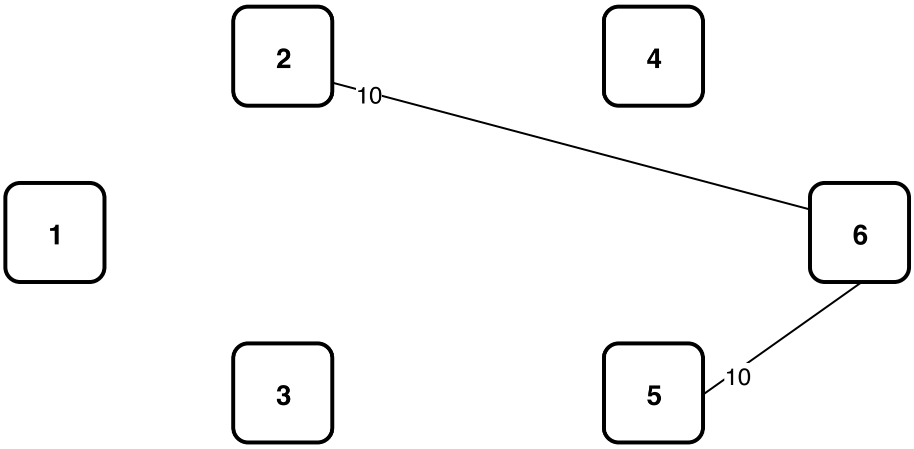


Figura 5.19: ODU4 logical topology defined by the ODU4 traffic matrix.

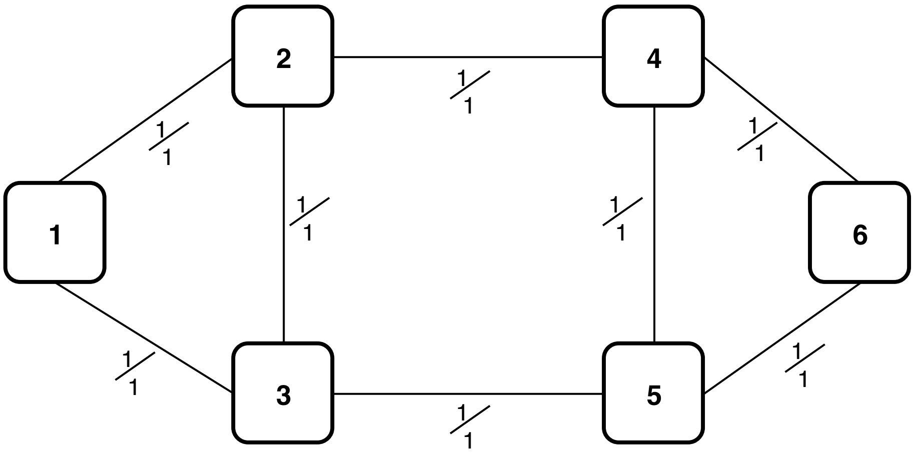


Figura 5.20: Physical topology after dimensioning.

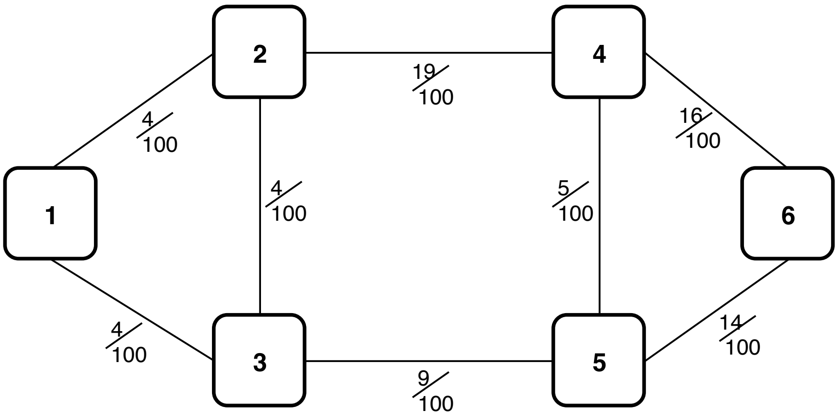


Figura 5.21: Optical topology after dimensioning.

In table 5.15 we can see the number of optical channels calculated using 5.2 and 5.1 and the number of amplifiers for each link calculated using 5.3.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	4	4
Node 1 <-> Node 3	4	6
Node 2 <-> Node 3	4	0
Node 2 <-> Node 4	19	6
Node 3 <-> Node 5	9	8
Node 4 <-> Node 5	5	1
Node 4 <-> Node 6	16	7
Node 5 <-> Node 6	14	3

Tabela 5.15: Table with information regarding links for opaque mode without survivability.

In table 5.16 we can see the resulting nodal degree at the physical layer, the number of line ports using 5.11 and the number of tributary ports using 5.12 for each node.

Information regarding nodes			
Node	Resulting Nodal Degree	Line Ports	Tributary Ports
1	2	8	290
2	3	27	230
3	3	17	180
4	3	40	200
5	3	28	240
6	2	30	220

Tabela 5.16: Table with information regarding nodes for opaque mode without survivability.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table with detailed information we can see how many ports are connected to a given node and its bit rate (in relation to the line ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
	Number of total demands	bit rate
290 tributary ports	130	ODU0
	130	ODU1
	30	ODU2
	Node <– Optical Channels –> Node	bit rate
8 line ports	1 <—- 4 —-> 2	100 Gbtis/s
	1 <—- 4 —-> 3	

Tabela 5.17: Table with detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2 .

Detailed description of Node 2		
	Number of total demands	bit rate
230 tributary ports	110	ODU0
	70	ODU1
	20	ODU2
	20	ODU3
	10	ODU4
	Node <– Optical Channels –> Node	bit rate
27 line ports	2 <—- 4 —-> 1	100 Gbtis/s
	2 <—- 4 —-> 3	
	2 <—- 19 —-> 4	

Tabela 5.18: Table with detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2.

Detailed description of Node 3		
	Number of total demands	bit rate
180 tributary ports	70	ODU0
	60	ODU1
	30	ODU2
	20	ODU3
	Node <– Optical Channels –> Node	bit rate
17 line ports	3 <—- 4 —-> 1	100 Gbtis/s
	3 <—- 4 —-> 2	
	3 <—- 9 —-> 5	

Tabela 5.19: Table with detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2.

Detailed description of Node 4		
	Number of total demands	bit rate
200 tributary ports	70	ODU0
	100	ODU1
	30	ODU2
	Node <– Optical Channels –> Node	bit rate
40 line ports	4 <—- 19 —-> 2	100 Gbtis/s
	4 <—- 5 —-> 5	
	4 <—- 16 —-> 6	

Tabela 5.20: Table with detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2.

Detailed description of Node 5		
	Number of total demands	bit rate
240 tributary ports	140	ODU0
	40	ODU1
	40	ODU2
	10	ODU3
	10	ODU4
	Node <– Optical Channels –> Node	bit rate
28 line ports	5 <—- 9 —-> 3	100 Gbtis/s
	5 <—- 5 —-> 4	
	5 <—- 14 —-> 6	

Tabela 5.21: Table with detailed description of node 5.

Detailed description of Node 6		
	Number of total demands	bit rate
220 tributary ports	80	ODU0
	100	ODU1
	10	ODU2
	10	ODU3
	20	ODU4
	Node <– Optical Channels –> Node	bit rate
30 line ports	6 <—- 16 —-> 4	100 Gbtis/s
	6 <—- 14 —-> 5	

Tabela 5.22: Table with detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2.

In next step let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 5.23 we can see all the routing obtained for all nodes.

Routing							
o	d	Links	ODU0	ODU1	ODU2	ODU3	ODU4
1	2	{(1,2)}	50	20	10	0	0
1	3	{(1,3)}	10	40	10	0	0
1	4	{(1,2),(2,4)}	30	20	10	0	0
1	5	{(1,3),(3,5)}	10	0	0	0	0
1	6	{(1,3),(3,5),(5,6)}	30	50	0	0	0
2	3	{(2,3)}	0	0	0	10	0
2	4	{(2,4)}	10	30	0	0	0
2	5	{(2,4),(4,5)}	50	10	10	0	0
2	6	{(2,4),(4,6)}	0	10	0	10	10
3	4	{(3,5),(5,4)}	10	10	10	0	0
3	5	{(3,5)}	40	10	10	10	0
3	6	{(3,5),(5,6)}	10	0	0	0	0
4	5	{(4,5)}	10	10	10	0	0
4	6	{(4,6)}	10	30	0	0	0
5	6	{(5,6)}	30	10	10	0	10

Tabela 5.23: Table with description of demands routing. We are assuming that between a pair of nodes all demands follow the same route.

Finally and most importantly through table 5.24 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above. In table 5.14 mentioned in previous scenario we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	75 520 000 €
	100 Gbits/s Transceivers		150	5 000 €/Gbit/s	75 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	15 085 900 €
		ODU0 Ports	600	10 €/port	6 000 €	
		ODU1 Ports	500	15 €/port	7 500 €	
		ODU2 Ports	160	30 €/port	4 800 €	
		ODU3 Ports	60	60 €/port	3 600 €	
		ODU4 Ports	40	100 €/port	4 000 €	
		Line Ports	150	100 000 €/port	15 000 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						90 605 900 €

Tabela 5.24: Table with detailed description of CAPEX for this scenario.

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.3. In a first phase we will show the various existing topologies of the network.

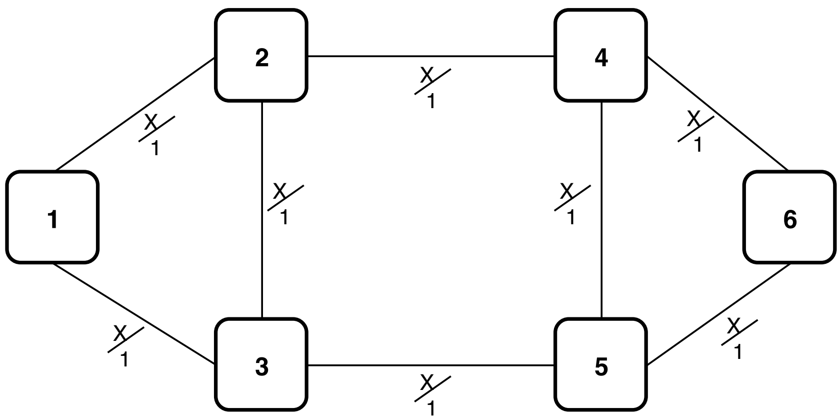


Figura 5.22: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

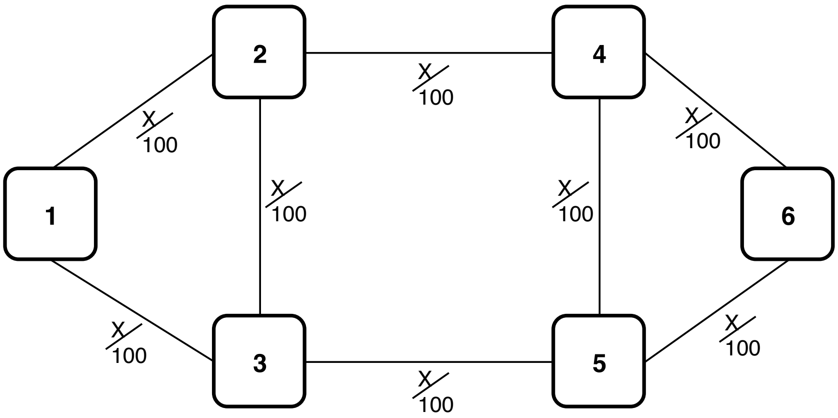


Figura 5.23: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

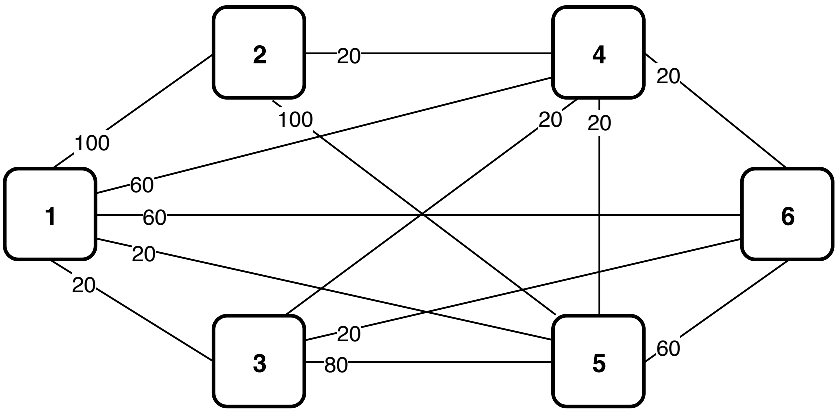


Figura 5.24: ODU0 logical topology defined by the ODU0 traffic matrix.

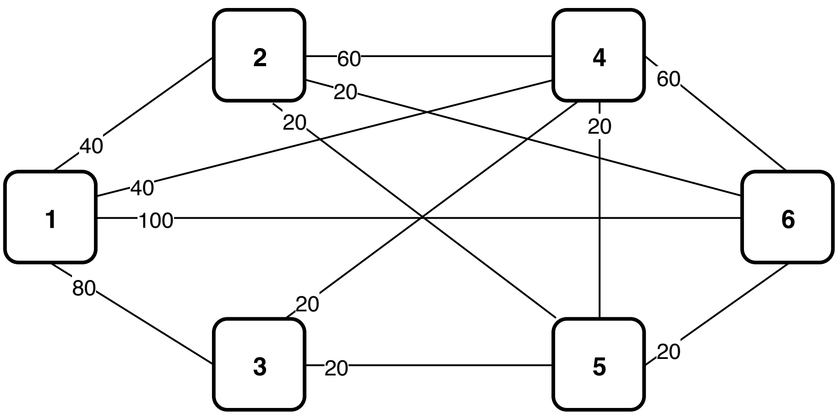


Figura 5.25: ODU1 logical topology defined by the ODU1 traffic matrix.

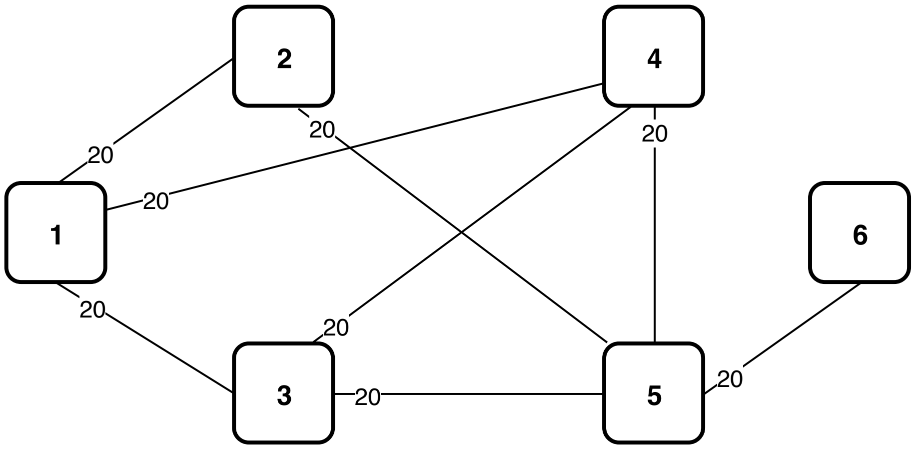


Figura 5.26: ODU2 logical topology defined by the ODU2 traffic matrix.

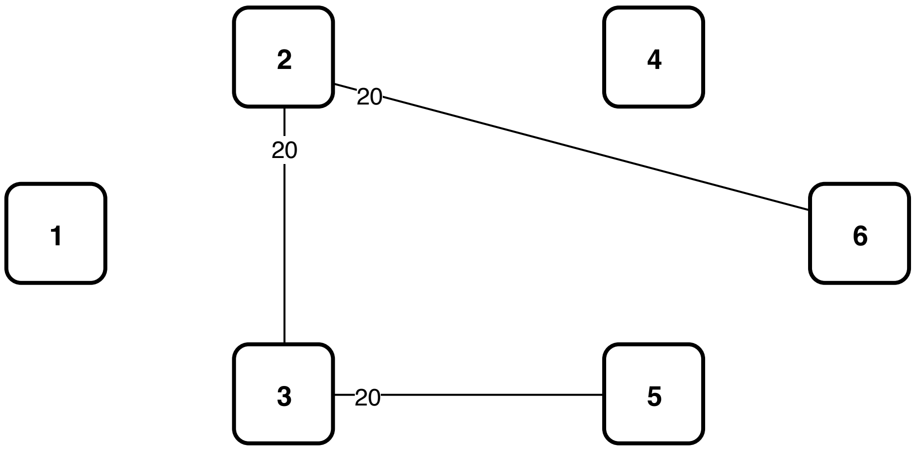


Figura 5.27: ODU3 logical topology defined by the ODU3 traffic matrix.

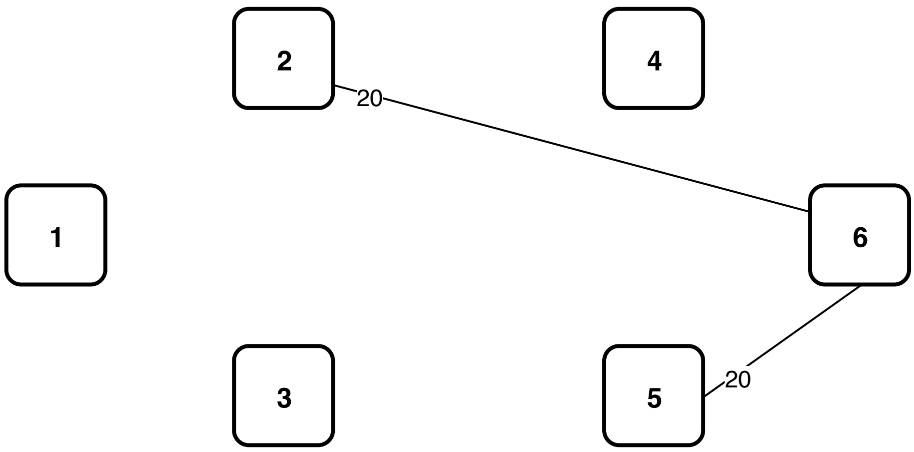


Figura 5.28: ODU4 logical topology defined by the ODU4 traffic matrix.

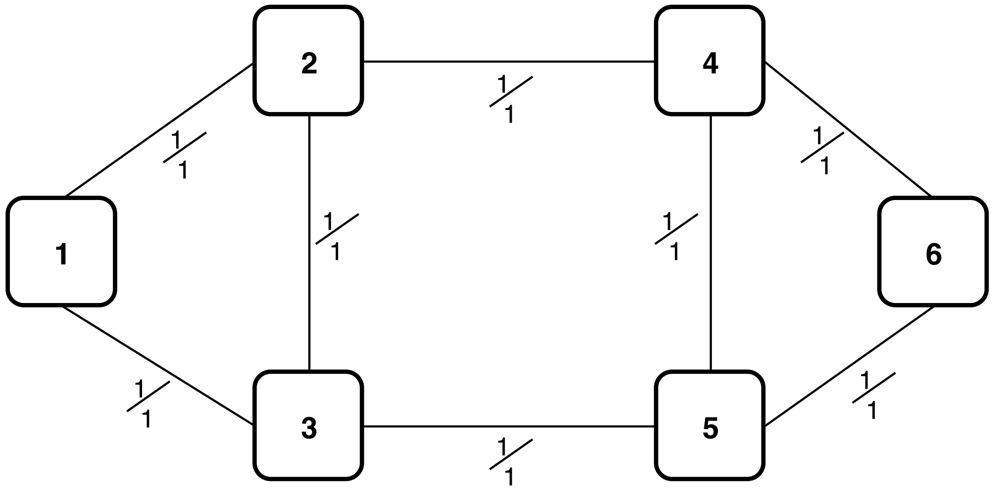


Figura 5.29: Physical topology after dimensioning.

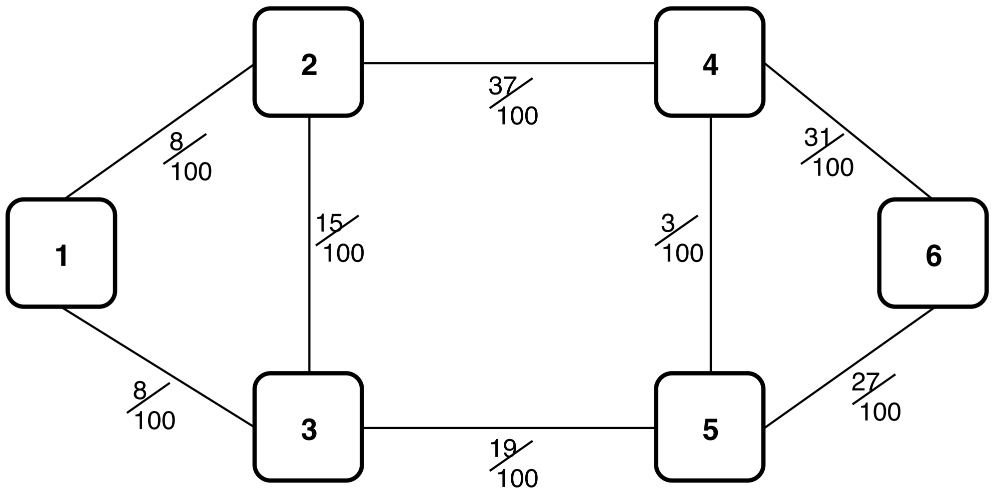


Figura 5.30: Optical topology after dimensioning.

In table 5.25 we can see the number of optical channels calculated using 5.2 and 5.1 and the number of amplifiers for each link calculated using 7.3.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	8	4
Node 1 <-> Node 3	8	6
Node 2 <-> Node 3	15	0
Node 2 <-> Node 4	37	6
Node 3 <-> Node 5	19	8
Node 4 <-> Node 5	3	1
Node 4 <-> Node 6	31	7
Node 5 <-> Node 6	27	3

Tabela 5.25: Table with information regarding links for opaque mode without survivability.

In table 5.26 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports calculated using 5.11 and the number of tributary ports calculated using 5.12 for each node.

Information regarding nodes			
Node	Resulting Nodal Degree	Line Ports	Tributary Ports
1	2	16	580
2	3	60	460
3	3	42	360
4	3	71	400
5	3	49	480
6	2	58	440

Tabela 5.26: Table with information regarding nodes for opaque mode without survivability.

In each table mentioned next with detailed information we can see how many ports are connected to a given node and its bit rate (in relation to the line ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
	Number of total demands	bit rate
580 tributary ports	260	ODU0
	260	ODU1
	60	ODU2
	Node <– Optical Channels –> Node	bit rate
16 line ports	1 <—- 8 —-> 2	100 Gbtis/s
	1 <—- 8 —-> 3	

Tabela 5.27: Table with detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3 .

Detailed description of Node 2		
	Number of total demands	bit rate
460 tributary ports	220	ODU0
	140	ODU1
	40	ODU2
	40	ODU3
	20	ODU4
	Node <– Optical Channels –> Node	bit rate
60 line ports	2 <—- 8 —-> 1	100 Gbtis/s
	2 <—- 15 —-> 3	
	2 <—- 37 —-> 4	

Tabela 5.28: Table with detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3.

Detailed description of Node 3		
	Number of total demands	bit rate
360 tributary ports	140	ODU0
	120	ODU1
	60	ODU2
	40	ODU3
	Node <– Optical Channels –> Node	bit rate
42 line ports	3 <—- 8 —-> 1	100 Gbtis/s
	3 <—- 15 —-> 2	
	3 <—- 19 —-> 5	

Tabela 5.29: Table with detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3.

Detailed description of Node 4		
	Number of total demands	bit rate
400 tributary ports	140	ODU0
	200	ODU1
	60	ODU2
	Node <– Optical Channels –> Node	bit rate
71 line ports	4 <—- 37 —-> 2	100 Gbtis/s
	4 <—- 3 —-> 5	
	4 <—- 31 —-> 6	

Tabela 5.30: Table with detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3.

Detailed description of Node 5		
	Number of total demands	bit rate
480 tributary ports	280	ODU0
	80	ODU1
	80	ODU2
	20	ODU3
	20	ODU4
	Node <– Optical Channels –> Node	bit rate
49 line ports	5 <—- 19 —-> 3	100 Gbtis/s
	5 <—- 3 —-> 4	
	5 <—- 27 —-> 6	

Tabela 5.31: Table with detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3.

Detailed description of Node 6		
	Number of total demands	bit rate
440 tributary ports	160	ODU0
	200	ODU1
	20	ODU2
	20	ODU3
	40	ODU4
	Node <– Optical Channels –> Node	bit rate
58 line ports	6 <—- 31 —-> 4	100 Gbtis/s
	6 <—- 27 —-> 5	

Tabela 5.32: Table with detailed description of node 6.

In next step let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 5.33 we can see all the routing obtained for all nodes.

Routing							
o	d	Links	ODU0	ODU1	ODU2	ODU3	ODU4
1	2	{(1,2)}	100	40	20	0	0
1	3	{(1,3)}	20	80	20	0	0
1	4	{(1,2),(2,4)}	60	40	20	0	0
1	5	{(1,3),(3,5)}	20	0	0	0	0
1	6	{(1,3),(3,5),(5,6)}	60	100	0	0	0
2	3	{(2,3)}	0	0	0	20	0
2	4	{(2,4)}	20	60	0	0	0
2	5	{(2,3),(3,5)}	100	20	20	0	0
2	6	{(2,4),(4,6)}	0	20	0	20	20
3	4	{(3,2),(2,4)}	20	20	20	0	0
3	5	{(3,5)}	80	20	20	20	0
3	6	{(3,5),(5,6)}	20	0	0	0	0
4	5	{(4,5)}	20	20	20	0	0
4	6	{(4,6)}	20	60	0	0	0
5	6	{(5,6)}	60	20	20	0	20

Tabela 5.33: Table with description of demands routing. We are assuming that between a pair of nodes all demands follow the same route.

Finally and most importantly through table 5.34 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above. In table 5.14 mentioned in previous scenario we can see how all the values were calculated.

<table>
<tr><th colspan="7">CAPEX of the Network</th></tr>
<tr><th colspan="3"></th><th>Quantity</th><th>Unit Price</th><th>Cost</th><th>Total</th></tr>
<tr><td rowspan="3">Link Cost</td><td colspan="2">OLTs</td><td>16</td><td>15 000 €</td><td>240 000 €</td><td rowspan="3">148 520 000 €</td></tr>
<tr><td colspan="2">100 Gbits/s Transceivers</td><td>296</td><td>5 000 €/Gbit/s</td><td>148 000 000 €</td></tr>
<tr><td colspan="2">Amplifiers</td><td>70</td><td>4 000 €</td><td>280 000 €</td></tr>
<tr><td rowspan="9">Node Cost</td><td rowspan="7">Electrical</td><td>EXCs</td><td>6</td><td>10 000 €</td><td>60 000 €</td><td rowspan="9">29 711 800 €</td></tr>
<tr><td>ODU0 Ports</td><td>1 200</td><td>10 €/port</td><td>12 000 €</td></tr>
<tr><td>ODU1 Ports</td><td>1 000</td><td>15 €/port</td><td>15 000 €</td></tr>
<tr><td>ODU2 Ports</td><td>320</td><td>30 €/port</td><td>9 600 €</td></tr>
<tr><td>ODU3 Ports</td><td>120</td><td>60 €/port</td><td>7 200 €</td></tr>
<tr><td>ODU4 Ports</td><td>80</td><td>100 €/port</td><td>8 000 €</td></tr>
<tr><td>Line Ports</td><td>296</td><td>100 000 €/port</td><td>29 600 000 €</td></tr>
<tr><td rowspan="2">Optical</td><td>OXCs</td><td>0</td><td>20 000 €</td><td>0 €</td></tr>
<tr><td>Ports</td><td>0</td><td>2 500 €/port</td><td>0 €</td></tr>
<tr><td colspan="6">Total Network Cost</td><td>178 231 800 €</td></tr>
</table>

Tabela 5.34: Table with detailed description of CAPEX for this scenario.

Conclusions

Once we have obtained the results for all the scenarios we will now draw some conclusions about these results. For a better analysis of the results will be created the table 5.35 with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

	Low Traffic	Medium Traffic	High Traffic
Traffic (Gbit/s)	500	5 000	10 000
Bidirectional Links used	6	8	8
Number of Line ports	18	150	296
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	18	150	296
Link Cost	9 404 000 €	75 520 000 €	148 520 000 €
Node Cost	1 862 590 €	15 085 900 €	29 711 800 €
CAPEX	**11 266 590 €**	**90 605 900 €**	**178 231 800 €**
CAPEX/Gbit/s	**22 533.18 €/Gbit/s**	**18 121.18 €/Gbit/s**	**17 823.18 €/Gbit/s**

Tabela 5.35: Table with the various CAPEX values obtained in the different traffic scenarios.

Looking at the previous table we can make some comparisons between the several scenarios:

- Low traffic scenario uses less links than the other two scenarios. This happens because as it has low traffic it is possible to carry this traffic throughout the network without having to use all available links;
- Comparing the low traffic scenario with the others we can see that despite having an increase of factor ten (medium scenario) and factor twenty (high scenario) the same increase does not occur in the final cost (it is lower). This happens because the number of transceivers is smaller than expected (medium scenario would be expected 180 and high scenario would be expected 360);
- Comparing the medium traffic scenario with the high traffic scenario we can see that the increase of the factor is double and in the final cost this factor is very close but still inferior. Again this happens because the number of transceivers is lower but very close to the expected (high scenario would be expected 300).
- Comparing the cost with traffic we see that as traffic increases the cost per traffic decreases. Soon we can conclude that it becomes more expensive a scenario of low traffic than a scenario of high traffic.

Opens Issues

The creation of this model for any scenario, started with some considerations and some open issues being:

- Allow blocking.

  The presented model assume that the solution is possible or impossible, does not support a partial solution where some demands are not routed (are blocked).
- Allow multiple transmission system.

  The presented model for each link only supports one transmission system.
- Allowing multi-path routing.

  The presented model for all demands sharing the same node pairs have to follow the same path.

5.1.2 Opaque with 1+1 Protection

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the ILP model for the opaque transport mode with 1 plus 1 protection.

Here, in this case, we must take into account table 5.3, previously mentioned, in order to better understand the objective function.

Before carrying out the description of the objective function we must take into account the following particularity of this mode of transport:

- $N_{OXC,n}$ = 0, $\forall$ n
- $N_{EXC,n}$ = 1, $\forall$ n that process traffic

The objective function of following the ILP is a minimization of the CAPEX through the equation 5.1 where in this case for the cost of nodes we only have in consideration the electric cost 5.5 because of the particularity previously mentioned. In this case the value of $P_{exc,c,n}$ is obtained by equation 5.20 for long-reach and by the equation 5.21 for short-reach.

As previously mentioned, equation 5.20 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e. the number of line ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} w_{nj} \tag{5.20}$$

where w_{nj} is the number of optical channels between node n and node j.

As previously mentioned, equation 5.12 refers to the number of sort-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{5.21}$$

where $D_{nd,c}$ are the client demands between nodes n and d with bit rate c.

In this case there is the following particularity:

- When n=d the value of client demands is always zero, i.e, $D_{nn,c} = 0$

The objective function, to be minimized, is the expression 5.7, i.e.,

$$minimize \quad \left\{ \;\; C_C \;\; \right\}$$

$subject\ to$

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = 2 \qquad \forall(o,d) : o < d, \forall i : i = o \tag{5.22}$$

This constraint are equal to the constraint 5.8 assuming that Z variable has the value of 2 (work and protection).

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = \sum_{j\backslash\{d\}} f_{ji}^{od} \qquad \forall(o,d) : o < d, \forall i : i \neq o, d \tag{5.23}$$

This constraint are equal to the constraint 5.9.

$$\sum_{j\backslash\{d\}} f_{ji}^{od} = 2 \qquad \forall(o,d) : o < d, \forall i : i = d \tag{5.24}$$

This constraint are equal to the constraint 5.10 assuming that Z variable has the value of 2 (work and protection).

$$\sum_{o=1} \sum_{d=o+1} \left(f_{ij}^{od} + f_{ji}^{od} \right) \sum_{c \in C} (B\,(c)\, D_{odc} \leq \tau W_{ij} G_{ij} \qquad \forall(i,j) : i < j \tag{5.25}$$

This restriction is considered grooming constraint, so it means the total client traffic flows can not be greater than the capacity of optical transmission system on all links where τ is always 100.

$$W_{ij} \leq K_{ij} L_{ij} \qquad \forall(i,j) : i < j \tag{5.26}$$

This restriction concerns the capacity of the optical channels which must be less or equal to the maximum number of optical channels. For any situation the maximum number of optical channels supported by each transmission system is 100, i.e., K_{ij} = 100.

$$L_{ij}, f_{ij}^{od}, f_{ji}^{od} \in \{0,1\} \qquad \forall(i,j) : i < j, \forall(o,d) : o < d \tag{5.27}$$

The number of flows per demand in this case can be zero if there are no traffic demands or one if considering working or protection traffic, in relation to the use of the link, can be zero if it is not being used or one if is being used.

$$W_{ij} \in \mathbb{N} \qquad \forall(i,j) : i < j \tag{5.28}$$

The last constraint is just needed to ensure the number optical of channels is a positive integer values greater than zero.

Result description

To perform the calculations using the implementation of the models described in previous subsection it is necessary to use the MATLAB once more.
We already have all the necessary to obtain the CAPEX value for the reference network 10.1. As described in the subsection of network traffic 4.2, we have three values of network traffic (low, medium and high traffic) so we have to obtain three different CAPEX. The value of the CAPEX of the network will be calculated based on the costs of the equipment present in the table 5.2.

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.1. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topology, the second are the logical topology for all ODUs and finally the resulting physical and optical topology.

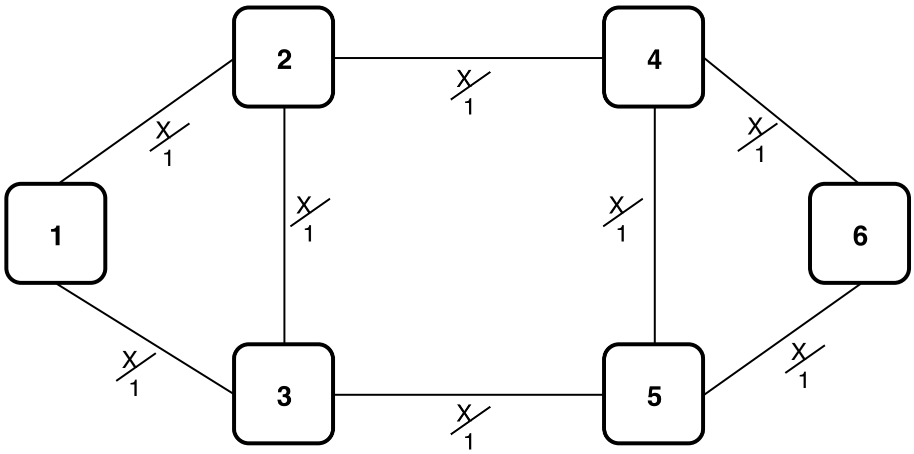


Figura 5.31: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

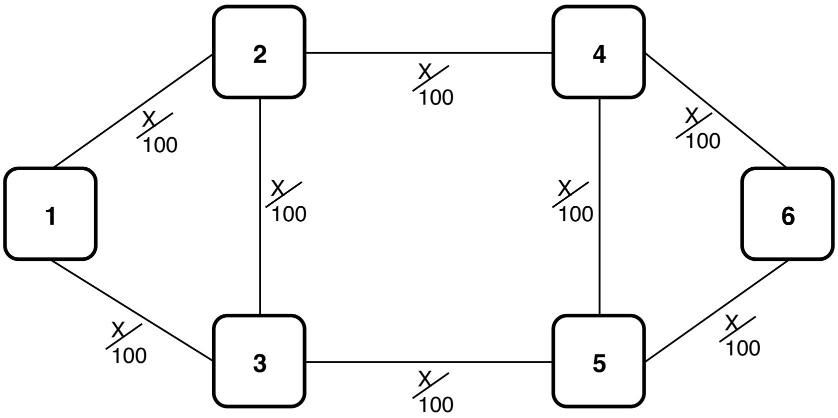


Figura 5.32: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

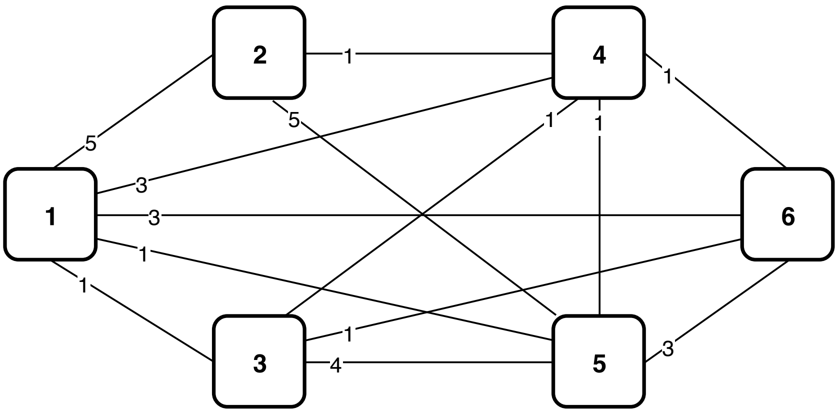


Figura 5.33: ODU0 logical topology defined by the ODU0 traffic matrix.

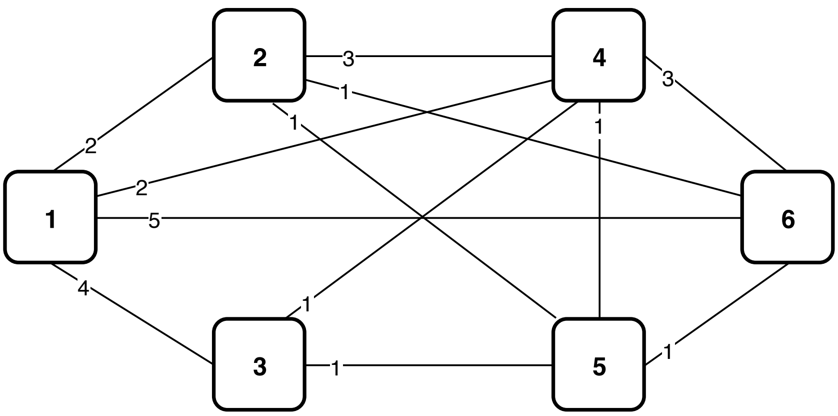


Figura 5.34: ODU1 logical topology defined by the ODU1 traffic matrix.

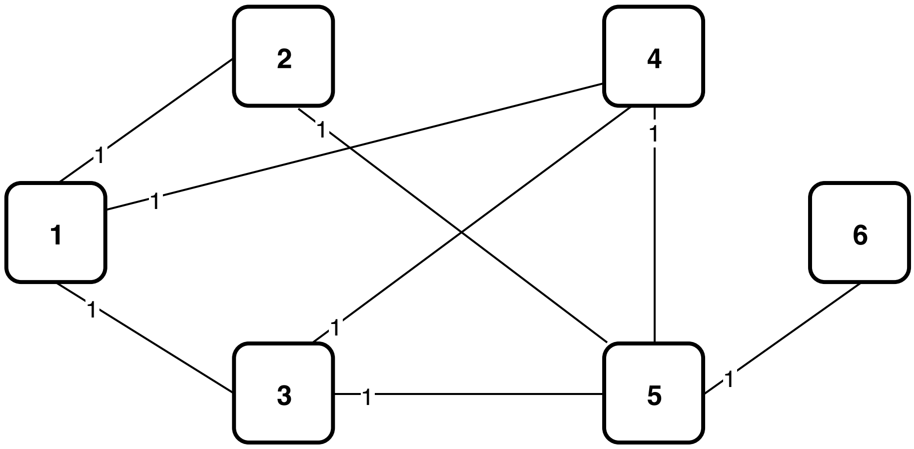


Figura 5.35: ODU2 logical topology defined by the ODU2 traffic matrix.

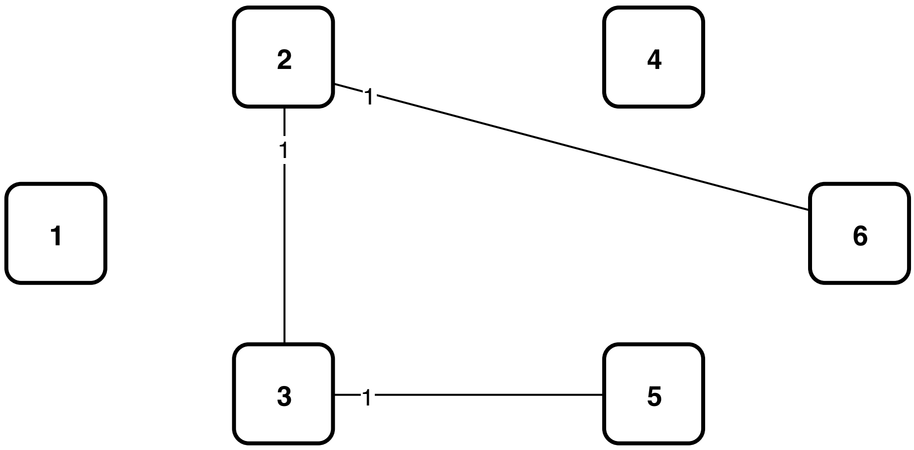


Figura 5.36: ODU3 logical topology defined by the ODU3 traffic matrix.

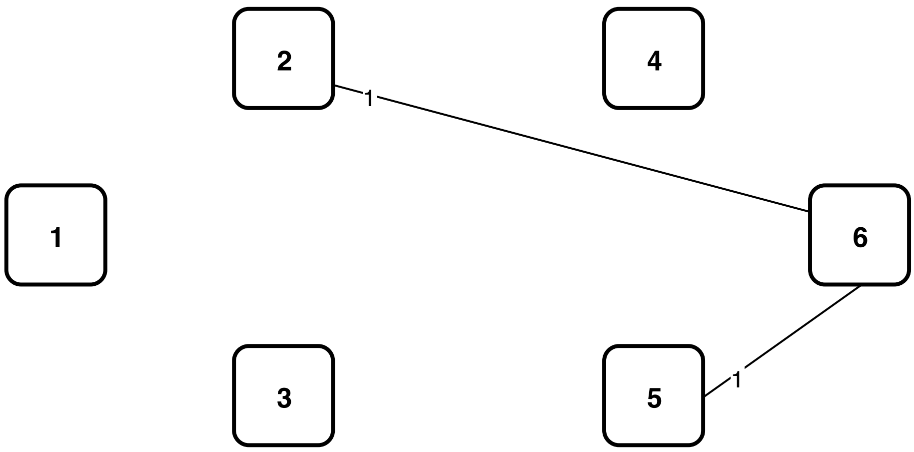


Figura 5.37: ODU4 logical topology defined by the ODU4 traffic matrix.

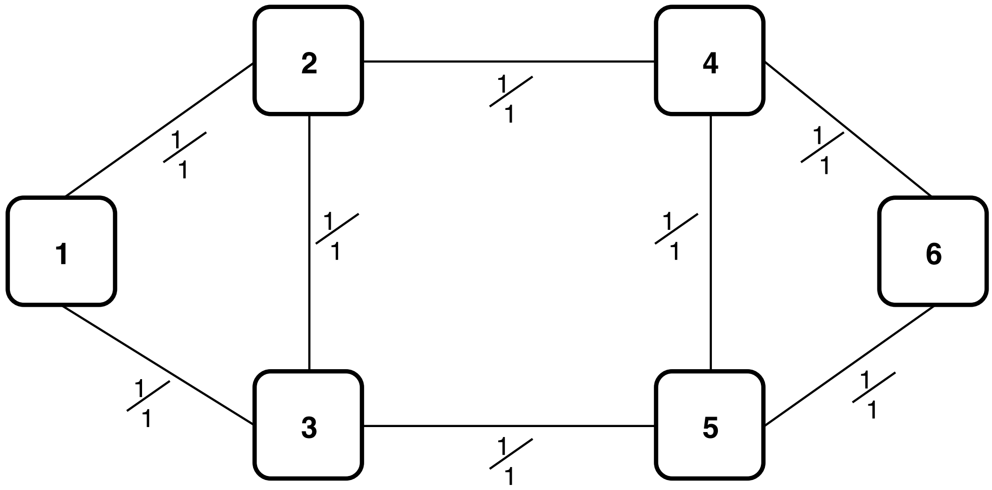


Figura 5.38: Physical topology after dimensioning.

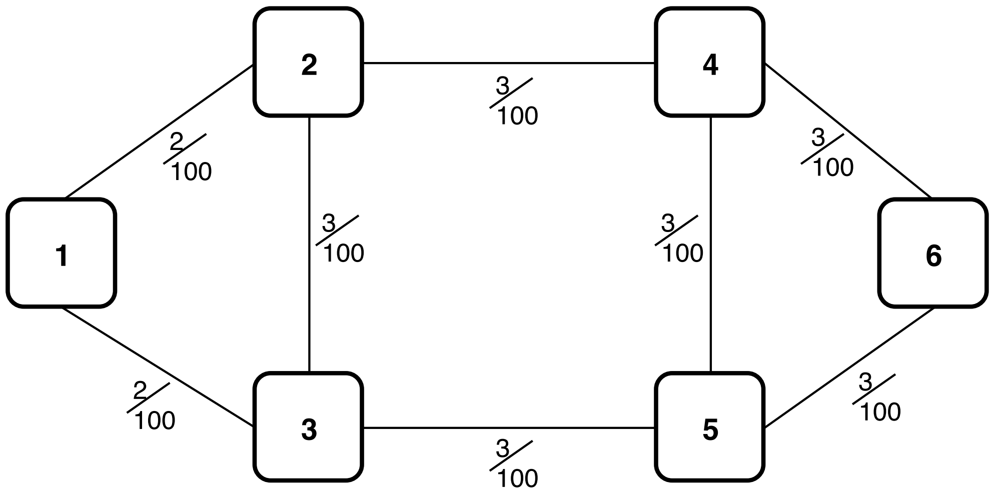


Figura 5.39: Optical topology after dimensioning.

In table 5.36 we can see the number of optical channels calculated using 5.2 and 5.7 and the number of amplifiers for each link calculated using 5.3.

In table 5.37 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports calculated using 5.20 and the number of tributary ports calculated using 5.21 for each node.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	2	4
Node 1 <-> Node 3	2	6
Node 2 <-> Node 3	3	0
Node 2 <-> Node 4	3	6
Node 3 <-> Node 5	3	8
Node 4 <-> Node 5	3	1
Node 4 <-> Node 6	3	7
Node 5 <-> Node 6	3	3

Tabela 5.36: Table with information regarding links for opaque mode with 1+1 protection.

Information regarding nodes			
Node	Resulting Nodal Degree	Line Ports	Tributary Ports
1	2	4	29
2	3	8	23
3	3	8	18
4	3	9	20
5	3	9	24
6	2	6	22

Tabela 5.37: Table with information regarding nodes for opaque mode with 1+1 protection.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate (in relation to the line ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
	Number of tributary ports	Bit rate
29 tributary ports	13	ODU0
	13	ODU1
	3	ODU2
	Node<–Optical Channels–>Node	Bit rate
4 line ports	1 <—- 2 —-> 2	100 Gbits/s
	1 <—- 2 —-> 3	

Tabela 5.38: Table with detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1.

Detailed description of Node 2		
	Number of total demands	Bit rate
23 tributary ports	11	ODU0
	7	ODU1
	2	ODU2
	2	ODU3
	1	ODU4
	Node<–Optical Channels–>Node	Bit rate
8 line ports	2 <—- 2 —-> 1 2 <—- 3 —-> 3 2 <—- 3 —-> 4	100 Gbits/s

Tabela 5.39: Table with detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1.

Detailed description of Node 3		
	Number of total demands	Bit rate
18 tributary ports	7	ODU0
	6	ODU1
	3	ODU2
	2	ODU3
	Node<–Optical Channels–>Node	Bit rate
8 line ports	3 <—- 2 —-> 1 3 <—- 3 —-> 2 3 <—- 3 —-> 5	100 Gbits/s

Tabela 5.40: Table with detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1.

Detailed description of Node 4		
	Number of total demands	Bit rate
20 tributary ports	7	ODU0
	10	ODU1
	3	ODU2
	Node<–Optical Channels–>Node	Bit rate
9 line ports	4 <—- 3 —-> 2 4 <—- 3 —-> 5 4 <—- 3 —-> 6	100 Gbits/s

Tabela 5.41: Table with detailed description of node 4.

Detailed description of Node 5		
	Number of total demands	Bit rate
24 tributary ports	14	ODU0
	4	ODU1
	4	ODU2
	1	ODU3
	1	ODU4
	Node<–Optical Channels–>Node	Bit rate
9 line ports	5 <—- 3 —-> 2	100 Gbits/s
	5 <—- 3 —-> 4	
	5 <—- 3 —-> 6	

Tabela 5.42: Table with detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1.

Detailed description of Node 6		
	Number of total demands	Bit rate
22 tributary ports	8	ODU0
	10	ODU1
	1	ODU2
	1	ODU3
	2	ODU4
	Node<–Optical Channels–>Node	Bit rate
6 line ports	6 <—- 3 —-> 4	100 Gbits/s
	6 <—- 3 —-> 5	

Tabela 5.43: Table with detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1.

Now in next page, let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 5.44 we can see all the routing obtained for all nodes. In the Links column we can see that there are two paths but it is not possible to distinguish them because we do not know which is protection and which is working.

Routing							
o	d	Links	ODU0	ODU1	ODU2	ODU3	ODU4
1	2	{(1,2)} {(1,3),(3,2)}	5	2	1	0	0
1	3	{(1,3)} {(1,2),(2,3)}	1	4	1	0	0
1	4	{(1,2),(2,4)} {(1,3),(3,5),(5,4)}	3	2	1	0	0
1	5	{(1,3),(3,5)} {(1,2),(2,4),(4,5)}	1	0	0	0	0
1	6	{(1,2),(2,4),(4,6)} {(1,3),(3,5),(5,6)}	3	5	0	0	0
2	3	{(2,3)} {(2,1),(1,3)}	0	0	0	1	0
2	4	{(2,4)} {(2,3),(3,5),(5,4)}	1	3	0	0	0
2	5	{(2,3),(3,5)} {(2,4),(4,5)}	5	1	1	0	0
2	6	{(2,4),(4,6)} {(2,3),(3,5),(5,6)}	0	1	0	1	1
3	4	{(3,2),(2,4)} {(3,5),(5,4)}	1	1	1	0	0
3	5	{(3,5)} {(3,1),(1,2),(2,4),(4,5)}	4	1	1	1	0
3	6	{(3,5),(5,6)} {(3,2),(2,4),(4,6)}	1	0	0	0	0
4	5	{(4,5)} {(4,6),(6,5)}	1	1	1	0	0
4	6	{(4,6)} {(4,5),(5,6)}	1	3	0	0	0
5	6	{(5,6)} {(5,4),(4,6)}	3	1	1	0	1

Tabela 5.44: Table with description of routing. We are assuming that between a pair of nodes all demands follow the same route.

Finally and most importantly through table 5.45 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above. In table 5.14 mentioned in first model we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	22 520 000 €
	100 Gbits/s Transceivers		44	5 000 €/Gbit/s	22 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	4 462 590 €
		ODU0 Ports	60	10 €/port	600 €	
		ODU1 Ports	50	15 €/port	750 €	
		ODU2 Ports	16	30 €/port	480 €	
		ODU3 Ports	6	60 €/port	360 €	
		ODU4 Ports	4	100 €/port	400 €	
		Line Ports	44	100 000 €/port	4 400 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/porto	0 €	
Total Network Cost						26 982 590 €

Tabela 5.45: Table with detailed description of CAPEX for this scenario.

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.2. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topology, the second are the logical topology for all ODUs and finally the resulting physical and optical topology.

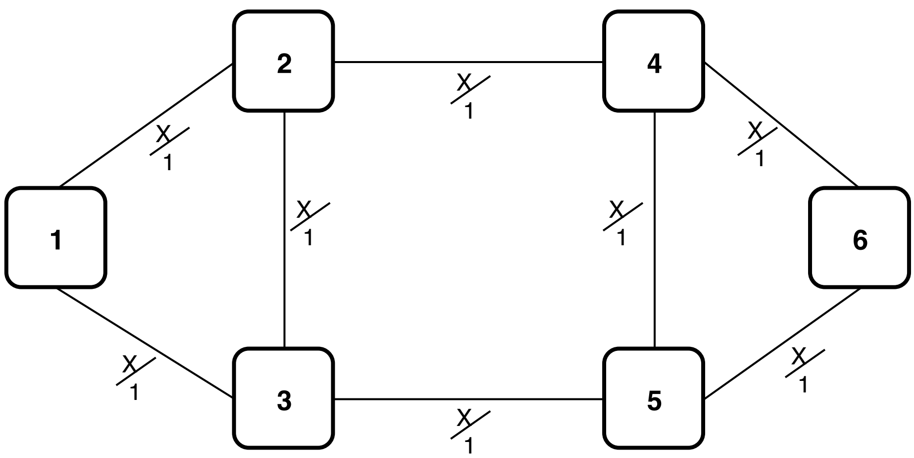


Figura 5.40: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

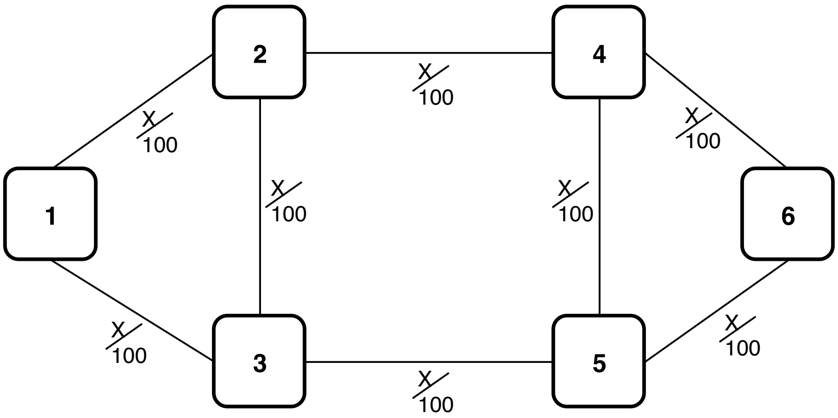


Figura 5.41: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

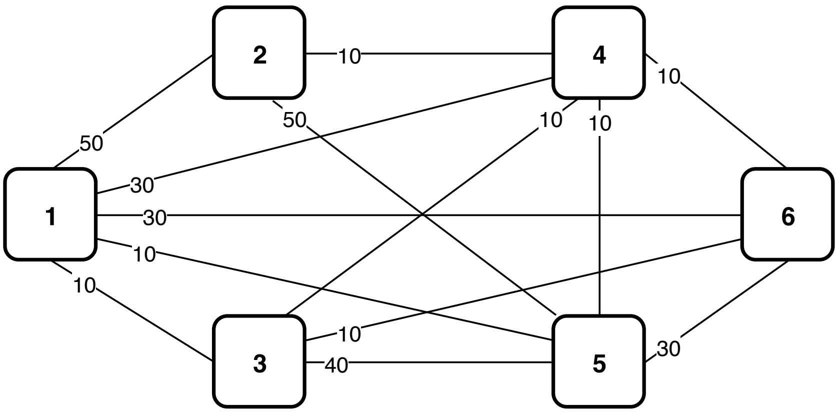


Figura 5.42: ODU0 logical topology defined by the ODU0 traffic matrix.

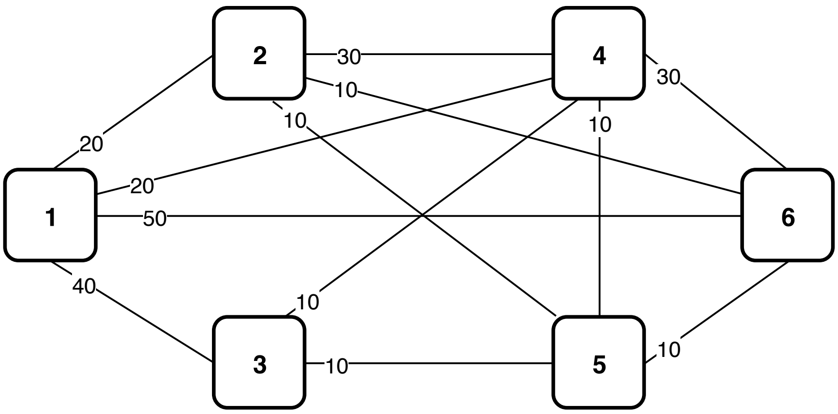


Figura 5.43: ODU1 logical topology defined by the ODU1 traffic matrix.

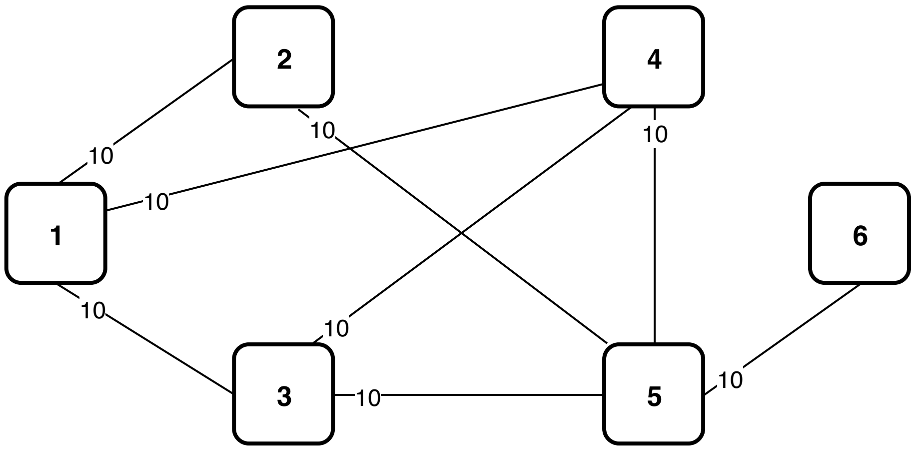


Figura 5.44: ODU2 logical topology defined by the ODU2 traffic matrix.

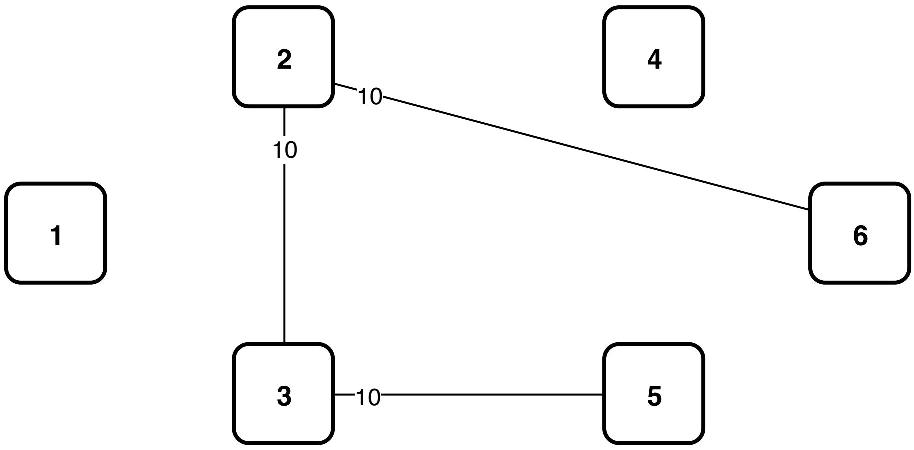


Figura 5.45: ODU3 logical topology defined by the ODU3 traffic matrix.

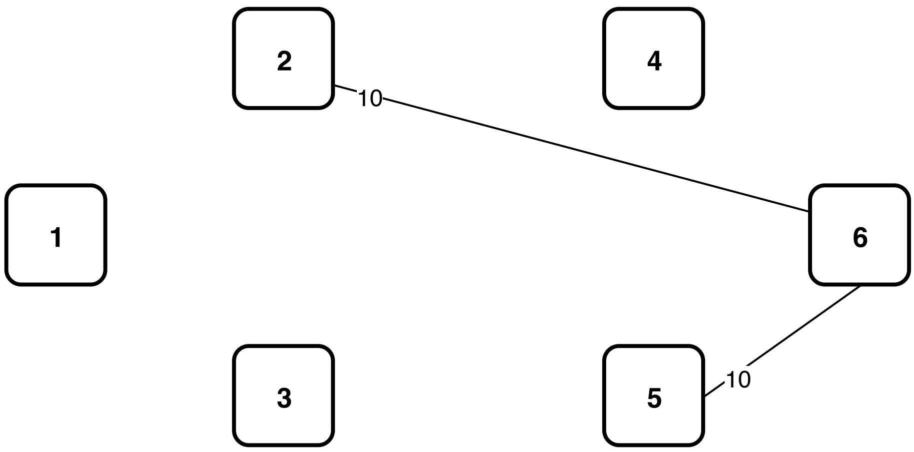


Figura 5.46: ODU4 logical topology defined by the ODU4 traffic matrix.

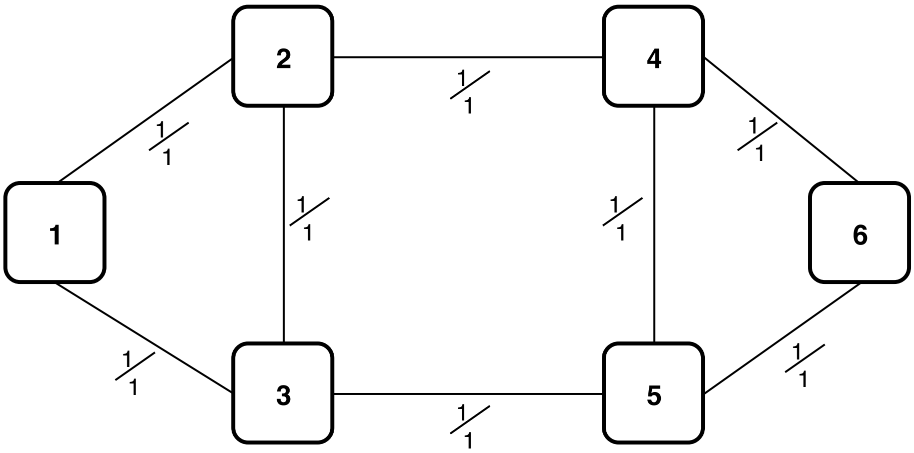


Figura 5.47: Physical topology after dimensioning.

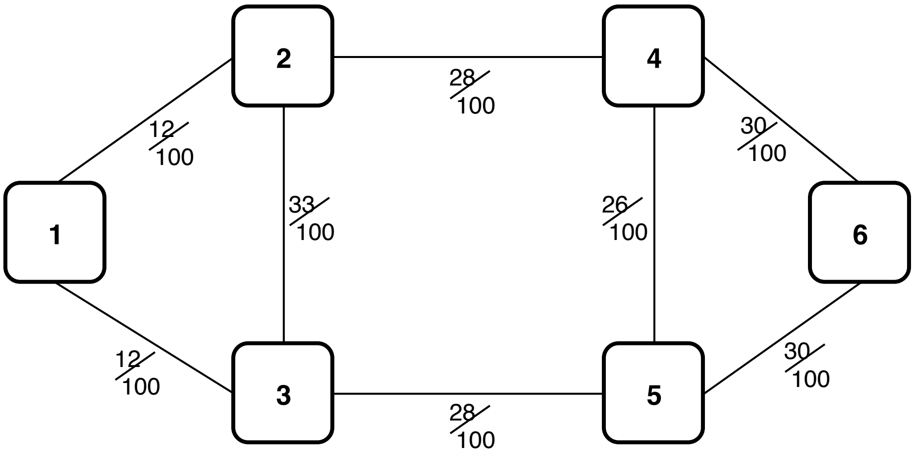


Figura 5.48: Optical topology after dimensioning.

In table 5.46 we can see the number of optical channels calculated using 5.2 and 5.7 and the number of amplifiers for each link calculated using 5.3.

In table 5.47 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports calculated using 5.20 and the number of tributary ports calculated using 5.21 for each node.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	12	4
Node 1 <-> Node 3	12	6
Node 2 <-> Node 3	33	0
Node 2 <-> Node 4	28	6
Node 3 <-> Node 5	28	8
Node 4 <-> Node 5	26	1
Node 4 <-> Node 6	30	7
Node 5 <-> Node 6	30	3

Tabela 5.46: Table with information regarding links for opaque mode with 1+1 protection.

Information regarding nodes			
Node	Connections	Line Ports	Tributary Ports
1	2	24	290
2	3	73	230
3	3	73	180
4	3	84	200
5	3	84	240
6	2	60	220

Tabela 5.47: Table with information regarding nodes for opaque mode with 1+1 protection.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate (in relation to the line ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
	Number of total demands	bit rate
290 tributary ports	130	ODU0
	130	ODU1
	30	ODU2
	Node <– Optical Channels –> Node	bit rate
24 line ports	1 <—- 12 —-> 2	100 Gbtis/s
	1 <—- 12 —-> 3	

Tabela 5.48: Table with detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2.

Detailed description of Node 2		
	Number of total demands	bit rate
230 tributary ports	110	ODU0
	70	ODU1
	20	ODU2
	20	ODU3
	10	ODU4
	Node <– Optical Channels –> Node	bit rate
73 line ports	2 <—- 12 —-> 1	100 Gbtis/s
	2 <—- 33 —-> 3	
	2 <—- 28 —-> 4	

Tabela 5.49: Table with detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2.

Detailed description of Node 3		
	Number of total demands	bit rate
180 tributary ports	70	ODU0
	60	ODU1
	30	ODU2
	20	ODU3
	Node <– Optical Channels –> Node	bit rate
73 line ports	3 <—- 12 —-> 1	100 Gbtis/s
	3 <—- 33 —-> 2	
	3 <—- 28 —-> 5	

Tabela 5.50: Table with detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2.

Detailed description of Node 4		
	Number of total demands	bit rate
200 tributary ports	70	ODU0
	100	ODU1
	30	ODU2
	Node <– Optical Channels –> Node	bit rate
84 line ports	4 <—- 28 —-> 2	100 Gbtis/s
	4 <—- 26 —-> 5	
	4 <—- 30 —-> 6	

Tabela 5.51: Table with detailed description of node 4.

Detailed description of Node 5		
	Number of total demands	bit rate
240 tributary ports	140	ODU0
	40	ODU1
	40	ODU2
	10	ODU3
	10	ODU4
	Node <– Optical Channels –> Node	bit rate
84 line ports	5 <—- 28 —-> 3	100 Gbtis/s
	5 <—- 26 —-> 4	
	5 <—- 30 —-> 6	

Tabela 5.52: Table with detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2.

Detailed description of Node 6		
	Number of total demands	bit rate
220 tributary ports	80	ODU0
	100	ODU1
	10	ODU2
	10	ODU3
	20	ODU4
	Node <– Optical Channels –> Node	bit rate
60 line ports	6 <—- 30 —-> 4	100 Gbtis/s
	6 <—- 30 —-> 5	

Tabela 5.53: Table with detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2 .

Now in next page, let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 5.54 we can see all the routing obtained for all nodes. In the Links column we can see that there are two paths but it is not possible to distinguish them because we do not know which is protection and which is working.

Routing							
o	d	Links	ODU0	ODU1	ODU2	ODU3	ODU4
1	2	{(1,2)} {(1,3),(3,2)}	5	2	1	0	0
1	3	{(1,3)} {(1,2),(2,3)}	1	4	1	0	0
1	4	{(1,2),(2,4)} {(1,3),(3,5),(5,4)}	3	2	1	0	0
1	5	{(1,3),(3,5)} {(1,2),(2,4),(4,5)}	1	0	0	0	0
1	6	{(1,2),(2,4),(4,6)} {(1,3),(3,5),(5,6)}	3	5	0	0	0
2	3	{(2,3)} {(2,1),(1,3)}	0	0	0	1	0
2	4	{(2,4)} {(2,3),(3,5),(5,4)}	1	3	0	0	0
2	5	{(2,4),(4,5)} {(2,3),(3,5)}	5	1	1	0	0
2	6	{(2,4),(4,6)} {(2,3),(3,5),(5,6)}	0	1	0	1	1
3	4	{(3,2),(2,4)} {(3,5),(5,4)}	1	1	1	0	0
3	5	{(3,5)} {(3,2),(2,4),(4,5)}	4	1	1	1	0
3	6	{(3,5),(5,6)} {(3,2),(2,4),(4,6)}	1	0	0	0	0
4	5	{(4,5)} {(4,6),(6,5)}	1	1	1	0	0
4	6	{(4,6)} {(4,5),(5,6)}	1	3	0	0	0
5	6	{(5,6)} {(5,4),(4,6)}	3	1	1	0	1

Tabela 5.54: Table with description of routing. We are assuming that between a pair of nodes all demands follow the same route.

Finally and most importantly through table 5.55 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above. In table 5.14 mentioned in first model we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	199 520 000 €
	100 Gbits/s Transceivers		398	5 000 €/Gbit/s	199 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	39 885 900 €
		ODU0 Ports	600	10 €/port	6 000 €	
		ODU1 Ports	500	15 €/port	7 500 €	
		ODU2 Ports	160	30 €/port	4 800 €	
		ODU3 Ports	60	60 €/port	3 600 €	
		ODU4 Ports	40	100 €/port	4 000 €	
		Line Ports	398	100 000 €/port	39 800 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/porto	0 €	
Total Network Cost						239 405 900 €

Tabela 5.55: Table with detailed description of CAPEX for this scenario.

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.3. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topology, the second are the logical topology for all ODUs and finally the resulting physical and optical topology.

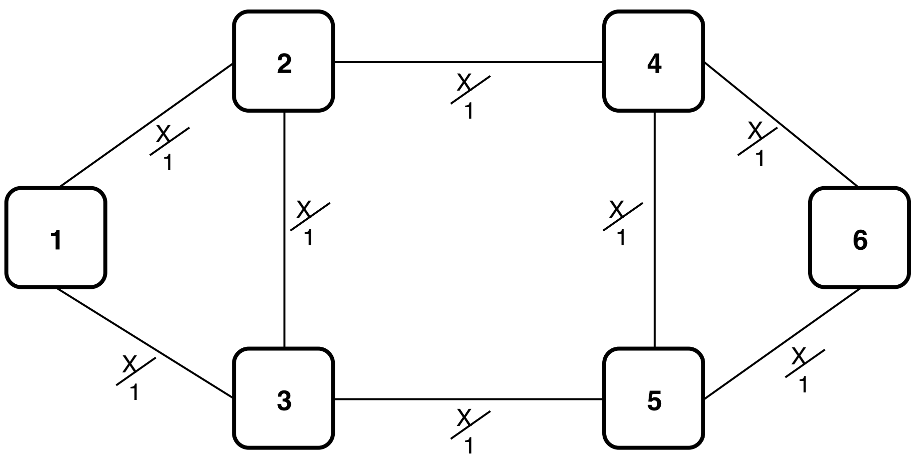


Figura 5.49: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

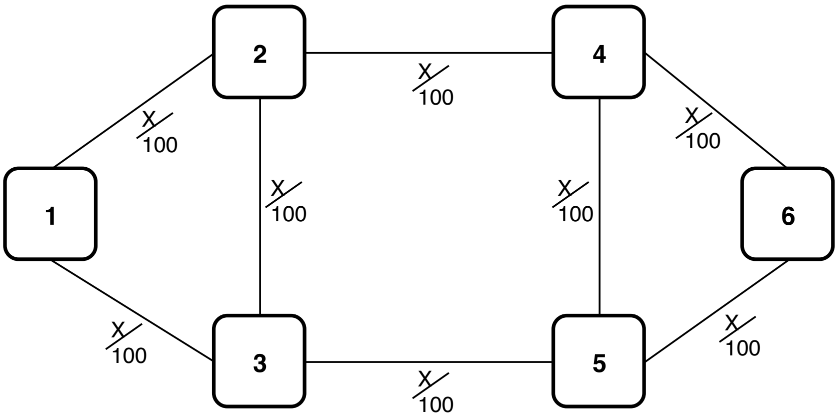


Figura 5.50: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

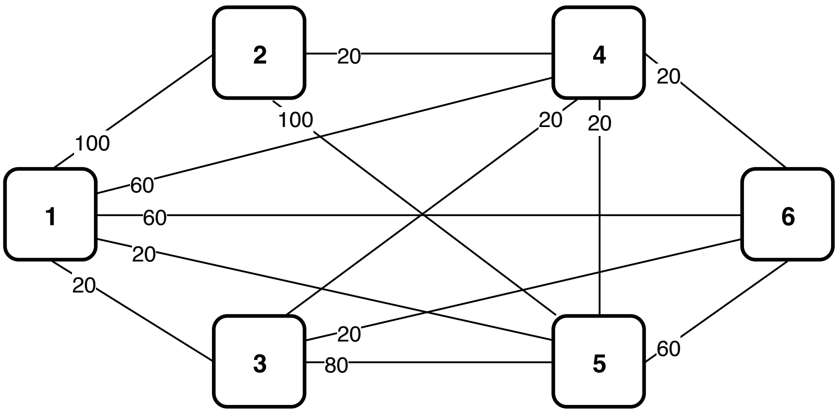


Figura 5.51: ODU0 logical topology defined by the ODU0 traffic matrix.

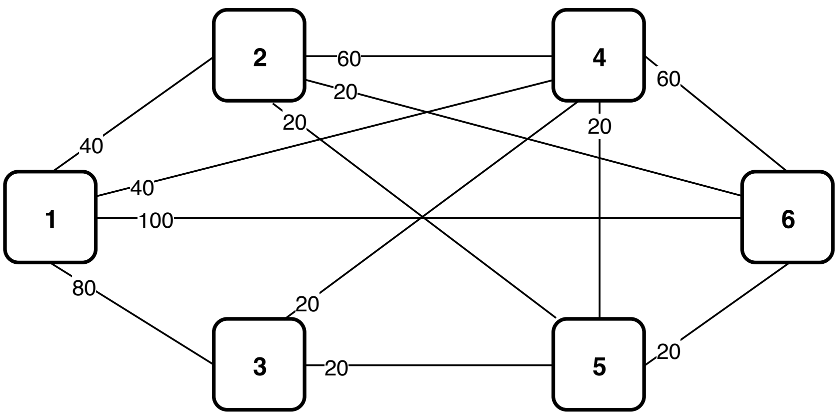


Figura 5.52: ODU1 logical topology defined by the ODU1 traffic matrix.

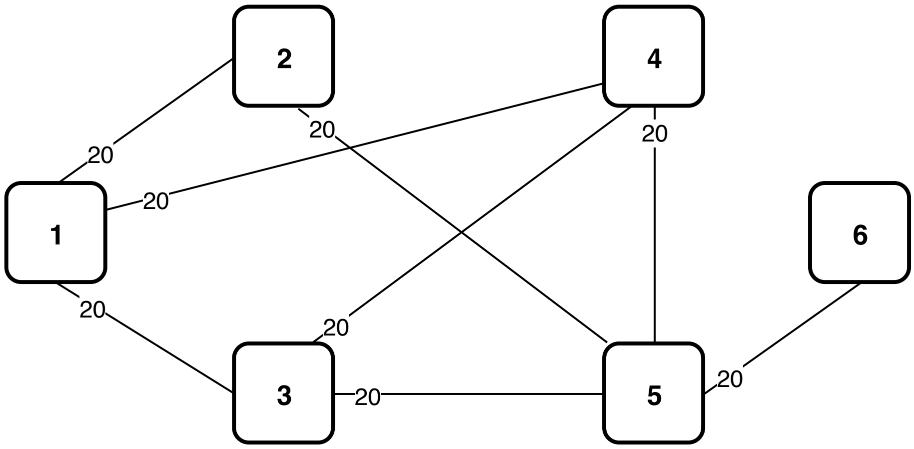


Figura 5.53: ODU2 logical topology defined by the ODU2 traffic matrix.

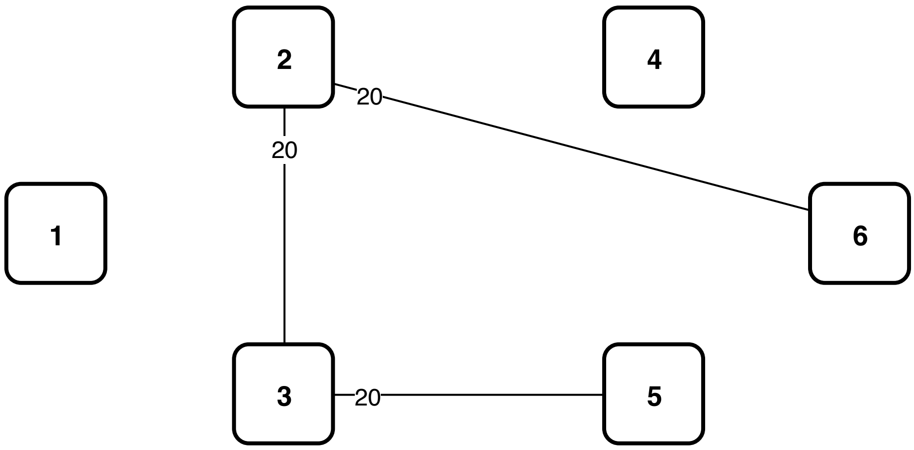


Figura 5.54: ODU3 logical topology defined by the ODU3 traffic matrix.

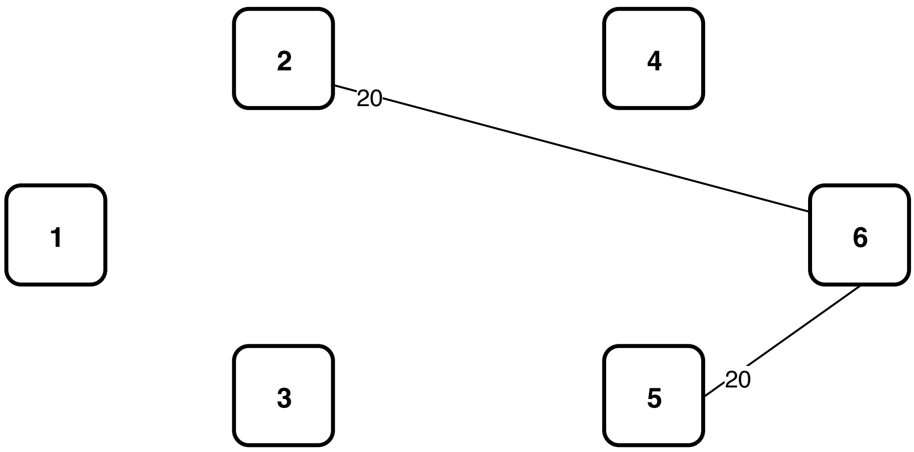


Figura 5.55: ODU4 logical topology defined by the ODU4 traffic matrix.

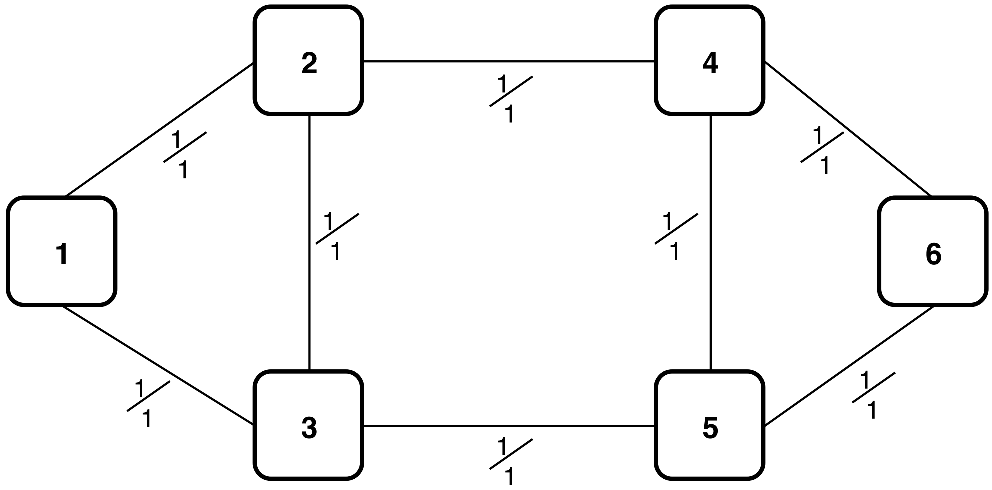


Figura 5.56: Physical topology after dimensioning.

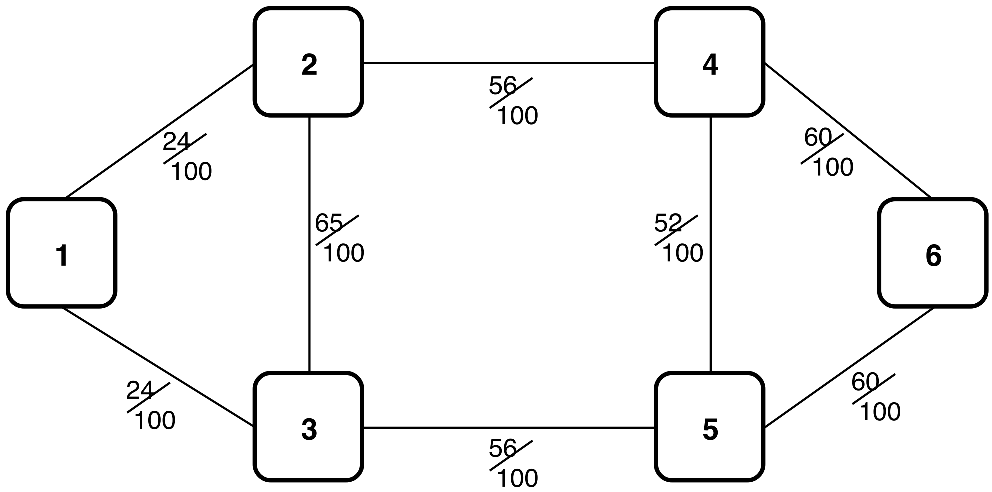


Figura 5.57: Optical topology after dimensioning.

In table 5.56 we can see the number of optical channels calculated using 5.2 and 5.1 and the number of amplifiers for each link calculated using 7.3.

In table 5.57 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports calculated using 5.20 and the number of tributary ports calculated using 5.21 for each node.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	24	4
Node 1 <-> Node 3	24	6
Node 2 <-> Node 3	65	0
Node 2 <-> Node 4	56	6
Node 3 <-> Node 5	56	8
Node 4 <-> Node 5	52	1
Node 4 <-> Node 6	60	7
Node 5 <-> Node 6	60	3

Tabela 5.56: Table with information regarding links for opaque mode with 1+1 protection.

Information regarding nodes			
Node	Resulting Nodal Degree	Line Ports	Tributary Ports
1	2	48	580
2	3	145	460
3	3	145	360
4	3	168	400
5	3	168	480
6	2	120	440

Tabela 5.57: Table with information regarding nodes for opaque mode with 1+1 protection.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate (in relation to the line ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
	Number of total demands	bit rate
580 tributary ports	260	ODU0
	260	ODU1
	60	ODU2
	Node <– Optical Channels –> Node	bit rate
48 line ports	1 <—- 24 —-> 2	100 Gbtis/s
	1 <—- 24 —-> 3	

Tabela 5.58: Table with detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3.

Detailed description of Node 2		
	Number of total demands	bit rate
460 tributary ports	220	ODU0
	140	ODU1
	40	ODU2
	40	ODU3
	20	ODU4
	Node <– Optical Channels –> Node	bit rate
145 line ports	2 <—- 24 —-> 1	100 Gbtis/s
	2 <—- 65 —-> 3	
	2 <—- 56 —-> 4	

Tabela 5.59: Table with detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3.

Detailed description of Node 3		
	Number of total demands	bit rate
360 tributary ports	140	ODU0
	120	ODU1
	60	ODU2
	40	ODU3
	Node <– Optical Channels –> Node	bit rate
145 line ports	3 <—- 24 —-> 1	100 Gbtis/s
	3 <—- 65 —-> 2	
	3 <—- 56 —-> 5	

Tabela 5.60: Table with detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3.

Detailed description of Node 4		
	Number of total demands	bit rate
400 tributary ports	140	ODU0
	200	ODU1
	60	ODU2
	Node <– Optical Channels –> Node	bit rate
168 line ports	4 <—- 56 —-> 2	100 Gbtis/s
	4 <—- 52 —-> 5	
	4 <—- 60 —-> 6	

Tabela 5.61: Table with detailed description of node 4.

Detailed description of Node 5		
	Number of total demands	bit rate
480 tributary ports	280	ODU0
	80	ODU1
	80	ODU2
	20	ODU3
	20	ODU4
	Node <– Optical Channels –> Node	bit rate
168 line ports	5 <—- 56 —-> 3	100 Gbtis/s
	5 <—- 52 —-> 4	
	5 <—- 60 —-> 6	

Tabela 5.62: Table with detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3.

Detailed description of Node 6		
	Number of total demands	bit rate
440 tributary ports	160	ODU0
	200	ODU1
	20	ODU2
	20	ODU3
	40	ODU4
	Node <– Optical Channels –> Node	bit rate
120 line ports	6 <—- 60 —-> 4	100 Gbtis/s
	6 <—- 60 —-> 5	

Tabela 5.63: Table with detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3.

Now in next page, let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 5.64 we can see all the routing obtained for all nodes. In the Links column we can see that there are two paths but it is not possible to distinguish them because we do not know which is protection and which is working.

Routing							
o	d	Links	ODU0	ODU1	ODU2	ODU3	ODU4
1	2	{(1,2)} {(1,3),(3,2)}	5	2	1	0	0
1	3	{(1,3)} {(1,2),(2,3)}	1	4	1	0	0
1	4	{(1,2),(2,4)} {(1,3),(3,5),(5,4)}	3	2	1	0	0
1	5	{(1,3),(3,5)} {(1,2),(2,4),(4,5)}	1	0	0	0	0
1	6	{(1,2),(2,4),(4,6)} {(1,3),(3,5),(5,6)}	3	5	0	0	0
2	3	{(2,3)} {(2,1),(1,3)}	0	0	0	1	0
2	4	{(2,4)} {(2,3),(3,5),(5,4)}	1	3	0	0	0
2	5	{(2,4),(4,5)} {(2,3),(3,5)}	5	1	1	0	0
2	6	{(2,4),(4,6)} {(2,3),(3,5),(5,6)}	0	1	0	1	1
3	4	{(3,2),(2,4)} {(3,5),(5,4)}	1	1	1	0	0
3	5	{(3,5)} {(3,2),(2,4),(4,5)}	4	1	1	1	0
3	6	{(3,5),(5,6)} {(3,2),(2,4),(4,6)}	1	0	0	0	0
4	5	{(4,5)} {(4,6),(6,5)}	1	1	1	0	0
4	6	{(4,6)} {(4,5),(5,6)}	1	3	0	0	0
5	6	{(5,6)} {(5,4),(4,6)}	3	1	1	0	1

Tabela 5.64: Table with description of routing. We are assuming that between a pair of nodes all demands follow the same route.

Finally and most importantly through table 5.65 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above. In table 5.14 mentioned in first model we can see how all the values were calculated.

<table>
<tr><th colspan="7">CAPEX of the Network</th></tr>
<tr><th colspan="3"></th><th>Quantity</th><th>Unit Price</th><th>Cost</th><th>Total</th></tr>
<tr><td rowspan="3">Link Cost</td><td colspan="2">OLTs</td><td>16</td><td>15 000 €</td><td>240 000 €</td><td rowspan="3">397 520 000 €</td></tr>
<tr><td colspan="2">100 Gbits/s Transceivers</td><td>794</td><td>5 000 €/Gbit/s</td><td>397 000 000 €</td></tr>
<tr><td colspan="2">Amplifiers</td><td>70</td><td>4 000 €</td><td>280 000 €</td></tr>
<tr><td rowspan="9">Node Cost</td><td rowspan="7">Electrical</td><td>EXCs</td><td>6</td><td>10 000 €</td><td>60 000 €</td><td rowspan="9">79 511 800 €</td></tr>
<tr><td>ODU0 Ports</td><td>1 200</td><td>10 €/port</td><td>12 000 €</td></tr>
<tr><td>ODU1 Ports</td><td>1 000</td><td>15 €/port</td><td>15 000 €</td></tr>
<tr><td>ODU2 Ports</td><td>320</td><td>30 €/port</td><td>9 600 €</td></tr>
<tr><td>ODU3 Ports</td><td>120</td><td>60 €/port</td><td>7 200 €</td></tr>
<tr><td>ODU4 Ports</td><td>80</td><td>100 €/port</td><td>8 000 €</td></tr>
<tr><td>Line Ports</td><td>794</td><td>100 000 €/port</td><td>79 400 000 €</td></tr>
<tr><td rowspan="2">Optical</td><td>OXCs</td><td>0</td><td>20 000 €</td><td>0 €</td></tr>
<tr><td>Ports</td><td>0</td><td>2 500 €/porto</td><td>0 €</td></tr>
<tr><td colspan="6">Total Network Cost</td><td>477 031 800 €</td></tr>
</table>

Tabela 5.65: Table with detailed description of CAPEX for this scenario.

Conclusions

Once we have obtained the results for all the scenarios we will now draw some conclusions about these results. For a better analysis of the results will be created the table 5.66 with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

	Low Traffic	Medium Traffic	High Traffic
CAPEX survivability	11 266 590 €	90 605 900 €	178 231 800 €
CAPEX/Gbit/s survivability	22 533.18 €/Gbit/s	18 121.18 €/Gbit/s	17 823.18 €/Gbit/s
Traffic (Gbit/s)	500	5 000	10 000
Bidirectional Links used	8	8	8
Number of Line ports	44	398	794
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	44	398	794
Link Cost	22 520 000 €	199 520 000 €	397 520 000 €
Node Cost	4 462 590 €	39 885 900 €	79 511 800 €
CAPEX	**26 982 590 €**	**239 405 900 €**	**477 031 800 €**
CAPEX/Gbit/s	**53 965.18 €/Gbit/s**	**47 881.18 €/Gbit/s**	**47 703.18 €/Gbit/s**

Tabela 5.66: Table with the various CAPEX values obtained in the different traffic scenarios.

Looking at the previous table we can make some comparisons between the several scenarios:

- All scenarios uses all available links. This is because in this case regardless of traffic we always need two possible paths.
- Comparing the low traffic scenario with the others we can see that despite having an increase of factor ten (medium traffic scenario) and factor twenty (high traffic scenario) the same increase does not occur in the final cost (it is lower). This happens because the number of transceivers is smaller than expected.
- Comparing the medium traffic scenario with the high traffic scenario we can see that the increase of the factor is double and in the final cost this factor is very close but still inferior. Again this happens because the number of transceivers is lower but very close to the expected (has two less than expected).
- Comparing the cost with the traffic, we see that, as the traffic increases the cost per Gbit/s is decreasing. We can conclude that the higher the traffic the lower the cost per Gbit/s.
- Comparing this cost with survivability cost we can conclude that protection is significantly more expensive. As can be seen in the table this increase is more than double soon with 1+1 protection we have a cost more than twice the cost without protection.

Opens Issues

The creation of this model for any scenario, started with some considerations and some open issues being:

- Allow blocking.

  The presented model assume that the solution is possible or impossible, does not support a partial solution where some demands are not routed (are blocked).
- Allow multiple transmission system.

  The presented model for each link only supports one transmission system.
- Allowing multi-path routing.

  The presented model for all demands sharing the same node pairs have to follow the same path.

5.1.3 Transparent without Survivability

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the ILP model for the transparent transport mode without survivability.

Model description

First, for a better understanding of the functions and variables used in the ILP, a table 5.67 will be created with all indexes, inputs and variables and with their respective description.

Description of notation used in the objective function	
i	index for start node of a physical link
j	index for end node of a physical link
o	index for node that is origin of a demand
d	index for node that is destination of a demand
c	index for bit rate of the client signal
(i,j)	physical link between the nodes i and j
(o,d)	demand between the nodes o and d
C	set of the client signal
f_{ij}^{od}	the number of 100 Gbit/s optical channels between the nodes o and d that uses link (i,j)
fp_{ij}^{od}	the number of 100 Gbit/s optical channels (with protection) between the nodes o and d that uses link (i,j)
L_{ij}	binary variable indicating if link between the nodes i and j is used
λ_{od}	the number of 100 Gbit/s optical channels between the nodes o and d
D_{odc}	client demands between nodes o and d with bit rate c
G	Network topology in form of adjacency matrix

Tabela 5.67: Table with description of variables

Before carrying out the description of the objective function we must take into account the following particularity of this mode of transport:

- $N_{OXC,n} = 1, \quad \forall$ n that process traffic
- $N_{EXC,n} = 1, \quad \forall$ n that process traffic

The objective function of following the ILP is a minimization of the CAPEX through the equation 5.1 where in this case for the cost of nodes we have in consideration electric 5.5 and optical cost 5.6. In this case the value of $P_{exc,c,n}$ is obtained by equation 5.29 for short-reach and by the equation 5.30 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 5.31.

The equation 5.29 refers to the number of sort-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{5.29}$$

where $D_{nd,c}$ are the client demands between nodes n and d with bit rate c.

In this case there is the following particularity:

- When n=d the value of client demands is always zero, i.e, $D_{nn,c} = 0$

As previously mentioned, the equation 5.30 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e. the number of add ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} \lambda_{nj} \tag{5.30}$$

where λ_{nj} is the number of optical channels between node n and node j.

The equation 5.31 refers to the number of ports in optical switch in node n, $P_{oxc,n}$, i.e. the number of line ports and the number of adding ports of node n which can be calculated as

$$P_{oxc,n} = \sum_{j=1}^{N} f_{nj}^{od} + \sum_{j=1}^{N} \lambda_{nj} \tag{5.31}$$

where f_{nj}^{od} refers to the number of line ports for all demand pairs (od) and λ_{nj} refers to the number of add ports.

The objective function, to be minimized, is the expression 5.7, i.e.,

$$minimize \quad \left\{ \quad C_C \quad \right\}$$

$subject\ to$

$$\sum_{c \in C} B\left(c\right) D_{odc} \leq \tau \lambda_{od} \qquad \forall (o,d) : o < d \tag{5.32}$$

This restriction is considered grooming constraint and for this model the grooming can be done before routing since the traffic is aggregated just for demands between the same nodes, thus not depending on the routes. The variable τ is always 100 Gbits/s.

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = \lambda_{od} \qquad \forall(o,d) : o < d, \forall i : i = o \tag{5.33}$$

This constraint are equal to the constraint 5.8 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = \sum_{j\backslash\{d\}} f_{ji}^{od} \qquad \forall(o,d) : o < d, \forall i : i \neq o, d \tag{5.34}$$

This constraint are equal to the constraint 5.9.

$$\sum_{j\backslash\{d\}} f_{ji}^{od} = \lambda_{od} \qquad \forall(o,d) : o < d, \forall i : i = d \tag{5.35}$$

This constraint are equal to the constraint 5.10 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{o=1} \sum_{d=o+1} \left(f_{ij}^{od} + f_{ji}^{od} \right) \leq K_{ij} G_{ij} L_{ij} \qquad \forall(i,j) : i < j \tag{5.36}$$

This restriction answers capacity constraint problem. Then, total flows must be less or equal to the capacity of network links. For any situation the maximum number of optical channels supported by each transmission system is 100, i.e., K_{ij} = 100.

$$f_{ij}^{od}, f_{ji}^{od}, \lambda_{od} \in \mathbb{N} \qquad \forall(i,j) : i < j, \forall(o,d) : o < d \tag{5.37}$$

Last constraint define the total number of flows and the number of optical channels must be a counting number.

Result description

To perform the calculations using the implementation of the models described previously it is necessary to use a mathematical software tool. For this we will use MATLAB which is ideal for dealing with linear programming problems and can call the LPsolve through an external interface.
We already have all the necessary to obtain the CAPEX value for the reference network 10.1. As described in the subsection of network traffic 4.2, we have three values of network traffic (low, medium and high traffic) so we have to obtain three different CAPEX. The value of the CAPEX of the network will be calculated based on the costs of the equipment present in the table 5.2.

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.1. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topology, the second are the logical topology for all ODUs and finally the resulting physical and optical topology.

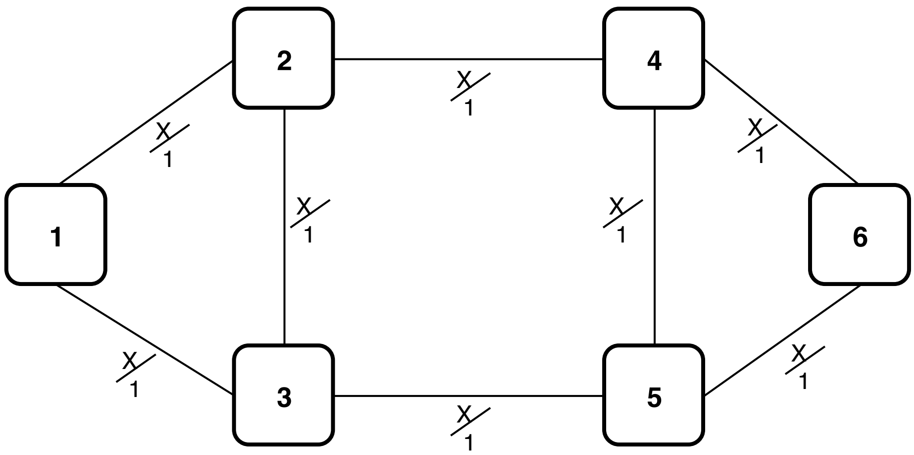


Figura 5.58: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

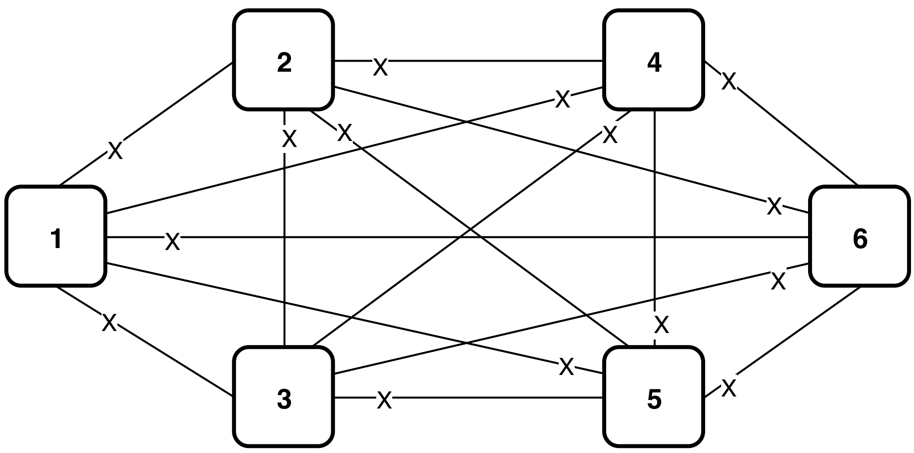


Figura 5.59: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

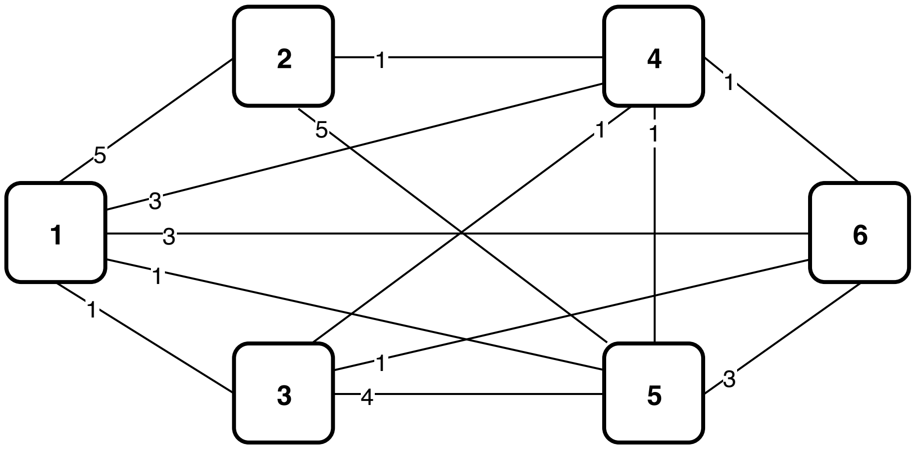


Figura 5.60: ODU0 logical topology defined by the ODU0 traffic matrix.

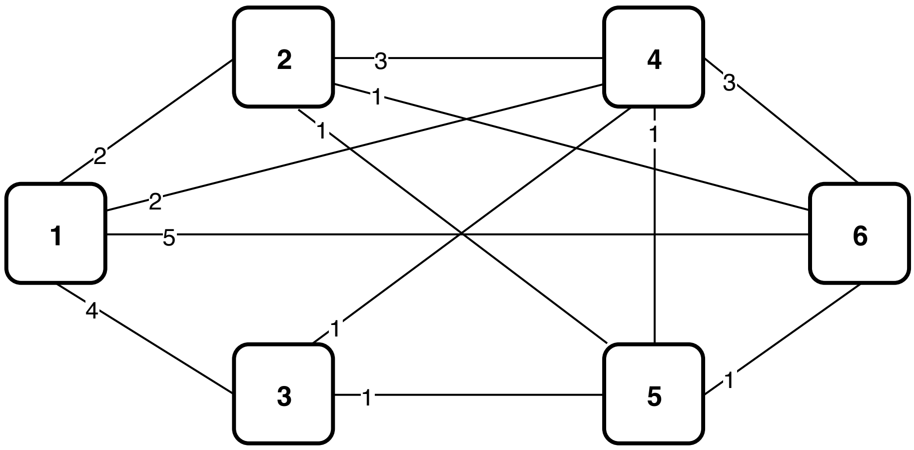


Figura 5.61: ODU1 logical topology defined by the ODU1 traffic matrix.

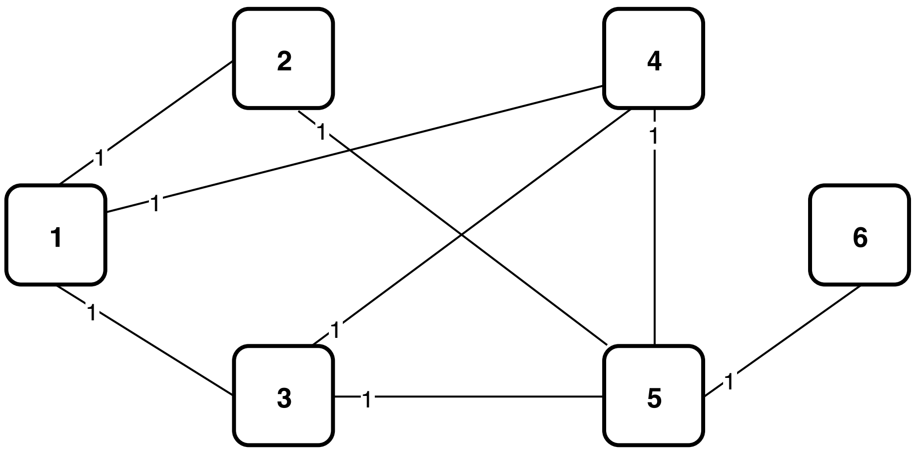


Figura 5.62: ODU2 logical topology defined by the ODU2 traffic matrix.

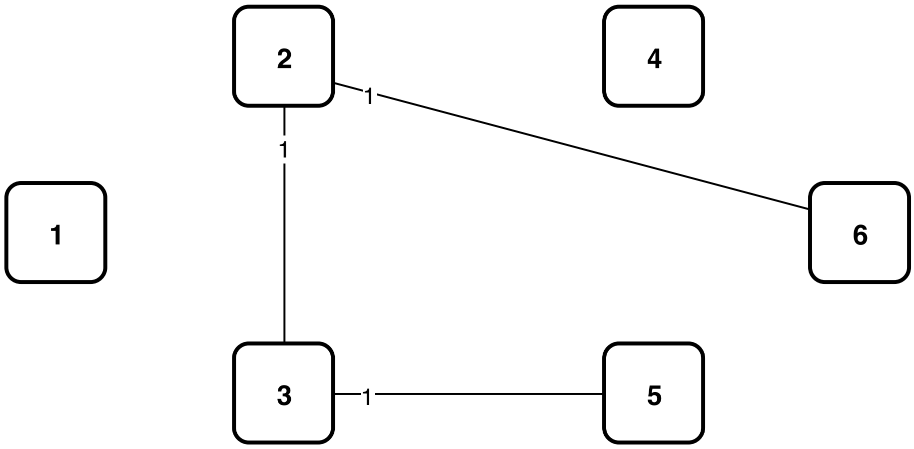


Figura 5.63: ODU3 logical topology defined by the ODU3 traffic matrix.

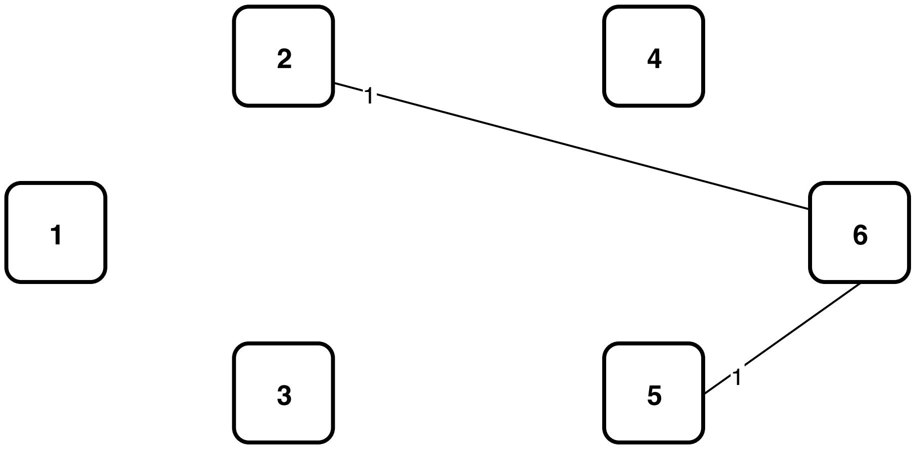


Figura 5.64: ODU4 logical topology defined by the ODU4 traffic matrix.

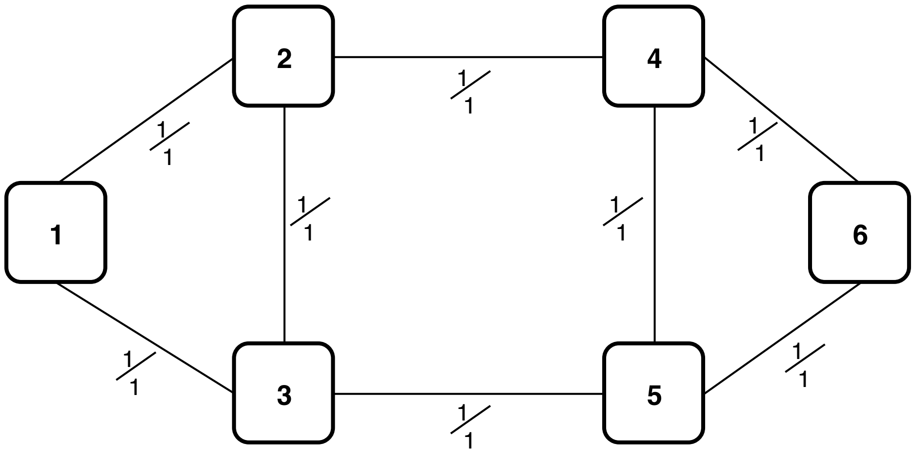


Figura 5.65: Physical topology after dimensioning.

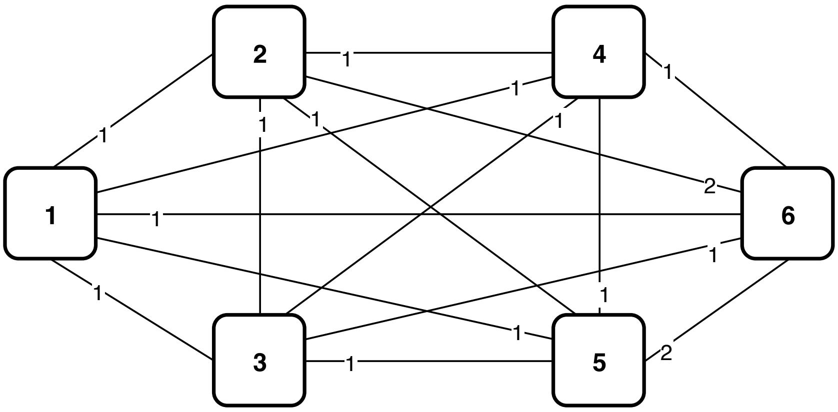


Figura 5.66: Optical topology after dimensioning.

In table 5.68 we can see the number of optical channels calculated using 5.2 and 5.7 and the number of amplifiers for each link calculated using 5.3.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	3	4
Node 1 <-> Node 3	2	6
Node 2 <-> Node 3	3	0
Node 2 <-> Node 4	6	6
Node 3 <-> Node 5	4	8
Node 4 <-> Node 5	1	1
Node 4 <-> Node 6	4	7
Node 5 <-> Node 6	3	3

Tabela 5.68: Table with information regarding links for transparent mode.

In table 5.69 we can see the number of line ports and add ports using 5.31 the number of long-reach transponders using 5.30 and the number of tributary ports using 5.29.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	29	5	5	5
2	3	23	6	6	12
3	3	18	5	5	9
4	3	20	5	5	11
5	3	24	6	6	8
6	2	22	7	7	7

Tabela 5.69: Table with information regarding nodes for transparent mode.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate (in relation to the line ports and the add ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
Electrical part	Number of total demands	Bit rate
29 tributary ports	13	ODU0
	13	ODU1
	3	ODU2
	Node<–Optical Channels–>Node	Bit rate
5 LR Transponders	1 <—- 1 —-> 2	100 Gbits/s
	1 <—- 1 —-> 3	
	1 <—- 1 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 1 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
5 add ports	1 <—- 1 —-> 2	100 Gbits/s
	1 <—- 1 —-> 3	
	1 <—- 1 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 1 —-> 6	
5 line ports	1 <—- 1 —-> 2	
	1 <—- 1 —-> 3	
	1 <—- 1 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 1 —-> 6	

Tabela 5.70: Table with detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

Detailed description of Node 2		
Electrical part	Number of total demands	Bit rate
23 tributary ports	11	ODU0
	7	ODU1
	2	ODU2
	2	ODU3
	1	ODU4
	Node<–Optical Channels–>Node	Bit rate
6 LR Transponders	2 <—- 1 —-> 1	100 Gbits/s
	2 <—- 1 —-> 3	
	2 <—- 1 —-> 4	
	2 <—- 1 —-> 5	
	2 <—- 2 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
6 add ports	2 <—- 1 —-> 1	100 Gbits/s
	2 <—- 1 —-> 3	
	2 <—- 1 —-> 4	
	2 <—- 1 —-> 5	
	2 <—- 2 —-> 6	
12 line ports	2 <—- 1 —-> 1	
	2 <—- 1 —-> 3	
	2 <—- 1 —-> 4	
	2 <—- 1 —-> 5	
	2 <—- 2 —-> 6	
	1 <—- 1 —-> 4	
	1 <—- 1 —-> 6	
	3 <—- 1 —-> 4	

Tabela 5.71: Table with detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases, the number of ports is double the number of optical channels.

Detailed description of Node 3		
Electrical part	Number of total demands	Bit rate
18 tributary ports	7	ODU0
	6	ODU1
	3	ODU2
	2	ODU3
	Node<–Optical Channels–>Node	Bit rate
5 LR Transponders	3 <—- 1 —-> 1	100 Gbits/s
	3 <—- 1 —-> 2	
	3 <—- 1 —-> 4	
	3 <—- 1 —-> 5	
	3 <—- 1 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
5 add ports	3 <—- 1 —-> 1	100 Gbits/s
	3 <—- 1 —-> 2	
	3 <—- 1 —-> 4	
	3 <—- 1 —-> 5	
	3 <—- 1 —-> 6	
9 line ports	3 <—- 1 —-> 1	
	3 <—- 1 —-> 2	
	3 <—- 1 —-> 4	
	3 <—- 1 —-> 5	
	3 <—- 1 —-> 6	
	1 <—- 1 —-> 5	
	2 <—- 1 —-> 5	

Tabela 5.72: Table with detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 4		
Electrical part	Number of total demands	Bit rate
20 tributary ports	7	ODU0
	10	ODU1
	3	ODU2
	Node<–Optical Channels–>Node	Bit rate
5 LR Transponders	4 <—- 1 —-> 1	100 Gbits/s
	4 <—- 1 —-> 2	
	4 <—- 1 —-> 3	
	4 <—- 1 —-> 5	
	4 <—- 1 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
5 add ports	4 <—- 1 —-> 1	100 Gbits/s
	4 <—- 1 —-> 2	
	4 <—- 1 —-> 3	
	4 <—- 1 —-> 5	
	4 <—- 1 —-> 6	
11 line ports	4 <—- 1 —-> 1	
	4 <—- 1 —-> 2	
	4 <—- 1 —-> 3	
	4 <—- 1 —-> 5	
	4 <—- 1 —-> 6	
	1 <—- 1 —-> 6	
	2 <—- 2 —-> 6	

Tabela 5.73: Table with detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 5		
Electrical part	Number of total demands	Bit rate
24 tributary ports	14	ODU0
	4	ODU1
	4	ODU2
	1	ODU3
	1	ODU4
	Node<–Optical Channels–>Node	Bit rate
6 LR Trasponders	5 <—- 1 —-> 1	100 Gbits/s
	5 <—- 1 —-> 2	
	5 <—- 1 —-> 3	
	5 <—- 1 —-> 4	
	5 <—- 2 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
6 add ports	5 <—- 1 —-> 1	100 Gbits/s
	5 <—- 1 —-> 2	
	5 <—- 1 —-> 3	
	5 <—- 1 —-> 4	
	5 <—- 2 —-> 6	
8 line ports	5 <—- 1 —-> 1	
	5 <—- 1 —-> 2	
	5 <—- 1 —-> 3	
	5 <—- 1 —-> 4	
	5 <—- 2 —-> 6	
	3 <—- 1 —-> 6	

Tabela 5.74: Table with detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 6		
Electrical part	Number of total demands	Bit rate
22 tributary ports	8	ODU0
	10	ODU1
	1	ODU2
	1	ODU3
	2	ODU4
	Node<–Optical Channels–>Node	Bit rate
7 LR Transponders	6 <—- 1 —-> 1	
	6 <—- 2 —-> 2	
	6 <—- 1 —-> 3	
	6 <—- 1 —-> 4	
	6 <—- 2 —-> 5	
Optical part	Node<–Optical Channels–>Node	Bit rate
7 add ports	6 <—- 1 —-> 1	100 Gbits/s
	6 <—- 2 —-> 2	
	6 <—- 1 —-> 3	
	6 <—- 1 —-> 4	
	6 <—- 2 —-> 5	
7 line ports	6 <—- 1 —-> 1	
	6 <—- 2 —-> 2	
	6 <—- 1 —-> 3	
	6 <—- 1 —-> 4	
	6 <—- 2 —-> 5	

Tabela 5.75: Table with detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

Now, in next page, let's focus on the routing information in table 5.76. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

Routing		
o	d	Links
1	2	{(1,2)}
1	3	{(1,3)}
1	4	{(1,2),(2,4)}
1	5	{(1,3),(3,5)}
1	6	{(1,2),(2,4),(4,6)}
2	3	{(2,3)}
2	4	{(2,4)}
2	5	{(2,3),(3,5)}
2	6	{(2,4),(4,6)}
3	4	{(3,2),(2,4)}
3	5	{(3,5)}
3	6	{(3,5),(5,6)}
4	5	{(4,5)}
4	6	{(4,6)}
5	6	{(5,6)}

Tabela 5.76: Table with description of routing.

Finally and most importantly through table 5.77 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above.

<table>
<tr><th colspan="7">CAPEX of the Network</th></tr>
<tr><th colspan="3"></th><th>Quantity</th><th>Unit Price</th><th>Cost</th><th>Total</th></tr>
<tr><td rowspan="3">Link Cost</td><td colspan="2">OLTs</td><td>16</td><td>15 000 €</td><td>240 000 €</td><td rowspan="3">26 520 000 €</td></tr>
<tr><td colspan="2">100 Gbits/s Transceivers</td><td>52</td><td>5 000 €/Gbit/s</td><td>26 000 000 €</td></tr>
<tr><td colspan="2">Amplifiers</td><td>70</td><td>4 000 €</td><td>280 000 €</td></tr>
<tr><td rowspan="10">Node Cost</td><td rowspan="7">Electrical</td><td>EXCs</td><td>6</td><td>10 000 €</td><td>60 000 €</td><td rowspan="10">3 797 590 €</td></tr>
<tr><td>ODU0 Ports</td><td>60</td><td>10 €/port</td><td>600 €</td></tr>
<tr><td>ODU1 Ports</td><td>50</td><td>15 €/port</td><td>750 €</td></tr>
<tr><td>ODU2 Ports</td><td>16</td><td>30 €/port</td><td>480 €</td></tr>
<tr><td>ODU3 Ports</td><td>6</td><td>60 €/port</td><td>360 €</td></tr>
<tr><td>ODU4 Ports</td><td>4</td><td>100 €/port</td><td>400 €</td></tr>
<tr><td>Transponders</td><td>34</td><td>100 000 €/port</td><td>3 400 000 €</td></tr>
<tr><td rowspan="3">Optical</td><td>OXCs</td><td>6</td><td>20 000 €</td><td>120 000 €</td></tr>
<tr><td>Line Ports</td><td>52</td><td>2 500 €/port</td><td>130 000 €</td></tr>
<tr><td>Add Ports</td><td>34</td><td>2 500 €/port</td><td>85 000 €</td></tr>
<tr><td colspan="6">Total Network Cost</td><td>30 317 590 €</td></tr>
</table>

Tabela 5.77: Table with detailed description of CAPEX for this scenario.

All the values calculated in the previous table were obtained through the equations 5.2 and 5.4 referred to in section 5.1, but for a more detailed analysis we created table 5.78 where we can see how all the parameters are calculated individually.

	Equation used to calculate the cost
OLTs	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}\gamma_0^{OLT}$
Transceivers	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij} f_{ij}^{od}\gamma_1^{OLT}\tau$
Amplifiers	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij} N_{ij}^{R} c^{R}$
EXCs	$\sum_{n=1}^{N} N_{exc,n}\gamma_{e0}$
ODU0 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n} D_{nd,0}\gamma_{e1,0}$
ODU1 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n} D_{nd,1}\gamma_{e1,1}$
ODU2 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n} D_{nd,2}\gamma_{e1,2}$
ODU3 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n} D_{nd,3}\gamma_{e1,3}$
ODU4 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n} D_{nd,4}\gamma_{e1,4}$
LR Transponders	$\sum_{n=1}^{N}\sum_{j=1}^{N} N_{exc,n}\lambda_{od}\gamma_{e1,-1}$
OXCs	$\sum_{n=1}^{N} N_{oxc,n}\gamma_{o0}$
Add Port	$\sum_{n=1}^{N}\sum_{j=1}^{N} N_{oxc,n}\lambda_{od}\gamma_{o1}$
Line Port	$\sum_{n=1}^{N}\sum_{j=1}^{N} N_{oxc,n} f_{ij}^{od}\gamma_{o1}$
CAPEX	The final cost is calculated by summing all previous results.

Tabela 5.78: Table with description of calculation

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.2. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topology, the second are the logical topology for all ODUs and finally the resulting physical and optical topology.

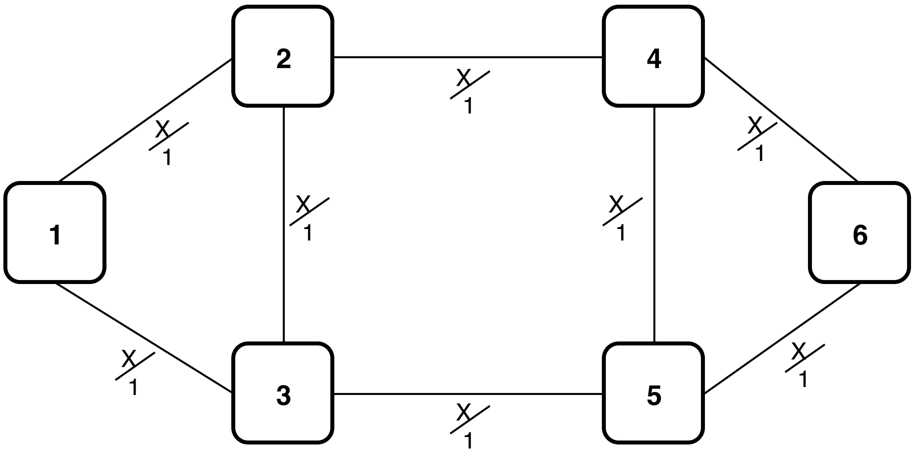


Figura 5.67: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

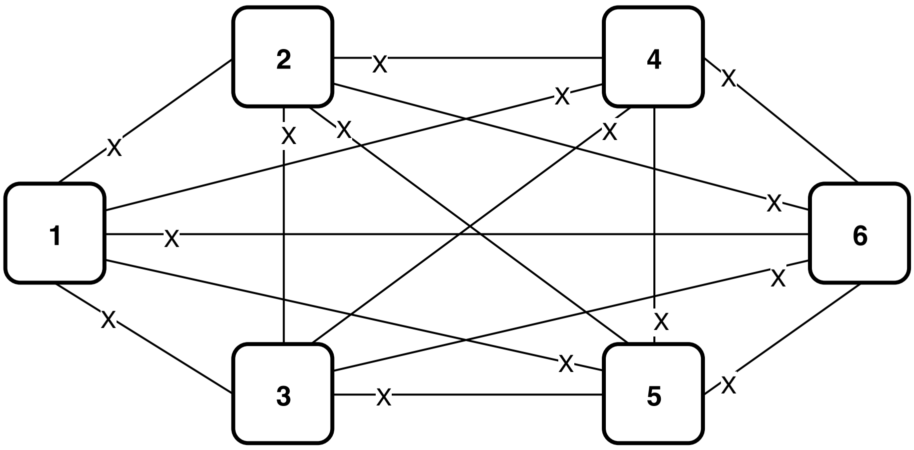


Figura 5.68: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

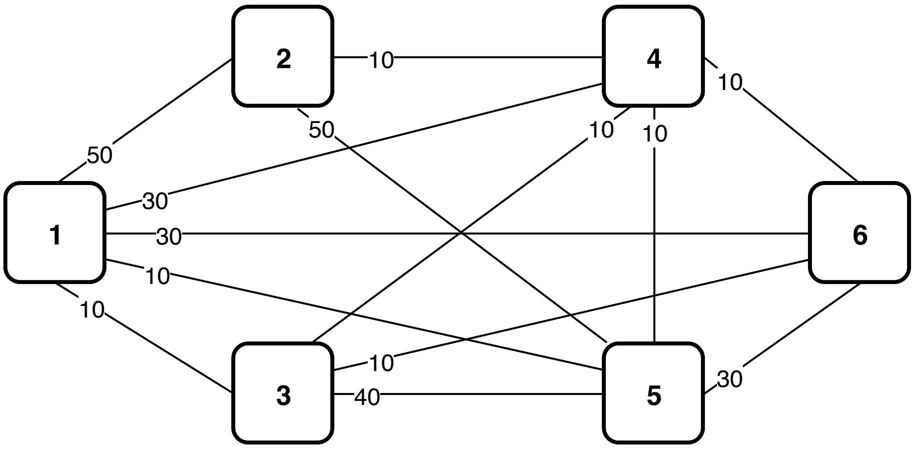


Figura 5.69: ODU0 logical topology defined by the ODU0 traffic matrix.

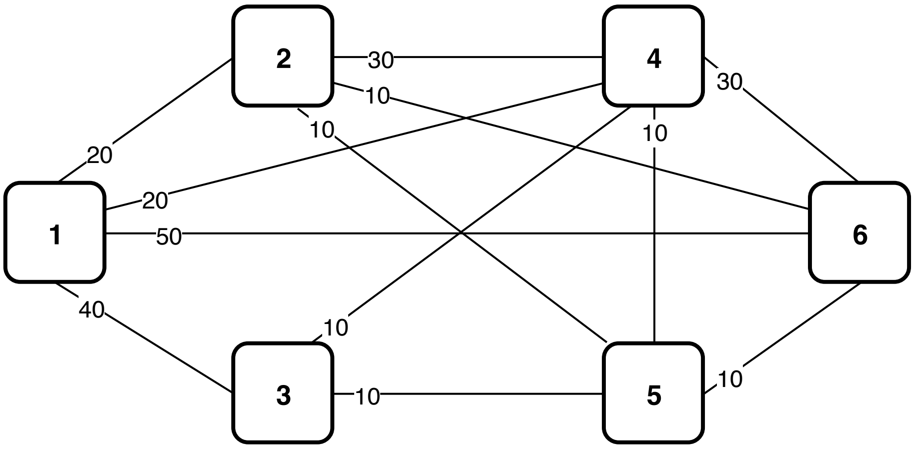


Figura 5.70: ODU1 logical topology defined by the ODU1 traffic matrix.

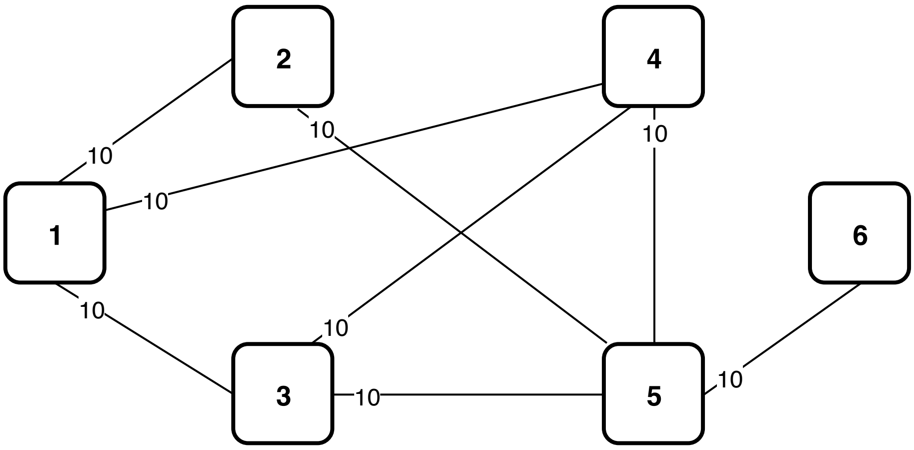


Figura 5.71: ODU2 logical topology defined by the ODU2 traffic matrix.

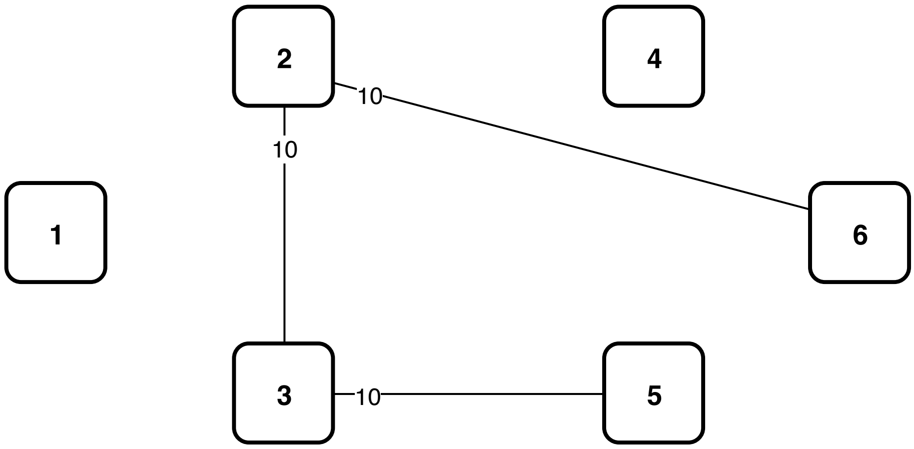


Figura 5.72: ODU3 logical topology defined by the ODU3 traffic matrix.

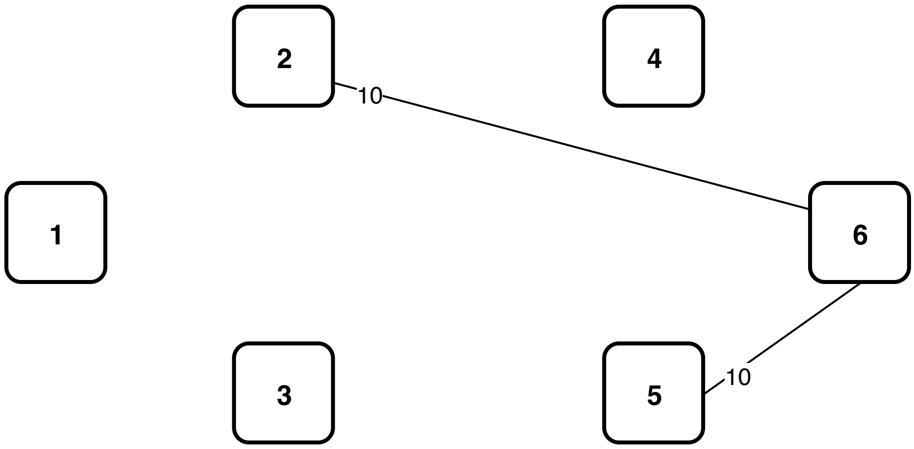


Figura 5.73: ODU4 logical topology defined by the ODU4 traffic matrix.

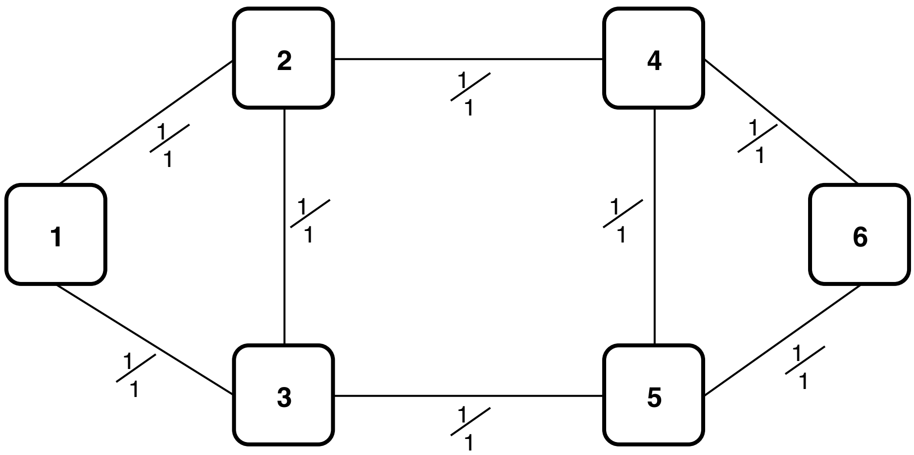


Figura 5.74: Physical topology after dimensioning.

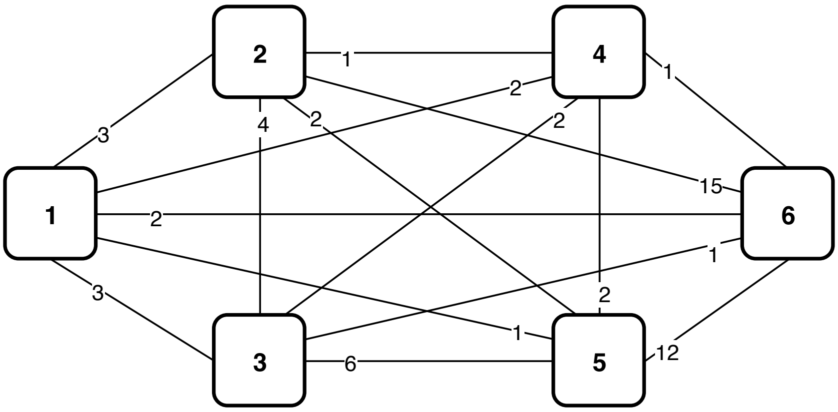


Figura 5.75: Optical topology after dimensioning.

In table 5.79 we can see the number of optical channels calculated using 5.2 and 5.7 and the number of amplifiers for each link calculated using 5.3.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	7	4
Node 1 <-> Node 3	4	6
Node 2 <-> Node 3	8	0
Node 2 <-> Node 4	22	6
Node 3 <-> Node 5	10	8
Node 4 <-> Node 5	2	1
Node 4 <-> Node 6	18	7
Node 5 <-> Node 6	13	3

Tabela 5.79: Table with information regarding links for transparent mode.

In table 5.80 we can see the number of line ports and add ports using 5.31 the number of long-reach transponders using 5.30 and the number of tributary ports using 5.29.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	290	11	11	11
2	3	230	25	25	37
3	3	180	16	16	22
4	3	200	8	8	42
5	3	240	23	23	25
6	2	220	31	31	31

Tabela 5.80: Table with information regarding nodes for transparent mode.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate (in relation to the line ports and the add ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
Electrical part	Number of total demands	Bit rate
290 tributary ports	130 130 30	ODU0 ODU1 ODU2
	Node<–Optical Channels–>Node	Bit rate
11 LR Transponders	1 <— 3 —> 2 1 <— 3 —> 3 1 <— 2 —> 4 1 <— 1 —> 5 1 <— 2 —> 6	100 Gbits/s
Optical part	Node<–Optical Channels–>Node	Bit rate
11 add ports	1 <— 3 —> 2 1 <— 3 —> 3 1 <— 2 —> 4 1 <— 1 —> 5 1 <— 2 —> 6	100 Gbits/s
11 line ports	1 <— 3 —> 2 1 <— 3 —> 3 1 <— 2 —> 4 1 <— 1 —> 5 1 <— 2 —> 6	

Tabela 5.81: Table with detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

Detailed description of Node 2		
Electrical part	Number of total demands	Bit rate
230 tributary ports	110	ODU0
	70	ODU1
	20	ODU2
	20	ODU3
	10	ODU4
	Node<–Optical Channels–>Node	Bit rate
25 LR Transponders	2 <—– 3 —–> 1	100 Gbits/s
	2 <—– 4 —–> 3	
	2 <—– 1 —–> 4	
	2 <—– 2 —–> 5	
	2 <—– 15 —–> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
25 add ports	2 <—– 3 —–> 1	100 Gbits/s
	2 <—– 4 —–> 3	
	2 <—– 1 —–> 4	
	2 <—– 2 —–> 5	
	2 <—– 15 —–> 6	
37 line ports	2 <—– 3 —–> 1	
	2 <—– 4 —–> 3	
	2 <—– 1 —–> 4	
	2 <—– 2 —–> 5	
	2 <—– 15 —–> 6	
	1 <—– 2 —–> 4	
	1 <—– 2 —–> 6	
	3 <—– 2 —–> 4	

Tabela 5.82: Table with detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 3		
Electrical part	Number of total demands	Bit rate
180 tributary ports	70	ODU0
	60	ODU1
	30	ODU2
	20	ODU3
	Node<–Optical Channels–>Node	Bit rate
16 LR Transponders	3 <—– 3 —–> 1	100 Gbits/s
	3 <—– 4 —–> 2	
	3 <—– 2 —–> 4	
	3 <—– 6 —–> 5	
	3 <—– 1 —–> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
16 add ports	3 <—– 3 —–> 1	100 Gbits/s
	3 <—– 4 —–> 2	
	3 <—– 2 —–> 4	
	3 <—– 6 —–> 5	
	3 <—– 1 —–> 6	
22 line ports	3 <—– 3 —–> 1	
	3 <—– 4 —–> 2	
	3 <—– 2 —–> 4	
	3 <—– 6 —–> 5	
	3 <—– 1 —–> 6	
	1 <—– 1 —–> 5	
	2 <—– 2 —–> 5	

Tabela 5.83: Table with detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 4		
Electrical part	Number of total demands	Bit rate
200 tributary ports	70	ODU0
	100	ODU1
	30	ODU2
	Node<–Optical Channels–>Node	Bit rate
8 add ports	4 <—- 2 —-> 1	100 Gbits/s
	4 <—- 1 —-> 2	
	4 <—- 2 —-> 3	
	4 <—- 2 —-> 5	
	4 <—- 1 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
8 add ports	4 <—- 2 —-> 1	100 Gbits/s
	4 <—- 1 —-> 2	
	4 <—- 2 —-> 3	
	4 <—- 2 —-> 5	
	4 <—- 1 —-> 6	
42 line ports	4 <—- 2 —-> 1	
	4 <—- 1 —-> 2	
	4 <—- 2 —-> 3	
	4 <—- 2 —-> 5	
	4 <—- 1 —-> 6	
	1 <—- 2 —-> 6	
	2 <—- 15 —-> 6	

Tabela 5.84: Table with detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 5		
Electrical part	Number of total demands	Bit rate
240 tributary ports	140	ODU0
	40	ODU1
	40	ODU2
	10	ODU3
	10	ODU4
	Node<–Optical Channels–>Node	Bit rate
23 LR Transponders	5 <—– 1 —–> 1	100 Gbits/s
	5 <—– 2 —–> 2	
	5 <—– 6 —–> 3	
	5 <—– 2 —–> 4	
	5 <—- 12 —–> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
23 add ports	5 <—– 1 —–> 1	100 Gbits/s
	5 <—– 2 —–> 2	
	5 <—– 6 —–> 3	
	5 <—– 2 —–> 4	
	5 <—- 12 —–> 6	
25 line ports	5 <—– 1 —–> 1	
	5 <—– 2 —–> 2	
	5 <—– 6 —–> 3	
	5 <—– 2 —–> 4	
	5 <—- 12 —–> 6	
	3 <—– 1 —–> 6	

Tabela 5.85: Table with detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 6		
Electrical part	Number of total demands	Bit rate
220 tributary ports	80	ODU0
	100	ODU1
	10	ODU2
	10	ODU3
	20	ODU4
	Node<–Optical Channels–>Node	Bit rate
31 LR Transponders	6 <—– 2 —–> 1	100 Gbits/s
	6 <—– 15 —–> 2	
	6 <—– 1 —–> 3	
	6 <—– 1 —–> 4	
	6 <—– 12 —–> 5	
Optical part	Node<–Optical Channels–>Node	Bit rate
31 add ports	6 <—– 2 —–> 1	100 Gbits/s
	6 <—– 15 —–> 2	
	6 <—– 1 —–> 3	
	6 <—– 1 —–> 4	
	6 <—– 12 —–> 5	
31 line ports	6 <—– 2 —–> 1	
	6 <—– 15 —–> 2	
	6 <—– 1 —–> 3	
	6 <—– 1 —–> 4	
	6 <—– 12 —–> 5	

Tabela 5.86: Table with detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

Now, in next page, let's focus on the routing information in table 5.87. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

Routing		
o	d	Links
1	2	{(1,2)}
1	3	{(1,3)}
1	4	{(1,2),(2,4)}
1	5	{(1,3),(3,5)}
1	6	{(1,2),(2,4),(4,6)}
2	3	{(2,3)}
2	4	{(2,4)}
2	5	{(2,3),(3,5)}
2	6	{(2,4),(4,6)}
3	4	{(3,2),(2,4)}
3	5	{(3,5)}
3	6	{(3,5),(5,6)}
4	5	{(4,5)}
4	6	{(4,6)}
5	6	{(5,6)}

Tabela 5.87: Table with description of routing

Finally and most importantly through table 5.88 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above. In table 5.78 mentioned in previous scenario we can see how all the values were calculated.

<table>
<tr><th colspan="7">CAPEX of the Network</th></tr>
<tr><th colspan="3"></th><th>Quantity</th><th>Unit Price</th><th>Cost</th><th>Total</th></tr>
<tr><td rowspan="3">Link Cost</td><td colspan="2">OLTs</td><td>16</td><td>15 000 €</td><td>240 000 €</td><td rowspan="3">84 520 000 €</td></tr>
<tr><td colspan="2">100 Gbits/s Transceivers</td><td>168</td><td>5 000 €/Gbit/s</td><td>84 000 000 €</td></tr>
<tr><td colspan="2">Amplifiers</td><td>70</td><td>4 000 €</td><td>280 000 €</td></tr>
<tr><td rowspan="10">Node Cost</td><td rowspan="7">Electrical</td><td>EXCs</td><td>6</td><td>10 000 €</td><td>60 000 €</td><td rowspan="10">12 310 900 €</td></tr>
<tr><td>ODU0 Ports</td><td>600</td><td>10 €/port</td><td>6 000 €</td></tr>
<tr><td>ODU1 Ports</td><td>500</td><td>15 €/port</td><td>7 500 €</td></tr>
<tr><td>ODU2 Ports</td><td>160</td><td>30 €/port</td><td>4 800 €</td></tr>
<tr><td>ODU3 Ports</td><td>60</td><td>60 €/port</td><td>3 600 €</td></tr>
<tr><td>ODU4 Ports</td><td>40</td><td>100 €/port</td><td>4 000 €</td></tr>
<tr><td>Transponders</td><td>114</td><td>100 000 €/port</td><td>11 400 000 €</td></tr>
<tr><td rowspan="3">Optical</td><td>OXCs</td><td>6</td><td>20 000 €</td><td>120 000 €</td></tr>
<tr><td>Line Ports</td><td>168</td><td>2 500 €/port</td><td>420 000 €</td></tr>
<tr><td>Add Ports</td><td>114</td><td>2 500 €/port</td><td>285 000 €</td></tr>
<tr><td colspan="6">Total Network Cost</td><td>96 830 900 €</td></tr>
</table>

Tabela 5.88: Table with detailed description of CAPEX

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.3. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topology, the second are the logical topology for all ODUs and finally the resulting physical and optical topology.

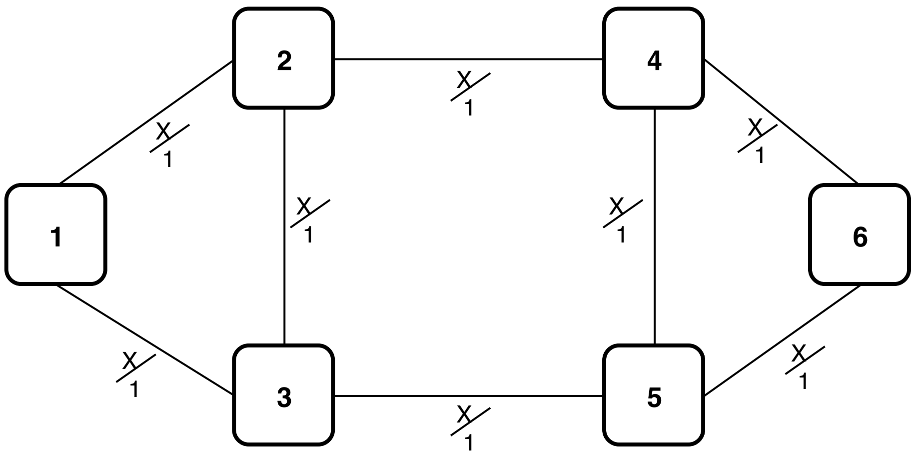


Figura 5.76: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

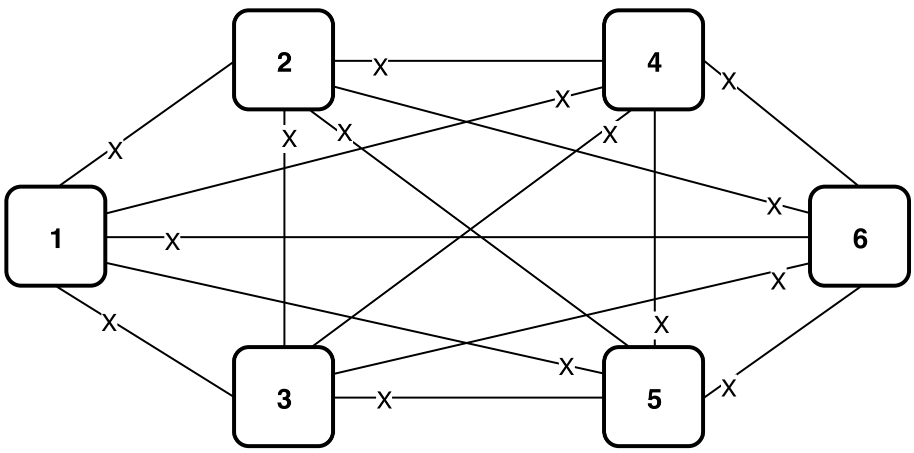


Figura 5.77: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

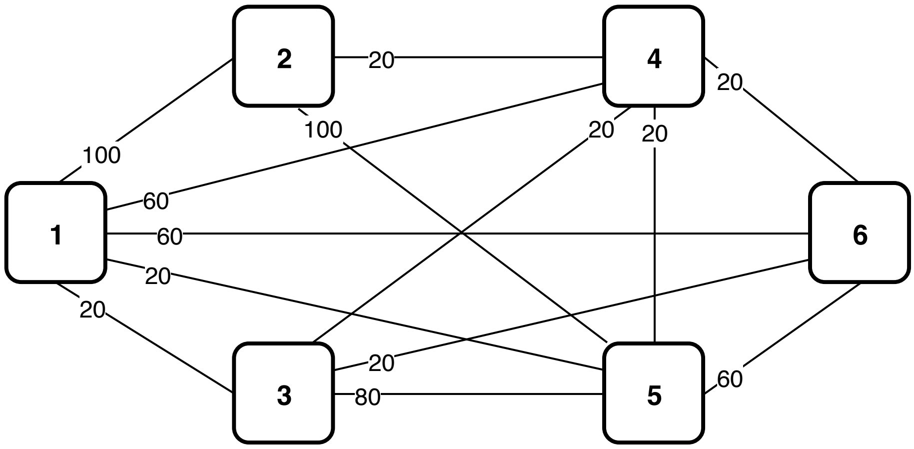


Figura 5.78: ODU0 logical topology defined by the ODU0 traffic matrix.

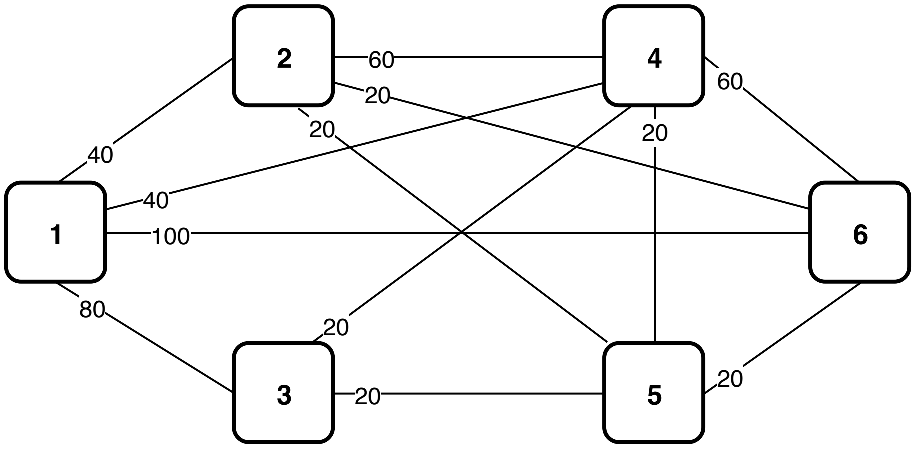


Figura 5.79: ODU1 logical topology defined by the ODU1 traffic matrix.

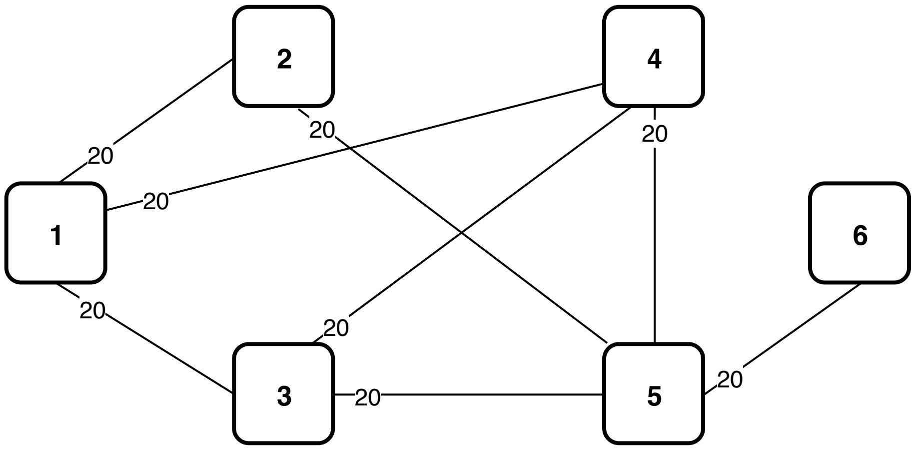


Figura 5.80: ODU2 logical topology defined by the ODU2 traffic matrix.

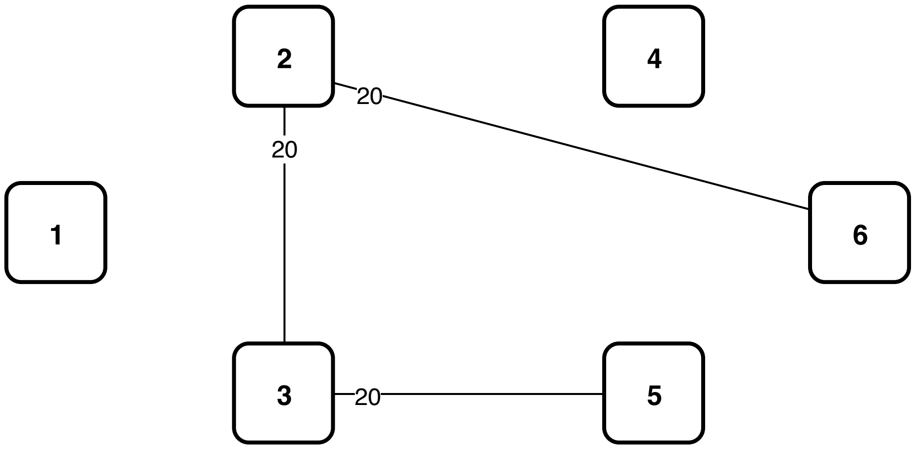


Figura 5.81: ODU3 logical topology defined by the ODU3 traffic matrix.

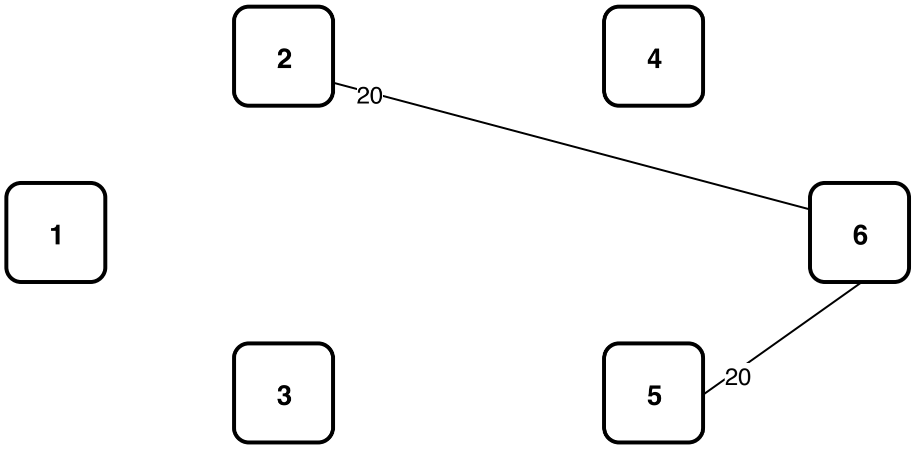


Figura 5.82: ODU4 logical topology defined by the ODU4 traffic matrix.

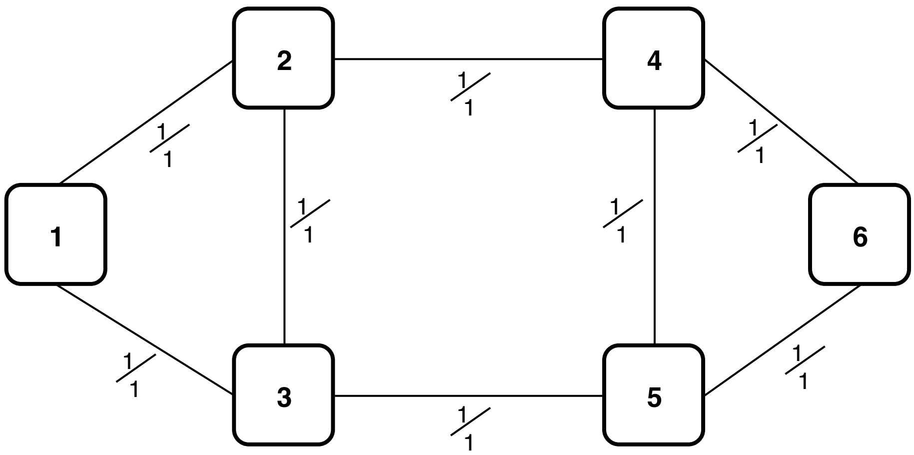


Figura 5.83: Physical topology after dimensioning.

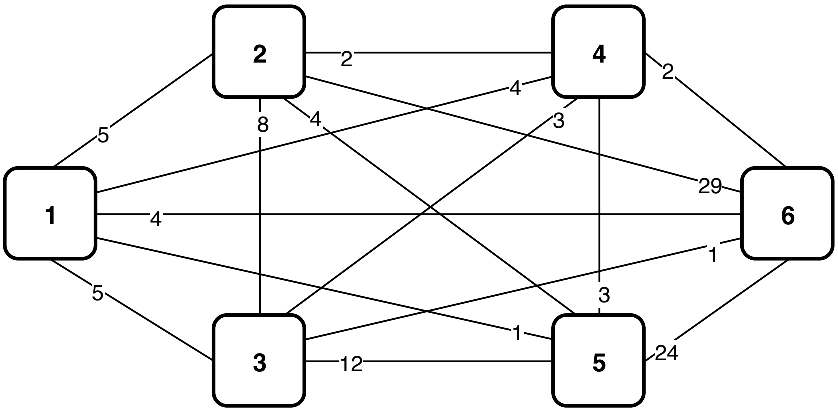


Figura 5.84: Optical topology after dimensioning.

In table 5.89 we can see the number of optical channels calculated using 5.2 and 5.7 and the number of amplifiers for each link calculated using 5.3.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	13	4
Node 1 <-> Node 3	6	6
Node 2 <-> Node 3	15	0
Node 2 <-> Node 4	42	6
Node 3 <-> Node 5	18	8
Node 4 <-> Node 5	3	1
Node 4 <-> Node 6	35	7
Node 5 <-> Node 6	25	3

Tabela 5.89: Table with information regarding links for transparent mode.

In table 5.90 we can see the number of line ports and add ports using 5.31 the number of long-reach transponders using 5.30 and the number of tributary ports using 5.29.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	580	19	19	19
2	3	460	48	48	70
3	3	360	29	29	39
4	3	400	14	14	80
5	3	480	44	44	46
6	2	440	60	60	60

Tabela 5.90: Table with information regarding nodes for transparent mode.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate (in relation to the line ports and the add ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
Electrical part	Number of total demands	Bit rate
580 tributary ports	260	ODU0
	260	ODU1
	60	ODU2
	Node<–Optical Channels–>Node	Bit rate
19 LR Transponders	1 <—- 5 —-> 2	100 Gbits/s
	1 <—- 5 —-> 3	
	1 <—- 4 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 4 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
19 add ports	1 <—- 5 —-> 2	100 Gbits/s
	1 <—- 5 —-> 3	
	1 <—- 4 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 4 —-> 6	
19 line ports	1 <—- 5 —-> 2	
	1 <—- 5 —-> 3	
	1 <—- 4 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 4 —-> 6	

Tabela 5.91: Table with detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

Detailed description of Node 2		
Electrical part	Number of total demands	Bit rate
460 tributary ports	220	ODU0
	140	ODU1
	40	ODU2
	40	ODU3
	20	ODU4
	Node<–Optical Channels–>Node	Bit rate
48 LR Transponders	2 <—– 5 —–> 1	100 Gbits/s
	2 <—– 8 —–> 3	
	2 <—– 2 —–> 4	
	2 <—– 4 —–> 5	
	2 <—- 29 —–> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
48 add ports	2 <—– 5 —–> 1	100 Gbits/s
	2 <—– 8 —–> 3	
	2 <—– 2 —–> 4	
	2 <—– 4 —–> 5	
	2 <—- 29 —–> 6	
70 line ports	2 <—– 5 —–> 1	
	2 <—– 8 —–> 3	
	2 <—– 2 —–> 4	
	2 <—– 4 —–> 5	
	2 <—- 29 —–> 6	
	1 <—– 4 —–> 4	
	1 <—– 4 —–> 6	
	3 <—– 3 —–> 4	

Tabela 5.92: Table with detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 3		
Electrical part	Number of total demands	Bit rate
360 tributary ports	140	ODU0
	120	ODU1
	60	ODU2
	40	ODU3
	Node<–Optical Channels–>Node	Bit rate
29 LR Transponders	3 <—– 5 —–> 1	100 Gbits/s
	3 <—– 8 —–> 2	
	3 <—– 3 —–> 4	
	3 <—– 12 —–> 5	
	3 <—– 1 —–> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
29 add ports	3 <—– 5 —–> 1	100 Gbits/s
	3 <—– 8 —–> 2	
	3 <—– 3 —–> 4	
	3 <—– 12 —–> 5	
	3 <—– 1 —–> 6	
39 line ports	3 <—– 5 —–> 1	
	3 <—– 8 —–> 2	
	3 <—– 3 —–> 4	
	3 <—– 12 —–> 5	
	3 <—– 1 —–> 6	
	1 <—– 1 —–> 5	
	2 <—– 4 —–> 5	

Tabela 5.93: Table with detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 4		
Electrical part	Number of total demands	Bit rate
400 tributary ports	140	ODU0
	200	ODU1
	60	ODU2
	Node<–Optical Channels–>Node	Bit rate
14 LR Transponders	4 <—– 4 —–> 1	100 Gbits/s
	4 <—– 2 —–> 2	
	4 <—– 3 —–> 3	
	4 <—– 3 —–> 5	
	4 <—– 2 —–> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
14 add ports	4 <—– 4 —–> 1	100 Gbits/s
	4 <—– 2 —–> 2	
	4 <—– 3 —–> 3	
	4 <—– 3 —–> 5	
	4 <—– 2 —–> 6	
80 line ports	4 <—– 4 —–> 1	
	4 <—– 2 —–> 2	
	4 <—– 3 —–> 3	
	4 <—– 3 —–> 5	
	4 <—– 2 —–> 6	
	1 <—– 4 —–> 6	
	2 <—- 29 —–> 6	

Tabela 5.94: Table with detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 5		
Electrical part	Number of total demands	Bit rate
480 tributary ports	280	ODU0
	80	ODU1
	80	ODU2
	20	ODU3
	20	ODU4
	Node<–Optical Channels–>Node	Bit rate
44 LR Transponders	5 <—– 1 —–> 1	100 Gbits/s
	5 <—– 4 —–> 2	
	5 <—- 12 —–> 3	
	5 <—– 3 —–> 4	
	5 <—- 24 —–> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
44 add ports	5 <—– 1 —–> 1	100 Gbits/s
	5 <—– 4 —–> 2	
	5 <—- 12 —–> 3	
	5 <—– 3 —–> 4	
	5 <—- 24 —–> 6	
46 line ports	5 <—– 1 —–> 1	
	5 <—– 4 —–> 2	
	5 <—- 12 —–> 3	
	5 <—– 3 —–> 4	
	5 <—- 24 —–> 6	
	3 <—– 1 —–> 6	

Tabela 5.95: Table with detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 6		
Electrical part	Number of total demands	Bit rate
440 tributary ports	160	ODU0
	200	ODU1
	20	ODU2
	20	ODU3
	40	ODU4
	Node<–Optical Channels–>Node	Bit rate
60 LR Transponders	6 <—– 4 —–> 1	100 Gbits/s
	6 <—- 29 —–> 2	
	6 <—– 1 —–> 3	
	6 <—– 2 —–> 4	
	6 <—- 24 —–> 5	
Optical part	Node<–Optical Channels–>Node	Bit rate
60 add ports	6 <—– 4 —–> 1	100 Gbits/s
	6 <—- 29 —–> 2	
	6 <—– 1 —–> 3	
	6 <—– 2 —–> 4	
	6 <—- 24 —–> 5	
60 line ports	6 <—– 4 —–> 1	
	6 <—- 29 —–> 2	
	6 <—– 1 —–> 3	
	6 <—– 2 —–> 4	
	6 <—- 24 —–> 5	

Tabela 5.96: Table with detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.3. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

Now, in next page, let's focus on the routing information in table 5.97. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

Routing		
o	d	Links
1	2	{(1,2)}
1	3	{(1,3)}
1	4	{(1,2),(2,4)}
1	5	{(1,3),(3,5)}
1	6	{(1,2),(2,4),(4,6)}
2	3	{(2,3)}
2	4	{(2,4)}
2	5	{(2,3),(3,5)}
2	6	{(2,4),(4,6)}
3	4	{(3,2),(2,4)}
3	5	{(3,5)}
3	6	{(3,5),(5,6)}
4	5	{(4,5)}
4	6	{(4,6)}
5	6	{(5,6)}

Tabela 5.97: Table with description of routing

Finally and most importantly through table 5.98 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above. In table 5.78 mentioned in previous scenario we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	157 520 000 €
	100 Gbits/s Transceivers		314	5 000 €/Gbit/s	157 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	22 951 800 €
		ODU0 Ports	1 200	10 €/port	12 000 €	
		ODU1 Ports	1 000	15 €/port	15 000 €	
		ODU2 Ports	320	30 €/port	9 600 €	
		ODU3 Ports	120	60 €/port	7 200 €	
		ODU4 Ports	80	100 €/port	8 000 €	
		Transponders	214	100 000 €/port	21 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	314	2 500 €/port	785 000 €	
		Add Ports	214	2 500 €/port	535 000 €	
Total Network Cost						180 471 800 €

Tabela 5.98: Table with detailed description of CAPEX for this scenario.

Conclusions

Once we have obtained the results for all the scenarios we will now draw some conclusions about these results. For a better analysis of the results will be created the table 5.99 with the number of line ports and add ports of the optical part, the tributary ports, the transponders and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

	Low Traffic	Medium Traffic	High Traffic
Traffic (Gbit/s)	500	5 000	10 000
Number of Add ports	34	114	214
Number of Line ports	52	168	314
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	52	168	314
Number of Transponders	34	114	214
Link Cost	26 520 000 €	84 520 000 €	157 520 000 €
Node Cost	3 797 590 €	12 310 900 €	22 951 800 €
CAPEX	**30 317 590 €**	**96 830 900 €**	**180 471 800 €**
CAPEX/Gbit/s	**60 635.18 €/Gbit/s**	**19 366.18 €/Gbit/s**	**18 047.68 €/Gbit/s**

Tabela 5.99: Table with the various CAPEX values obtained in the different traffic scenarios.

Looking at the previous table we can make some comparisons between the several scenarios:

- Comparing the low traffic scenario with the others, we can see that, despite having an increase of factor ten (average scenario) and factor twenty (high scenario), the same increase does not occur in the final cost (it is lower). This happens because the number of transceivers is smaller than expected (an average scenario of 520 would be expected and a high scenario would be expected in 1040);
- Comparing the medium traffic scenario with the high traffic scenario, we can see that the factor increase is double and in the final cost this factor is very close but still lower. Again, this happens because the number of transceivers is smaller, but very close to what was expected (the high scenario would be expected at 336);
- Comparing the cost with the traffic, we see that, for the low traffic scenario, the cost per traffic is very high in relation to the other two. We can conclude that a low traffic scenario becomes more expensive than a high traffic scenario.

Opens Issues

The creation of this model for any scenario, started with some considerations and some open issues being:

- Allow blocking.

  The presented model assume that the solution is possible or impossible, does not support a partial solution where some demands are not routed (are blocked).

- Allow multiple transmission system.

  The presented model for each link only supports one transmission system.

5.1.4 Transparent with 1+1 Protection

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the ILP model for the transparent transport mode with 1 plus 1 protection.

Here, in this case, we must take into account table 5.67, previously mentioned, in order to better understand the objective function.

Before carrying out the description of the objective function we must take into account the following particularity of this mode of transport:

- $N_{OXC,n}$ = 1, $\forall$ n that process traffic
- $N_{EXC,n}$ = 1, $\forall$ n that process traffic

The objective function of following the ILP is a minimization of the CAPEX through the equation 5.1 where in this case for the cost of nodes we have in consideration the electric cost 5.5 and the optical cost 5.6. In this case the value of $P_{exc,c,n}$ is obtained by equation 5.38 for short-reach and by the equation 5.39 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 5.40.

The equation 5.38 refers to the number of sort-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{5.38}$$

where $D_{nd,c}$ are the client demands between nodes n and d with bit rate c.

In this case there is the following particularity:

- When n=d the value of client demands is always zero, i.e, $D_{nn,c} = 0$

As previously mentioned, the equation 5.39 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e. the number of add ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} \lambda_{nj} \tag{5.39}$$

where λ_{nj} is the number of optical channels between node n and node j.

The equation 5.40 refers to the number of ports in optical switch in node n, $P_{oxc,n}$, i.e. the number of line ports and the number of adding ports of node n which can be calculated as

$$P_{oxc,n} = \sum_{j=1}^{N} f_{nj}^{od} + \sum_{j=1}^{N} \lambda_{nj} \tag{5.40}$$

where f_{nj}^{od} refers to the number of line ports for all demand pairs (od) and λ_{nj} refers to the number of add ports.

The objective function, to be minimized, is the expression 5.7, i.e.,

$$minimize \qquad \left\{ \quad C_C \quad \right\}$$

$subject\ to$

$$\sum_{c \in C} B\left(c\right) D_{odc} \leq \tau \lambda_{od} \qquad \forall (o,d) : o < d \tag{5.41}$$

This restriction is considered grooming constraint and for this model the grooming can be done before routing since the traffic is aggregated just for demands between the same nodes, thus not depending on the routes. The variable τ is always 100 Gbits/s.

$$\sum_{j \backslash \{o\}} f_{ij}^{od} = \lambda_{od} \qquad \forall (o,d) : o < d, \forall i : i = o \tag{5.42}$$

This constraint are equal to the constraint 5.8 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{j \backslash \{o\}} f_{ij}^{od} = \sum_{j \backslash \{d\}} f_{ji}^{od} \qquad \forall (o,d) : o < d, \forall i : i \neq o, d \tag{5.43}$$

This constraint are equal to the constraint 5.9.

$$\sum_{j \backslash \{d\}} f_{ji}^{od} = \lambda_{od} \qquad \forall (o,d) : o < d, \forall i : i = d \tag{5.44}$$

This constraint are equal to the constraint 5.10 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{j\backslash\{o\}} fp_{ij}^{od} = \lambda_{od} \qquad \forall(o,d) : o < d, \forall i : i = o \qquad (5.45)$$

This flow conservation ensures that, for all demand pairs (*o*,*d*), is equal to number of optical channels between this demand for all bidirectional links (*i*,*j*) when j is not equal to the origin of the demand.

$$\sum_{j\backslash\{o\}} fp_{ij}^{od} = \sum_{j\backslash\{d\}} fp_{ji}^{od} \qquad \forall(o,d) : o < d, \forall i : i \neq o, d \qquad (5.46)$$

This flow conservation ensures that, assuming bidirectional traffic, so the number of flows in both directions of the link is the same.

$$\sum_{j\backslash\{d\}} fp_{ji}^{od} = \lambda_{od} \qquad \forall(o,d) : o < d, \forall i : i = d \qquad (5.47)$$

This flow conservation is based on the same idea of 5.45, however applied in reverse direction.

$$\sum_{o=1} \sum_{d=o+1} \left(f_{ij}^{od} + fp_{ij}^{od} \right) \leq \lambda_{od} \qquad \forall(o,d), (i,j) \qquad (5.48)$$

This constraint assures us that the variable f_{ij}^{od} (working flow) and fp_{ij}^{od} (protection flow) are different.

$$\sum_{o=1} \sum_{d=o+1} \left(f_{ij}^{od} + f_{ji}^{od} + fp_{ij}^{od} + fp_{ji}^{od} \right) \leq K_{ij} G_{ij} L_{ij} \qquad \forall(i,j) : i < j \qquad (5.49)$$

This restriction answers capacity constraint problem. Then, total flows must be less or equal to the capacity of network links. For any situation the maximum number of optical channels supported by each transmission system is 100, i.e., K_{ij} = 100.

$$f_{ij}^{od}, f_{ji}^{od}, fp_{ij}^{od}, fp_{ji}^{od}, \lambda_{od} \in \mathbb{N} \qquad \forall(i,j) : i < j, \forall(o,d) : o < d \qquad (5.50)$$

This constraint define the total number of flows and the number of optical channels must be a counting number.

$$L_{i,j} \in \{0, 1\} \qquad \forall(i,j) \qquad (5.51)$$

Last constraint refers to the use of the link where this variable can be zero if it is not being used or one if is being used.

Result description

To perform the calculations using the implementation of the models described previously it is necessary to use a mathematical software tool. For this we will use MATLAB which is ideal for dealing with linear programming problems and can call the LPsolve through an external interface. We already have all the necessary to obtain the CAPEX value for the reference network 10.1. As described in the subsection of network traffic 4.2, we have three values of network traffic (low, medium and high traffic) so we have to obtain three different CAPEX. The value of the CAPEX of the network will be calculated based on the costs of the equipment present in the table 5.2.

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.1. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topology, the second are the logical topology for all ODUs and finally the resulting physical and optical topology.

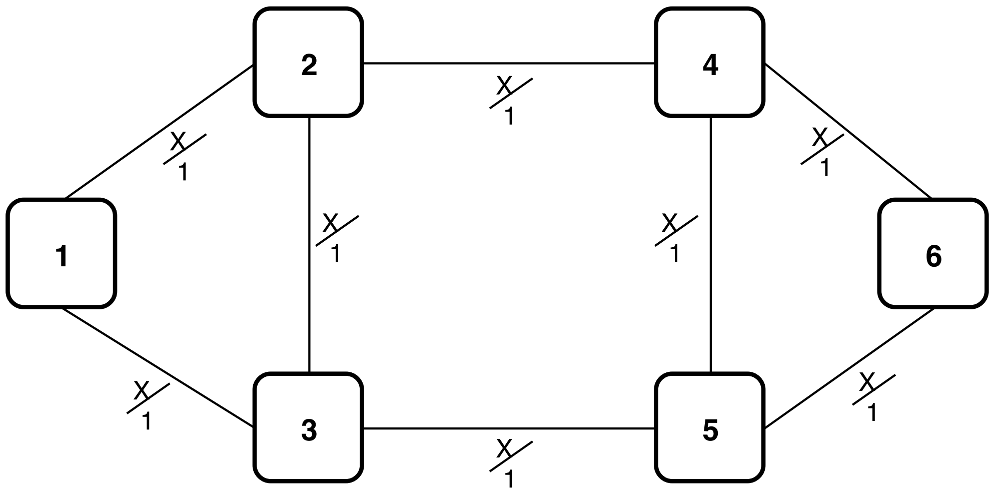


Figura 5.85: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

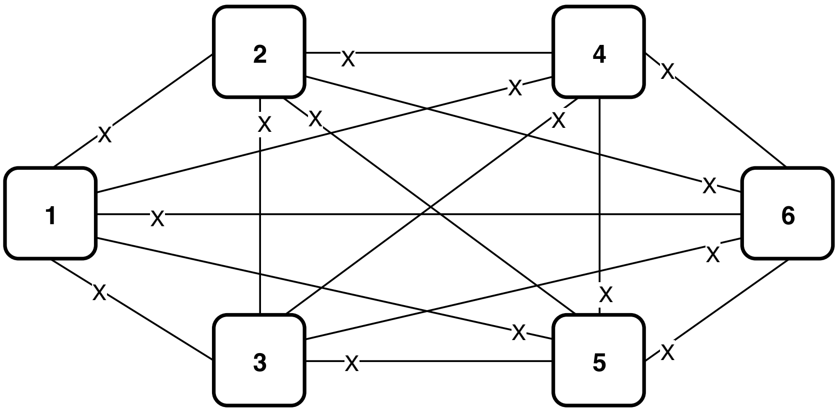


Figura 5.86: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

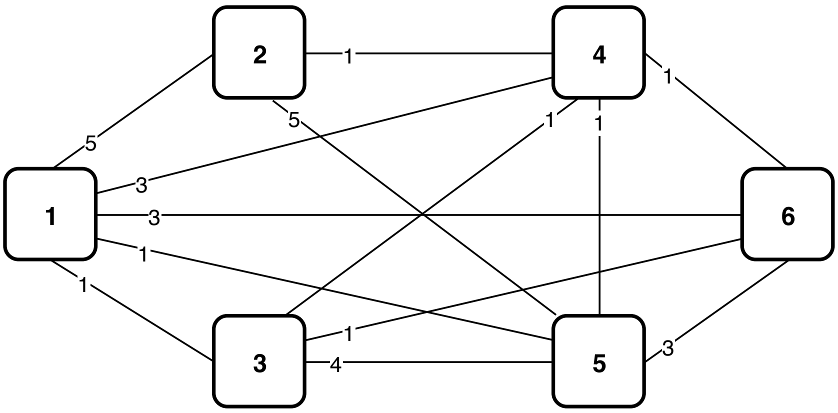


Figura 5.87: ODU0 logical topology defined by the ODU0 traffic matrix.

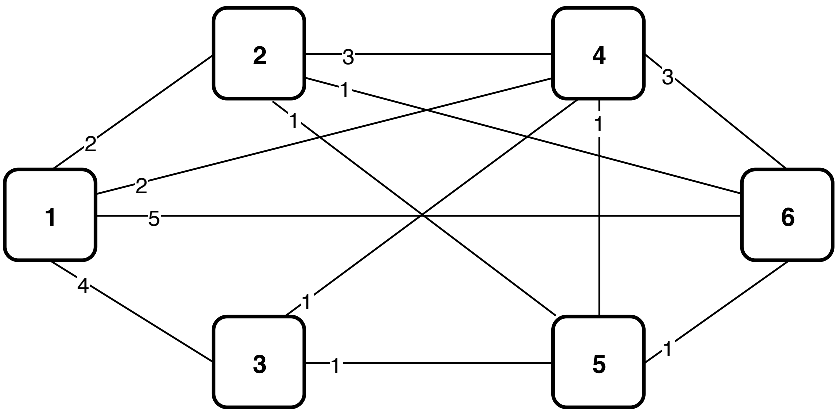


Figura 5.88: ODU1 logical topology defined by the ODU1 traffic matrix.

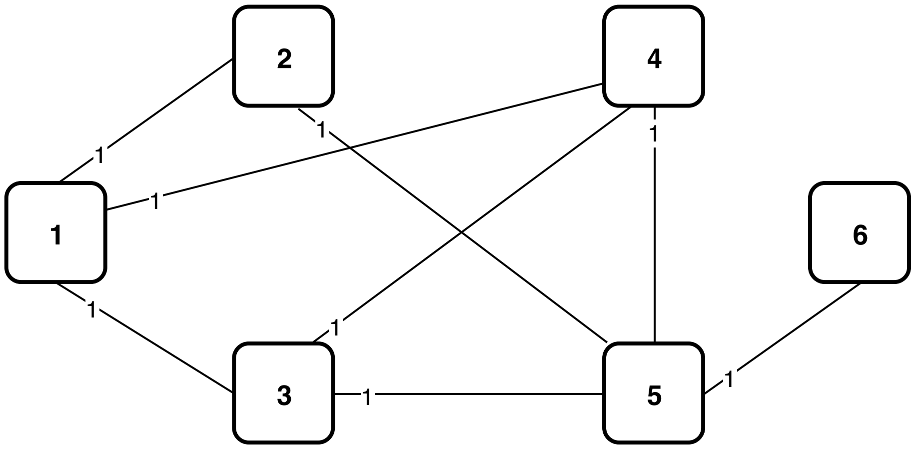


Figura 5.89: ODU2 logical topology defined by the ODU2 traffic matrix.

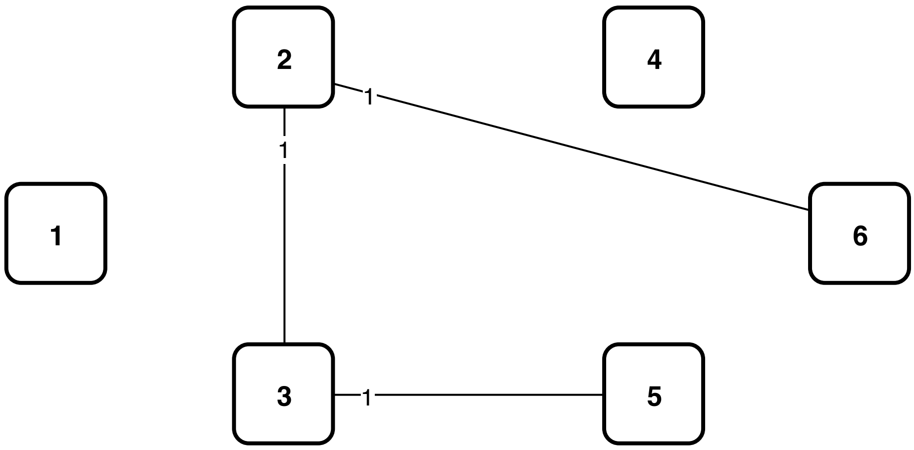


Figura 5.90: ODU3 logical topology defined by the ODU3 traffic matrix.

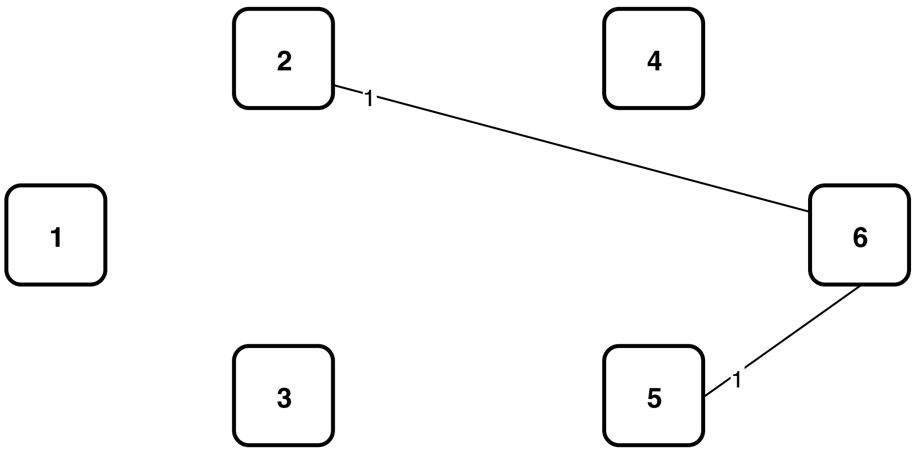


Figura 5.91: ODU4 logical topology defined by the ODU4 traffic matrix.

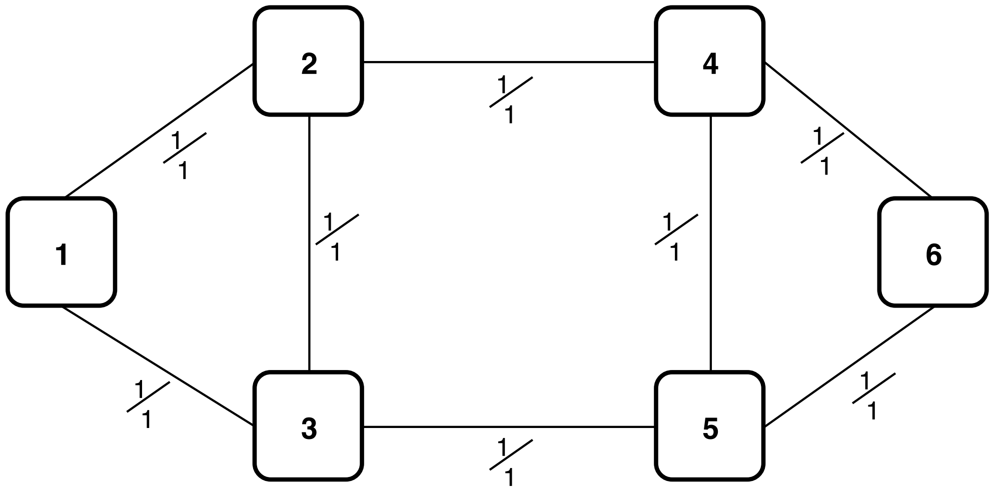


Figura 5.92: Physical topology after dimensioning.

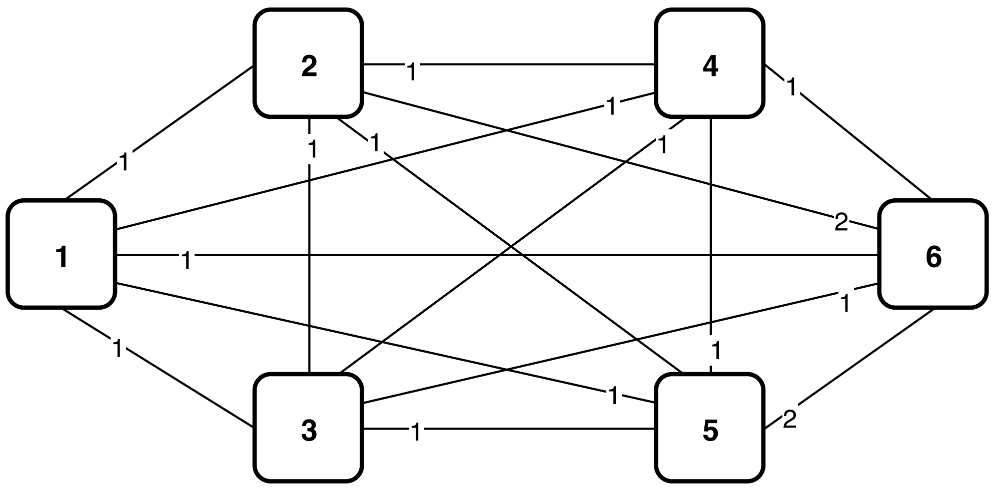


Figura 5.93: Optical topology after dimensioning.

In table 5.100 we can see the number of optical channels calculated using 5.2 and 5.7 and the number of amplifiers for each link calculated using 5.3.

In table 5.101 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports and the number of add ports for the optical part calculated using 5.40 the number of long-reach transponders calculated using 5.39 and the number of tributary ports calculated using 5.38 for each node.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	6	4
Node 1 <-> Node 3	6	6
Node 2 <-> Node 3	10	0
Node 2 <-> Node 4	10	6
Node 3 <-> Node 5	10	8
Node 4 <-> Node 5	10	1
Node 4 <-> Node 6	8	7
Node 5 <-> Node 6	8	3

Tabela 5.100: Table with information regarding links for transparent mode with 1+1 protection.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	29	5	5	12
2	3	23	6	6	26
3	3	18	5	5	26
4	3	20	5	5	28
5	3	24	6	6	28
6	2	22	7	7	16

Tabela 5.101: Table with information regarding nodes for transparent mode with 1+1 protection.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate (in relation to the line ports and the add ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
Electrical part	Number of tributary ports	Bit rate
29 tributary ports	13	ODU0
	13	ODU1
	3	ODU2
	Node<–Optical Channels–>Node	Bit rate
5 LR Transponders	1 <—- 1 —-> 2	100 Gbits/s
	1 <—- 1 —-> 3	
	1 <—- 1 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 1 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
5 add ports	1 <—- 1 —-> 2	100 Gbits/s
	1 <—- 1 —-> 3	
	1 <—- 1 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 1 —-> 6	
12 line ports	1 <—- 1 —-> 2	
	1 <—- 1 —-> 3	
	1 <—- 1 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 1 —-> 6	
	2 <—- 1 —-> 3	

Tabela 5.102: Table with detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 2		
Electrical part	Number of tributary ports	Bit rate
23 tributary ports	11	ODU0
	7	ODU1
	2	ODU2
	2	ODU3
	1	ODU4
	Node<–Optical Channels–>Node	Bit rate
6 LR Transponders	2 <—- 1 —-> 1	100 Gbits/s
	2 <—- 1 —-> 3	
	2 <—- 1 —-> 4	
	2 <—- 1 —-> 5	
	2 <—- 2 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
6 add ports	2 <—- 1 —-> 1	100 Gbits/s
	2 <—- 1 —-> 3	
	2 <—- 1 —-> 4	
	2 <—- 1 —-> 5	
	2 <—- 2 —-> 6	
26 line ports	2 <—- 1 —-> 1	
	2 <—- 1 —-> 3	
	2 <—- 1 —-> 4	
	2 <—- 1 —-> 5	
	2 <—- 2 —-> 6	
	1 <—- 1 —-> 3	
	1 <—- 1 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 1 —-> 6	
	3 <—- 1 —-> 4	
	3 <—- 1 —-> 5	
	3 <—- 1 —-> 6	

Tabela 5.103: Table with detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 3		
Electrical part	Number of tributary ports	Bit rate
18 tributary ports	7	ODU0
	6	ODU1
	3	ODU2
	2	ODU3
	Node<–Optical Channels–>Node	Bit rate
5 LR Transponders	3 <—- 1 —-> 1	100 Gbits/s
	3 <—- 1 —-> 2	
	3 <—- 1 —-> 4	
	3 <—- 1 —-> 5	
	3 <—- 1 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
5 add ports	3 <—- 1 —-> 1	
	3 <—- 1 —-> 2	
	3 <—- 1 —-> 4	
	3 <—- 1 —-> 5	
	3 <—- 1 —-> 6	
26 line ports	3 <—- 1 —-> 1	
	3 <—- 1 —-> 2	
	3 <—- 1 —-> 4	
	3 <—- 1 —-> 5	100 Gbits/s
	3 <—- 1 —-> 6	
	1 <—- 1 —-> 2	
	1 <—- 1 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 1 —-> 6	
	2 <—- 1 —-> 4	
	2 <—- 1 —-> 5	
	2 <—- 2 —-> 6	

Tabela 5.104: Table with detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 4		
Electrical part	Number of tributary ports	Bit rate
20 tributary ports	7	ODU0
	10	ODU1
	3	ODU2
	Node<–Optical Channels–>Node	Bit rate
5 LR Transponders	4 <—- 1 —-> 1	100 Gbits/s
	4 <—- 1 —-> 2	
	4 <—- 1 —-> 3	
	4 <—- 1 —-> 5	
	4 <—- 1 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
5 add ports	4 <—- 1 —-> 1	100 Gbits/s
	4 <—- 1 —-> 2	
	4 <—- 1 —-> 3	
	4 <—- 1 —-> 5	
	4 <—- 1 —-> 6	
28 line ports	4 <—- 1 —-> 1	
	4 <—- 1 —-> 2	
	4 <—- 1 —-> 3	
	4 <—- 1 —-> 5	
	4 <—- 1 —-> 6	
	1 <—- 1 —-> 5	
	1 <—- 1 —-> 6	
	2 <—- 1 —-> 5	
	2 <—- 2 —-> 6	
	3 <—- 1 —-> 5	
	3 <—- 1 —-> 6	
	5 <—- 2 —-> 6	

Tabela 5.105: Table with detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 5		
Electrical part	Number of tributary ports	Bit rate
24 tributary ports	14	ODU0
	4	ODU1
	4	ODU2
	1	ODU3
	1	ODU4
	Node<–Optical Channels–>Node	Bit rate
6 LR Transponders	5 <—- 1 —-> 1	100 Gbits/s
	5 <—- 1 —-> 2	
	5 <—- 1 —-> 3	
	5 <—- 1 —-> 4	
	5 <—- 2 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
6 add ports	5 <—- 1 —-> 1	100 Gbits/s
	5 <—- 1 —-> 2	
	5 <—- 1 —-> 3	
	5 <—- 1 —-> 4	
	5 <—- 2 —-> 6	
28 line ports	5 <—- 1 —-> 1	
	5 <—- 1 —-> 2	
	5 <—- 1 —-> 3	
	5 <—- 1 —-> 4	
	5 <—- 2 —-> 6	
	1 <—- 1 —-> 4	
	1 <—- 1 —-> 6	
	2 <—- 1 —-> 4	
	2 <—- 2 —-> 6	
	3 <—- 1 —-> 4	
	3 <—- 1 —-> 6	
	4 <—- 1 —-> 6	

Tabela 5.106: Table with detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

Detailed description of Node 6		
Electrical part	Number of tributary ports	Bit rate
22 tributary ports	8	ODU0
	10	ODU1
	1	ODU2
	1	ODU3
	2	ODU4
	Node<–Optical Channels–>Node	Bit rate
7 add ports	6 <—- 1 —-> 1	100 Gbits/s
	6 <—- 2 —-> 2	
	6 <—- 1 —-> 3	
	6 <—- 1 —-> 4	
	6 <—- 2 —-> 5	
Optical part	Node<–Optical Channels–>Node	Bit rate
7 add ports	6 <—- 1 —-> 1	100 Gbits/s
	6 <—- 2 —-> 2	
	6 <—- 1 —-> 3	
	6 <—- 1 —-> 4	
	6 <—- 2 —-> 5	
16 line ports	6 <—- 1 —-> 1	
	6 <—- 2 —-> 2	
	6 <—- 1 —-> 3	
	6 <—- 1 —-> 4	
	6 <—- 2 —-> 5	
	4 <—- 1 —-> 5	

Tabela 5.107: Table with detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 4.2.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

In next step let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 5.108 we can see all the routing obtained for all nodes.

Routing		
o	d	Links
1	2	{(1,3),(3,2)} {(1,2)}
1	3	{(1,2),(2,3)} {(1,3)}
1	4	{(1,3),(3,5),(5,4)} {(1,2),(2,4)}
1	5	{(1,2),(2,4),(4,5)} {(1,3),(3,5)}
1	6	{(1,3),(3,5),(5,6)} {(1,2),(2,4),(4,6)}
2	3	{(2,1),(1,3)} {(2,3)}
2	4	{(2,3),(3,5),(5,4)} {(2,4)}
2	5	{(2,4),(4,5)} {(2,3),(3,5)}
2	6	{(2,3),(3,5),(5,6)} {(2,4),(4,6)}
3	4	{(3,5),(5,4)} {(3,2),(2,4)}
3	5	{(3,2),(2,4),(4,5)} {(3,5)}
3	6	{(3,2),(2,4),(4,6)} {(3,5),(5,6)}
4	5	{(4,6),(6,5)} {(4,5)}
4	6	{(4,5),(5,6)} {(4,6)}
5	6	{(5,4),(4,6)} {(5,6)}

Tabela 5.108: Table with description of routing

Finally and most importantly through table 5.109 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above. In table 5.78 mentioned in previous model we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	68 520 000 €
	100 Gbits/s Transceivers		136	5 000 €/Gbit/s	68 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	3 947 590 €
		ODU0 Ports	60	10 €/port	600 €	
		ODU1 Ports	50	15 €/port	750 €	
		ODU2 Ports	16	30 €/port	480 €	
		ODU3 Ports	6	60 €/port	360 €	
		ODU4 Ports	4	100 €/port	400 €	
		Transponders	34	100 000 €/port	3 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	136	2 500 €/port	340 000 €	
		Add Ports	34	2 500 €/port	85 000 €	
Total Network Cost						72 467 590 €

Tabela 5.109: Table with detailed description of CAPEX for this scenario.

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.2. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topology, the second are the logical topology for all ODUs and finally the resulting physical and optical topology.

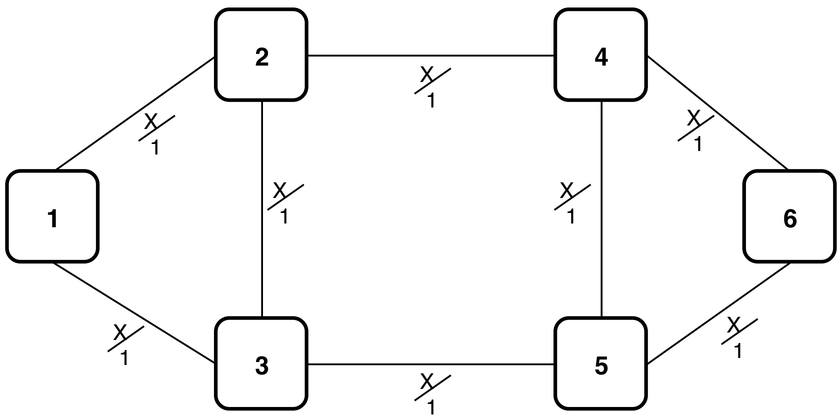


Figura 5.94: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

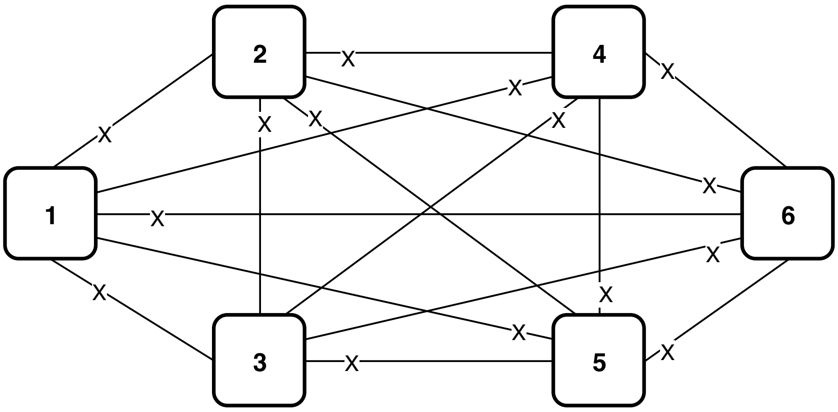


Figura 5.95: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

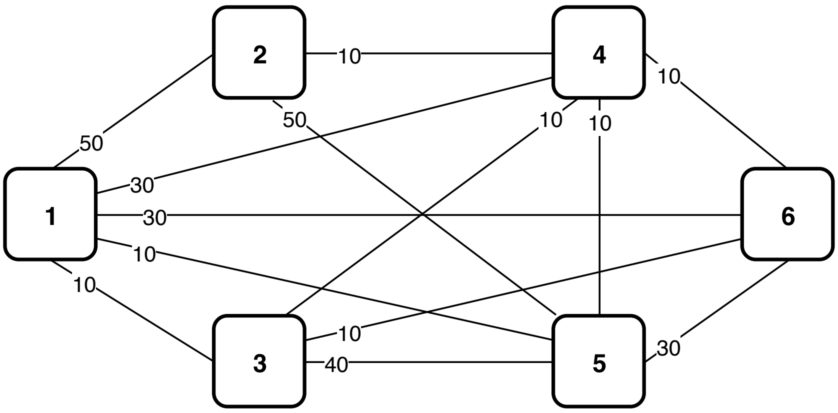


Figura 5.96: ODU0 logical topology defined by the ODU0 traffic matrix.

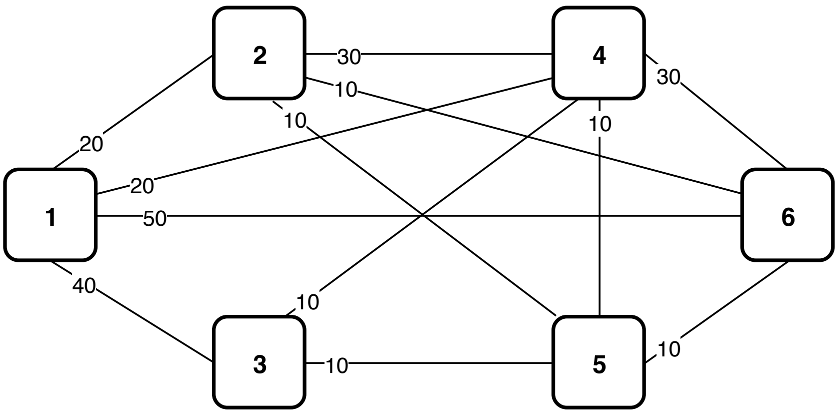


Figura 5.97: ODU1 logical topology defined by the ODU1 traffic matrix.

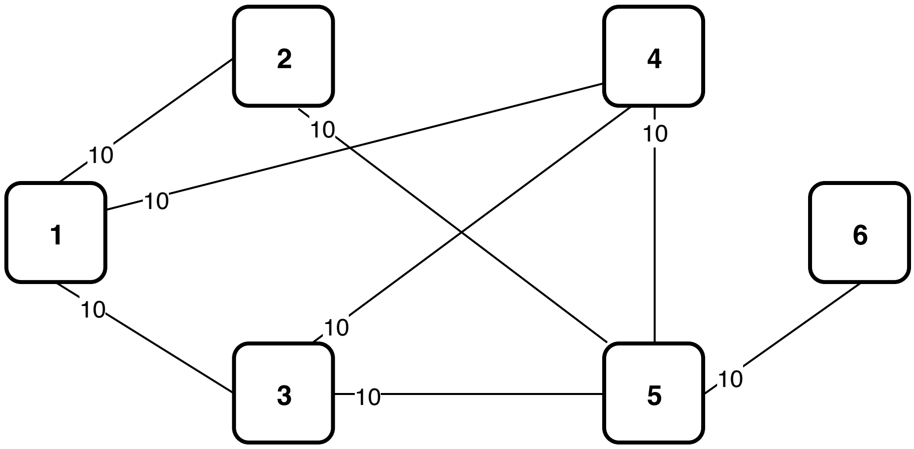


Figura 5.98: ODU2 logical topology defined by the ODU2 traffic matrix.

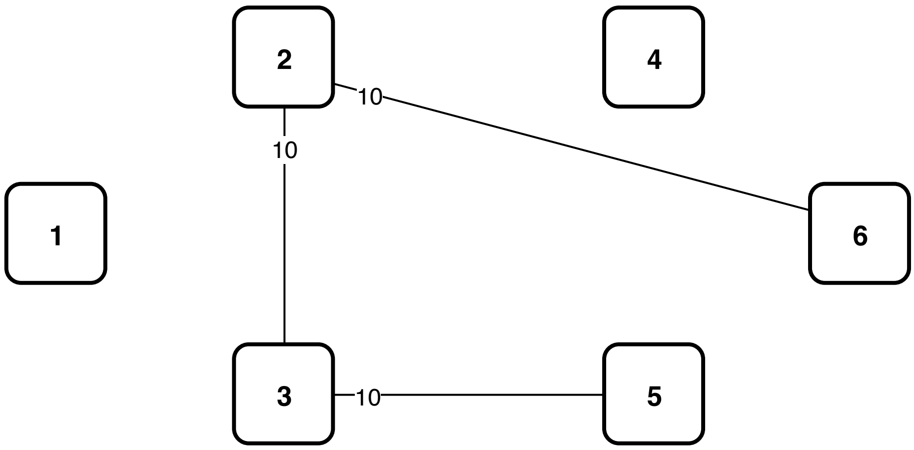


Figura 5.99: ODU3 logical topology defined by the ODU3 traffic matrix.

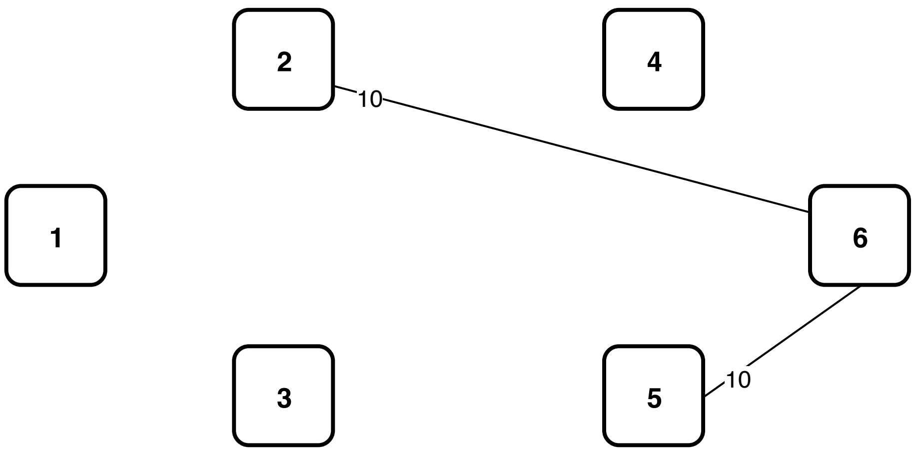


Figura 5.100: ODU4 logical topology defined by the ODU4 traffic matrix.

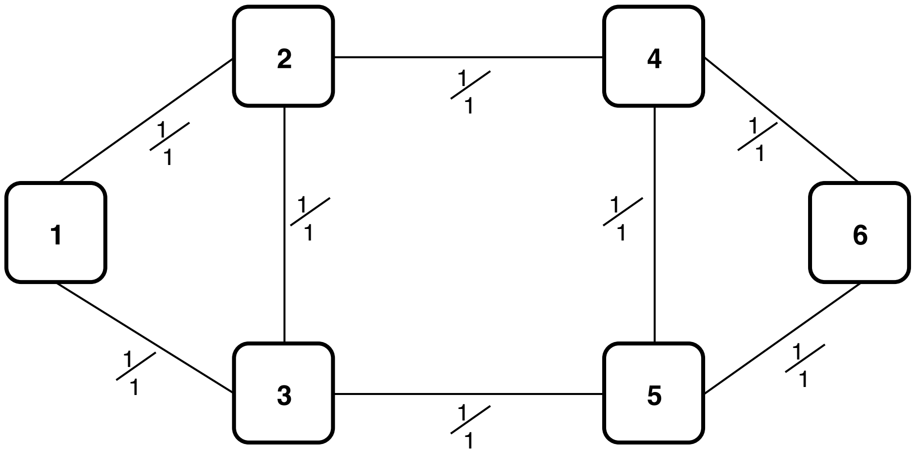


Figura 5.101: Physical topology after dimensioning.

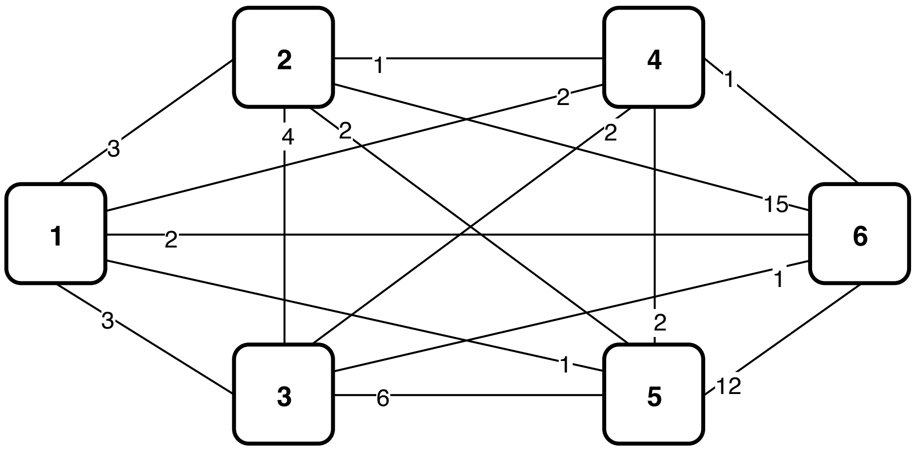


Figura 5.102: Optical topology after dimensioning.

In table 5.110 we can see the number of optical channels calculated using 5.2 and 5.7 and the number of amplifiers for each link calculated using 5.3.

In table 5.111 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports for the optical part and the number of add ports calculated using 5.40 the number of line ports for the electrical part calculated using 5.39 and the number of tributary ports calculated using 5.38 for each node.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	x	4
Node 1 <-> Node 3	x	6
Node 2 <-> Node 3	x	0
Node 2 <-> Node 4	x	6
Node 3 <-> Node 5	x	8
Node 4 <-> Node 5	x	1
Node 4 <-> Node 6	x	7
Node 5 <-> Node 6	x	3

Tabela 5.110: Table with information regarding links

Information regarding nodes					
		Optical part		Electrical part	
Node	Resulting Nodal Degree	Line Ports	Add Ports	Line Ports	Tributary Ports
1	2	x	11	x	290
2	3	x	25	x	230
3	3	x	16	x	180
4	3	x	8	x	200
5	3	x	23	x	240
6	2	x	31	x	220

Tabela 5.111: Table with information regarding nodes

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate (in relation to the line ports and the add ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	1 <—- x —-> 2	100 Gbits/s
	1 <—- x —-> 3	
	OXC <—- x —-> EXC	
11 add ports	1 <—- 3 —-> 2	
	1 <—- 3 —-> 3	
	1 <—- 2 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 2 —-> 6	
Electrical part	Number of tributary ports	Bit rate
290 tributary ports	130	ODU0
	130	ODU1
	30	ODU2

Tabela 5.112: Table with detailed description of node 1. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

Detailed description of Node 2		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	2 <—- x —-> 1	100 Gbits/s
	2 <—- x —-> 3	
	2 <—- x —-> 4	
	OXC <—- x —-> EXC	
25 add ports	2 <—- 3 —-> 1	
	2 <—- 4 —-> 3	
	2 <—- 1 —-> 4	
	2 <—- 2 —-> 5	
	2 <—- 15 —-> 6	
Electrical part	Number of tributary ports	Bit rate
230 tributary ports	110	ODU0
	70	ODU1
	20	ODU2
	20	ODU3
	10	ODU4

Tabela 5.113: Table with detailed description of node 2. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

Detailed description of Node 3		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	3 <—- x —-> 1	100 Gbits/s
	3 <—- x —-> 2	
	3 <—- x —-> 5	
	OXC <—- x —-> EXC	
16 add ports	3 <—- 3 —-> 1	
	3 <—- 4 —-> 2	
	3 <—- 2 —-> 4	
	3 <—- 6 —-> 5	
	3 <—- 1 —-> 6	
Electrical part	Number of tributary ports	Bit rate
180 tributary ports	70	ODU0
	60	ODU1
	30	ODU2
	20	ODU3

Tabela 5.114: Table with detailed description of node 3. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

Detailed description of Node 4		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	4 <—- x —-> 2	100 Gbits/s
	4 <—- x —-> 5	
	4 <—- x —-> 6	
	OXC <—- x —-> EXC	
8 add ports	4 <—- 2 —-> 1	
	4 <—- 1 —-> 2	
	4 <—- 2 —-> 3	
	4 <—- 2 —-> 5	
	4 <—- 1 —-> 6	
Electrical part	Number of tributary ports	Bit rate
200 tributary ports	70	ODU0
	100	ODU1
	30	ODU2

Tabela 5.115: Table with detailed description of node 4. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

Detailed description of Node 5		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	5 <—- x —-> 3	100 Gbits/s
	5 <—- x —-> 4	
	5 <—- x —-> 6	
	OXC <—- x —-> EXC	
23 add ports	5 <—- 1 —-> 1	
	5 <—- 2 —-> 2	
	5 <—- 6 —-> 3	
	5 <—- 2 —-> 4	
	5 <—- 12 —-> 6	
Electrical part	Number of tributary ports	Bit rate
240 tributary ports	140	ODU0
	40	ODU1
	40	ODU2
	10	ODU3
	10	ODU4

Tabela 5.116: Table with detailed description of node 5. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

Detailed description of Node 6		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	6 <—- x —-> 4	100 Gbits/s
	6 <—- x —-> 5	
	OXC <—- x —-> EXC	
31 add ports	6 <—- 2 —-> 1	
	6 <—- 15 —-> 2	
	6 <—- 1 —-> 3	
	6 <—- 1 —-> 4	
	6 <—- 12 —-> 5	
Electrical part	Number of tributary ports	Bit rate
220 tributary ports	80	ODU0
	100	ODU1
	10	ODU2
	10	ODU3
	20	ODU4

Tabela 5.117: Table with detailed description of node 6. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

In next step let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 5.118 we can see all the routing obtained for all nodes.

Routing		
o	d	Links
1	2	{(1,3),(3,2)} {(1,2)}
1	3	{(1,2),(2,3)} {(1,3)}
1	4	{(1,3),(3,5),(5,4)} {(1,2),(2,4)}
1	5	{(1,2),(2,4),(4,5)} {(1,3),(3,5)}
1	6	{(1,3),(3,5),(5,6)} {(1,2),(2,4),(4,6)}
2	3	{(2,1),(1,3)} {(2,3)}
2	4	{(2,3),(3,5),(5,4)} {(2,4)}
2	5	{(2,4),(4,5)} {(2,3),(3,5)}
2	6	{(2,3),(3,5),(5,6)} {(2,4),(4,6)}
3	4	{(3,5),(5,4)} {(3,2),(2,4)}
3	5	{(3,2),(2,4),(4,5)} {(3,5)}
3	6	{(3,2),(2,4),(4,6)} {(3,5),(5,6)}
4	5	{(4,6),(6,5)} {(4,5)}
4	6	{(4,5),(5,6)} {(4,6)}
5	6	{(5,4),(4,6)} {(5,6)}

Tabela 5.118: Table with description of routing

Finally and most importantly through table 5.119 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above. In table 5.78 mentioned in previous model we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	xxxxxxxxx €
	100 Gbits/s Transceivers		xx	5 000 €/Gbit/s	xxxxxxxxx €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	xxx xxxx xxx €
		ODU0 Ports	600	10 €/port	6 000 €	
		ODU1 Ports	500	15 €/port	7 500 €	
		ODU2 Ports	160	30 €/port	4 800 €	
		ODU3 Ports	80	60 €/port	3 600 €	
		ODU4 Ports	40	100 €/port	4 000 €	
		Line Ports	xx	100 000 €/port	xxxxxxxx €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	xx	2 500 €/port	xxxxxxx €	
		Add Ports	114	2 500 €/port	285 000 €	
Total Network Cost						xxxxxxx €

Tabela 5.119: Table with detailed description of CAPEX

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.3. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topology, the second are the logical topology for all ODUs and finally the resulting physical and optical topology.

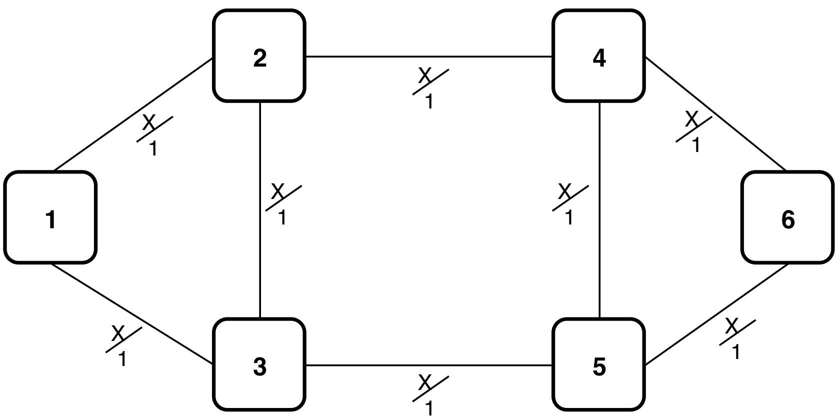


Figura 5.103: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

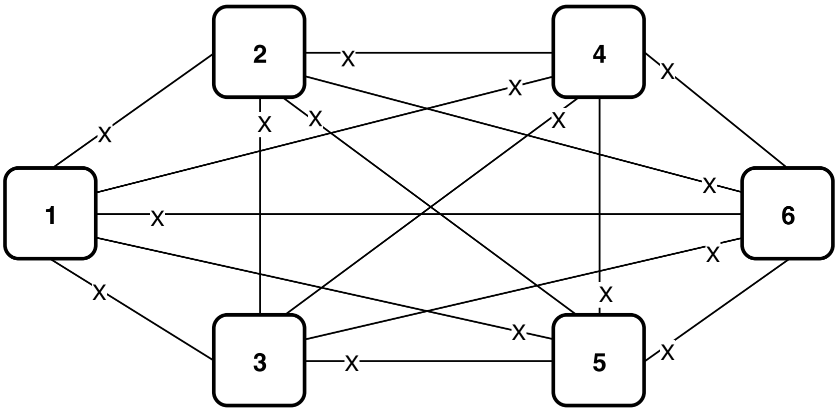


Figura 5.104: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

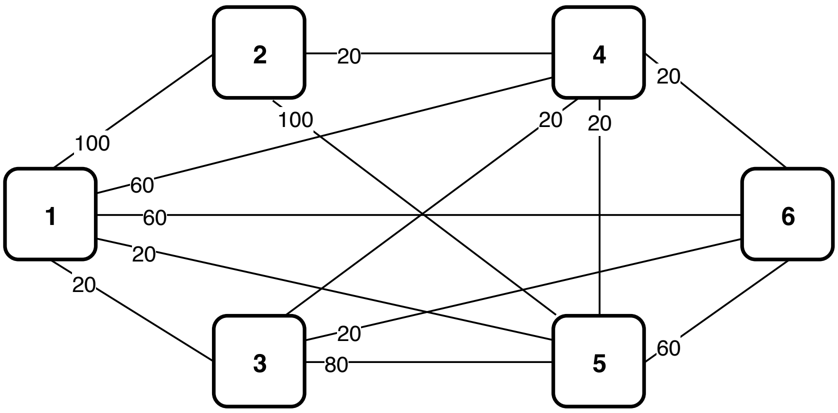


Figura 5.105: ODU0 logical topology defined by the ODU0 traffic matrix.

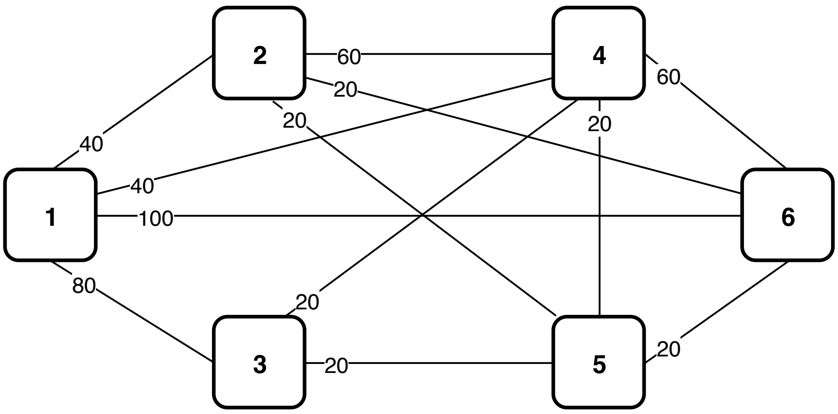


Figura 5.106: ODU1 logical topology defined by the ODU1 traffic matrix.

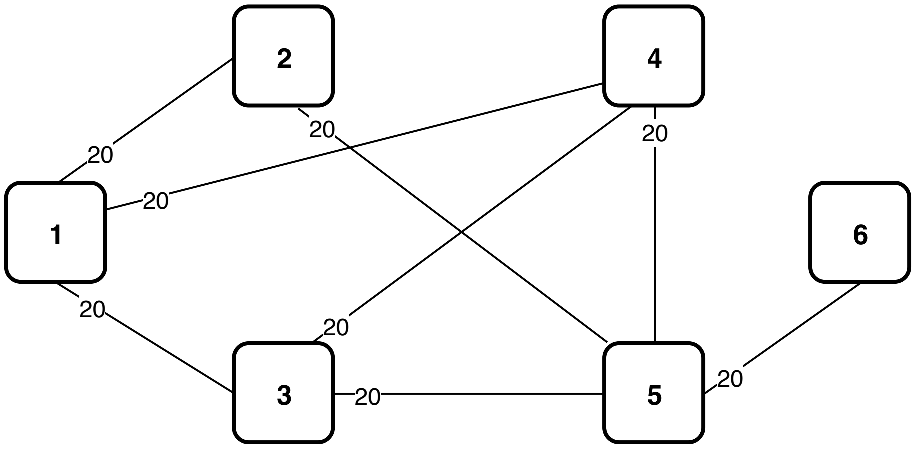


Figura 5.107: ODU2 logical topology defined by the ODU2 traffic matrix.

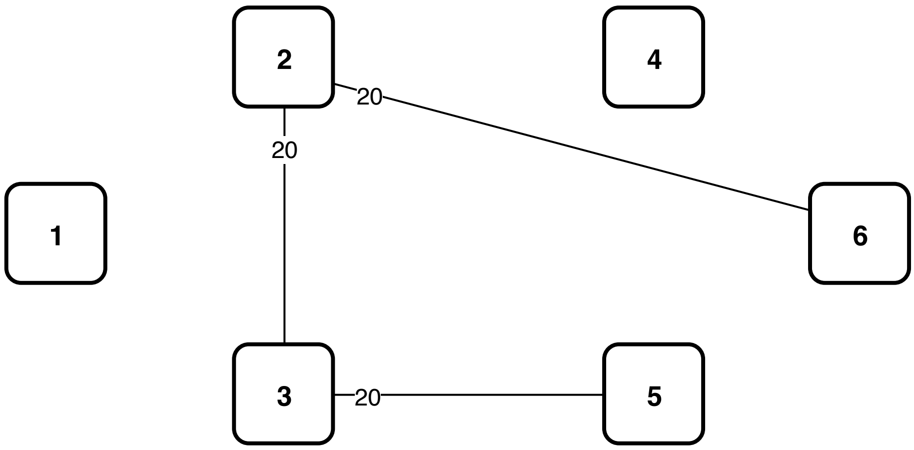


Figura 5.108: ODU3 logical topology defined by the ODU3 traffic matrix.

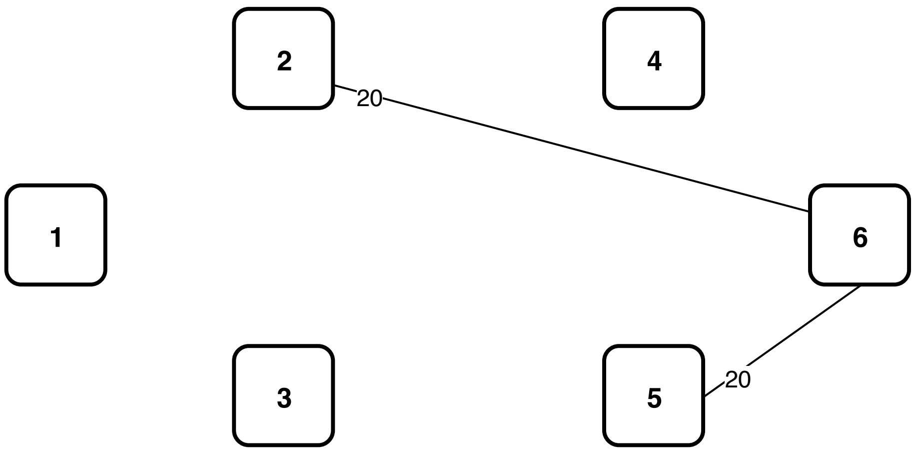


Figura 5.109: ODU4 logical topology defined by the ODU4 traffic matrix.

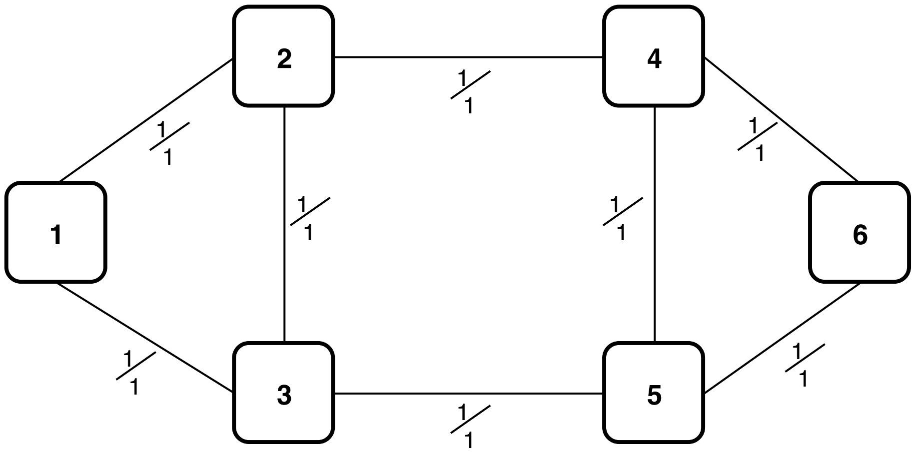


Figura 5.110: Physical topology after dimensioning.

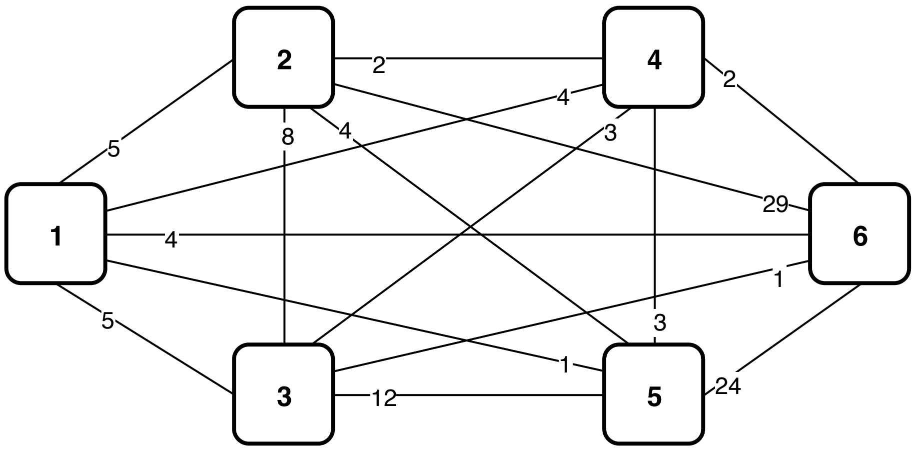


Figura 5.111: Optical topology after dimensioning.

In table 5.120 we can see the number of optical channels calculated using 5.2 and 5.7 and the number of amplifiers for each link calculated using 5.3.

In table 5.121 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports for the optical part and the number of add ports calculated using 5.40 the number of line ports for the electrical part calculated using 5.39 and the number of tributary ports calculated using 5.38 for each node.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	x	4
Node 1 <-> Node 3	x	6
Node 2 <-> Node 3	x	0
Node 2 <-> Node 4	x	6
Node 3 <-> Node 5	x	8
Node 4 <-> Node 5	x	1
Node 4 <-> Node 6	x	7
Node 5 <-> Node 6	x	3

Tabela 5.120: Table with information regarding links

Information regarding nodes					
		Optical part		Electrical part	
Node	Resulting Nodal Degree	Line Ports	Add Ports	Line Ports	Tributary Ports
1	2	x	19	x	580
2	3	x	48	x	460
3	3	x	29	x	360
4	3	x	14	x	400
5	3	x	44	x	480
6	2	x	60	x	440

Tabela 5.121: Table with information regarding nodes

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate (in relation to the line ports and the add ports) and how many ports are assigned to each different bit rate (in relation to the tributary ports).

Detailed description of Node 1		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	1 <—- x —-> 2	100 Gbits/s
	1 <—- x —-> 3	
	OXC <—- x —-> EXC	
19 add ports	1 <—- 5 —-> 2	
	1 <—- 5 —-> 3	
	1 <—- 4 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 4 —-> 6	
Electrical part	Number of tributary ports	Bit rate
580 tributary ports	260	ODU0
	260	ODU1
	60	ODU2

Tabela 5.122: Table with detailed description of node 1. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

Detailed description of Node 2		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	2 <—- x —-> 1	100 Gbits/s
	2 <—- x —-> 3	
	2 <—- x —-> 4	
	OXC <—- x —-> EXC	
48 add ports	2 <—- 5 —-> 1	
	2 <—- 8 —-> 3	
	2 <—- 2 —-> 4	
	2 <—- 4 —-> 5	
	2 <—- 29 —-> 6	
Electrical part	Number of tributary ports	Bit rate
460 tributary ports	220	ODU0
	140	ODU1
	40	ODU2
	40	ODU3
	20	ODU4

Tabela 5.123: Table with detailed description of node 2. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

Detailed description of Node 3		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	3 <—- x —-> 1	100 Gbits/s
	3 <—- x —-> 2	
	3 <—- x —-> 5	
	OXC <—- x —-> EXC	
29 add ports	3 <—- 5 —-> 1	
	3 <—- 8 —-> 2	
	3 <—- 3 —-> 4	
	3 <—- 12 —-> 5	
	3 <—- 1 —-> 6	
Electrical part	Number of tributary ports	Bit rate
360 tributary ports	140	ODU0
	120	ODU1
	60	ODU2
	40	ODU3

Tabela 5.124: Table with detailed description of node 3. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

Detailed description of Node 4		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	4 <—- x —-> 2	100 Gbits/s
	4 <—- x —-> 5	
	4 <—- x —-> 6	
	OXC <—- x —-> EXC	
14 add ports	4 <—- 4 —-> 1	
	4 <—- 2 —-> 2	
	4 <—- 3 —-> 3	
	4 <—- 3 —-> 5	
	4 <—- 2 —-> 6	
Electrical part	Number of tributary ports	Bit rate
400 tributary ports	140	ODU0
	200	ODU1
	60	ODU2

Tabela 5.125: Table with detailed description of node 4. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

Detailed description of Node 5		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	5 <—- x —-> 3 5 <—- x —-> 4 5 <—- x —-> 6 OXC <—- x —-> EXC	100 Gbits/s
44 add ports	5 <—- 1 —-> 1 5 <—- 4 —-> 2 5 <—- 12 —-> 3 5 <—- 3 —-> 4 5 <—- 24 —-> 6	
Electrical part	Number of tributary ports	Bit rate
480 tributary ports	280 80 80 20 20	ODU0 ODU1 ODU2 ODU3 ODU4

Tabela 5.126: Table with detailed description of node 5. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

Detailed description of Node 6		
Optical part	Node<–Optical Channels–>Node	Bit rate
x line ports	6 <—- x —-> 4 6 <—- x —-> 5 OXC <—- x —-> EXC	100 Gbits/s
60 add ports	6 <—- 4 —-> 1 6 <—- 29 —-> 2 6 <—- 1 —-> 3 6 <—- 2 —-> 4 6 <—- 24 —-> 5	
Electrical part	Number of tributary ports	Bit rate
440 tributary ports	160 200 20 20 40	ODU0 ODU1 ODU2 ODU3 ODU4

Tabela 5.127: Table with detailed description of node 6. Regarding the electrical part the line ports were not mentioned because they are all connected with the optical part.

Now let's focus on the routing information in table 5.128. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

Routing		
o	d	Links
1	2	{(1,3),(3,2)} {(1,2)}
1	3	{(1,2),(2,3)} {(1,3)}
1	4	{(1,3),(3,5),(5,4)} {(1,2),(2,4)}
1	5	{(1,2),(2,4),(4,5)} {(1,3),(3,5)}
1	6	{(1,3),(3,5),(5,6)} {(1,2),(2,4),(4,6)}
2	3	{(2,1),(1,3)} {(2,3)}
2	4	{(2,3),(3,5),(5,4)} {(2,4)}
2	5	{(2,4),(4,5)} {(2,3),(3,5)}
2	6	{(2,3),(3,5),(5,6)} {(2,4),(4,6)}
3	4	{(3,5),(5,4)} {(3,2),(2,4)}
3	5	{(3,2),(2,4),(4,5)} {(3,5)}
3	6	{(3,2),(2,4),(4,6)} {(3,5),(5,6)}
4	5	{(4,6),(6,5)} {(4,5)}
4	6	{(4,5),(5,6)} {(4,6)}
5	6	{(5,4),(4,6)} {(5,6)}

Tabela 5.128: Table with description of routing

Finally and most importantly through table 5.98 we can see the CAPEX result for this model. This value is obtained using equation 5.7 and all of the constraints mentioned above. In table 5.78 mentioned in previous scenario we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	xxxxx €
	100 Gbits/s Transceivers		xx	5 000 €/Gbit/s	xxxxxxxxxx €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	xxxxxxxxx €
		ODU0 Ports	1 200	10 €/port	12 000 €	
		ODU1 Ports	1 000	15 €/port	15 000 €	
		ODU2 Ports	320	30 €/port	9 600 €	
		ODU3 Ports	160	60 €/port	7 200 €	
		ODU4 Ports	80	100 €/port	8 000 €	
		Line Ports	xxx	100 000 €/port	xxxxxxxx €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	xxx	2 500 €/port	xxxxxxxx €	
		Add Ports	214	2 500 €/port	535 000 €	
Total Network Cost						xxxxxxx €

Tabela 5.129: Table with detailed description of CAPEX

Conclusions

Once we have obtained the results for all the scenarios we will now draw some conclusions about these results. For a better analysis of the results will be created the table 5.99.

	Low Traffic	Medium Traffic	High Traffic
CAPEX survivability	32 247 590 €	102 650 900 €	191 256 800 €
CAPEX/Gbit/s survivability	64 495.18 €/Gbit/s	20 530.18 €/Gbit/s	19 125.68 €/Gbit/s
Traffic (Gbit/s)	500	5 000	10 000
Number of Add ports	34	114	214
Number of Line ports	136	xx	xx
Number of Tributary ports	138	1 380	2 760
Number of Transceivers	136	xx	xx
Link Cost	68 520 000 €	xxxxxxxx €	xxxxxxx €
Node Cost	14 547 590 €	xxxxxxxx €	xxxxxxx €
CAPEX	**83 067 590 €**	**xxxxxxxx€**	**xxxxxxxx €**
CAPEX/Gbit/s	**166 135.18 €/Gbit/s**	**xxxxxxxx €/Gbit/s**	**xxxxxxxx €/Gbit/s**

Tabela 5.130: Table with different value of CAPEX for this case.

Looking at the previous table we can make some comparisons between the several scenarios:

- Comparing the low traffic scenario with the others, we can see that, despite having an increase of factor ten (average scenario) and factor twenty (high scenario), the same increase does not occur in the final cost (it is lower). This happens because the number of transceivers is smaller than expected (an average scenario of 520 would be expected and a high scenario would be expected in 1040);
- Comparing the average traffic scenario with the high traffic scenario, we can see that the factor increase is double and in the final cost this factor is very close but still lower. Again, this happens because the number of transceivers is smaller, but very close to what was expected (the high scenario would be expected at 336);
- Comparing the cost with the traffic, we see that, for the low traffic scenario, the cost per traffic is very high in relation to the other two. We can conclude that a low traffic scenario becomes more expensive than a high traffic scenario.

Opens Issues

The creation of this model for any scenario, started with some considerations and some open issues being:

- Allow blocking.

  The presented model assume that the solution is possible or impossible, does not support a partial solution where some demands are not routed (are blocked).
- Allow multiple transmission system.

  The presented model for each link only supports one transmission system.

5.1.5 Translucent without Survivability

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the ILP model for the translucent transport mode without survivability.

Model description

First, for a better understanding of the functions and variables used in the ILP, a table 5.131 will be created with all indexes, inputs and variables and with their respective description.

Description of notation used in the objective function	
i	index for start node of a physical link
j	index for end node of a physical link
o	index for node that is origin of a demand
d	index for node that is destination of a demand
c	index for bit rate of the client signal
(i,j)	physical link between the nodes i and j
(o,d)	demand between the nodes o and d
C	set of the client signal
L_{ij}	binary variable indicating if link between the nodes i and j is used
Ls_{ij}^{od}	Number of ODU-o low speed signals from node o to node d employing lightpath (i,j)
f_{ij}^{od}	Number of 100 Gbit/s optical channels (number of flows) between the link i and j for all demand pairs between o and d
λ_{od}	Number of lightpath channels between the nodes o and d
B	Client signals granularities (1.25, 2.5, 10, 40, 100)
D_{odc}	Client traffic demands between the nodes o and d with bit rate c
G	Network topology in form of adjacency matrix

Tabela 5.131: Table with description of variables

Before carrying out the description of the objective function we must take into account the following particularity of this mode of transport:

- $N_{OXC,n} = 1, \quad \forall$ n that process traffic
- $N_{EXC,n} = 1, \quad \forall$ n that process traffic

The objective function of following the ILP is a minimization of the CAPEX through the equation 5.1 where in this case for the cost of nodes we have in consideration the electric cost 5.5 and the optical cost 5.6. In this case the value of $P_{exc,c,n}$ is obtained by equation 5.52

for short-reach and by the equation 5.53 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 5.54.

The equation 5.52 refers to the number of sort-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{5.52}$$

where $D_{nd,c}$ are the client demands between nodes n and d with bit rate c.

In this case there is the following particularity:

- When n=d the value of client demands is always zero, i.e, $D_{nn,c} = 0$

As previously mentioned, the equation 5.53 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e. the number of line ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} f_{nj}^{od} \tag{5.53}$$

where f_{nj}^{od} is the number of optical channels between node n and node j for all demand pairs (od).

The equation 5.54 refers to the number of long-reach ports of the optical switch in node n, $P_{oxc,n}$, i.e. the number of line ports and the number of adding ports of node n which can be calculated as

$$P_{oxc,n} = \sum_{j=1}^{N} 2f_{nj}^{od} + \sum_{j=1}^{N} \lambda_{nj} \tag{5.54}$$

where f_{nj}^{od} refers to the number of line ports for all demand pairs (od) and λ_{nj} refers to the number of adding ports.

The objective function, to be minimized, is the expression 5.7.

subject to

$$\sum_{j\backslash\{o\}} Ls_{ij}^{odc} = D_{odc} \qquad \forall(o,d) : o < d, \forall i : i = o \tag{5.55}$$

$$\sum_{j \setminus \{i,o\}} Ls_{ij}^{odc} = \sum_{j \setminus \{i,d\}} Ls_{ji}^{odc} \qquad \forall (o,d) : o < d, \forall i : i \neq o, d \quad (5.56)$$

$$\sum_{j \setminus \{d\}} Ls_{ji}^{odc} = D_{odc} \qquad \forall (o,d) : o < d, \forall i : i = d \quad (5.57)$$

$$\sum_{o=1} \sum_{d=o+1} B(c) Ls_{ij}^{odc} \leq 100 \lambda_{od} \qquad \forall (i,j) \quad (5.58)$$

$$\sum_{j \setminus \{o\}} f_{ij}^{od} = \lambda_{od} \qquad \forall (o,d) : o < d, \forall i : i = o \quad (5.59)$$

This constraint are equal to the constraint 5.8 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{j \setminus \{o\}} f_{ij}^{od} = \sum_{j \setminus \{d\}} f_{ji}^{od} \qquad \forall (o,d) : o < d, \forall i : i \neq o, d \quad (5.60)$$

This constraint are equal to the constraint 5.9.

$$\sum_{j \setminus \{d\}} f_{ji}^{od} = \lambda_{od} \qquad \forall (o,d) : o < d, \forall i : i = d \quad (5.61)$$

This constraint are equal to the constraint 5.10 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{o=1} \sum_{d=o+1} \left(f_{ij}^{od} + f_{ji}^{od} \right) \leq K_{ij} G_{ij} L_{ij} \qquad \forall (i,j) : i < j \quad (5.62)$$

This restriction answers capacity constraint problem. Then, total flows must be less or equal to the capacity of network links. For any situation the maximum number of optical channels supported by each transmission system is 100, i.e., K_{ij} = 100.

$$f_{ij}^{od}, f_{ji}^{od}, Ls_{ij}^{odc}, Ls_{ji}^{odc}, \lambda_{od} \in \mathbb{N} \qquad \forall (i,j) : i < j, \forall (o,d) : o < d \quad (5.63)$$

This constraint defines that these variables must be a counting number.

$$L_{i,j} \in \{0, 1\} \qquad \forall (i,j) \quad (5.64)$$

Last constraint refers to the use of the link where this variable can be zero if it is not being used or one if is being used.

5.1.6 Translucent with 1+1 Protection

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the ILP model for the translucent transport mode with 1 plus 1 protection.

Here, in this case, we must take into account table 5.131, previously mentioned, in order to better understand the objective function.

The objective function of following the ILP is a minimization of the sum of two equations: the cost of the links 5.2 and cost of the nodes 5.4 where in this case we have in consideration the electric cost and the optical cost. In this case the value of $P_{exc,c,n}$ is obtained by equation **??** and the value of $P_{oxc,n}$ is obtained by equation **??**.

The objective function, to be minimized, is the expression 5.7.

$subject\ to$

$$\sum_{j\backslash\{o\}} Ls_{ij}^{od} = D_{odc} \qquad \forall(o,d) : o < d, \forall i : i = o \tag{5.65}$$

$$\sum_{j\backslash\{i,o\}} Ls_{ij}^{od} = \sum_{j\backslash\{i,d\}} Ls_{ji}^{od} \qquad \forall(o,d) : o < d, \forall i : i \neq o, d \tag{5.66}$$

$$\sum_{j\backslash\{d\}} Ls_{ji}^{od} = D_{odc} \qquad \forall(o,d) : o < d, \forall i : i = d \tag{5.67}$$

$$\sum_{o=1} \sum_{d=o+1} B(c) Ls_{ij}^{od} \leq 100\lambda_{od} \qquad \forall(i,j) \tag{5.68}$$

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = \lambda_{od} \qquad \forall(o,d) : o < d, \forall i : i = o \tag{5.69}$$

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = \sum_{j\backslash\{d\}} f_{ji}^{od} \qquad \forall(o,d) : o < d, \forall i : i \neq o, d \tag{5.70}$$

$$\sum_{j\backslash\{d\}} f_{ji}^{od} = \lambda_{od} \qquad \forall(o,d) : o < d, \forall i : i = d \tag{5.71}$$

$$\sum_{j\setminus\{o\}} fp_{ij}^{od} = \lambda_{od} \qquad \forall(o,d) : o < d, \forall i : i = o \tag{5.72}$$

$$\sum_{j\setminus\{o\}} fp_{ij}^{od} = \sum_{j\setminus\{d\}} f_{ji}^{od} \qquad \forall(o,d) : o < d, \forall i : i \neq o, d \tag{5.73}$$

$$\sum_{j\setminus\{d\}} fp_{ji}^{od} = \lambda_{od} \qquad \forall(o,d) : o < d, \forall i : i = d \tag{5.74}$$

$$\sum_{o=1} \sum_{d=o+1} \left(f_{ij}^{od} + fp_{ij}^{od}\right) \leq \lambda_{od} \qquad \forall(o,d), (i,j) \tag{5.75}$$

$$\sum_{o=1} \sum_{d=o+1} \left(f_{ij}^{od} + f_{ji}^{od} + fp_{ij}^{od} + fp_{ji}^{od}\right) \leq K_{ij} G_{ij} \qquad \forall(i,j) : i < j \tag{5.76}$$

$$L_{ij}^{od} \geq 0; \qquad \forall(i,j), \forall(o,d) : o < d \tag{5.77}$$

$$f_{ij}^{od}, fp_{ij}^{od} \geq 0 \qquad \forall(i,j)\forall(o,d) \tag{5.78}$$

Capítulo 6

Heuristic Models

Heuristic algorithms are used in this report with an objective to minimize the total CAPEX of the network. It is important to have these comparison results with the linear programming ones, because these formulations are faster than the optimal methods and can generate also a near optimal solution. Another advantage of the heuristic approach is that heuristic solutions leads to good performances in practical network scenarios when we present a sufficiently feasible solution, instead of an optimal solution.
In order to get the total network cost for the reference network, the CAPEX is calculated by routing and grooming heuristic algorithms implemented in Java and it is considered that all network equipment is bidirectional. These algorithms are tested in a network design software called Net2Plan.
This chapter consists in demonstrating how the matrices are created, how the heuristic algorithms work and analyzing the results. It is divided in six subsections and the results differ into three different transport modes: opaque (link-by-link grooming method), transparent (single-hop grooming method) and translucent (multi-hop grooming method). Each one of these transport methods are also distinguished and compared by the possibility of being without survivability or with 1+1 protection and for the cases of low, medium and high traffic in the network.

6.1 CAPEX

Student Name	:	Pedro Coelho (01/03/2018 -)
Goal	:	Implement of the heuristic model to obtain the best possible CAPEX of a given network.

The total CAPEX of a network, as it was already described in 5.1, is the sum between two differentiated costs. Firstly, the link cost depends on the link length, which has integrated components such as OLTs, transceivers and amplifiers and the node cost depends on the traffic intensity by each node.

In order to get the results for the heuristic approach, routing and grooming algorithms are used which try to obtain the most near optimal solution for the six cases detailed in this chapter. Then, it will be applied a cost report with all the detailed information about the costs of the network. The final CAPEX depends on the transport mode (opaque, transparent and translucent), possibility of the network having a dedicated 1+1 protection scheme or not and the network traffic (low - 0.5 Tbit/s, medium - 5 Tbit/s and high - 10 Tbit/s).

To calculate the total network cost it has to be considered the links cost and the nodes cost. The CAPEX value of a network, C_C, in monetary units (e.g. euros, or dollars), is calculated by the equation 6.1

$$C_C = C_L + C_N \tag{6.1}$$

where

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

On the first hand, the links' cost, C_L, in monetary units (e.g. euros, or dollars), is calculated by the equation 6.2. If the length of the link is longer, the resulting costs will be higher due to of the necessity of having more components which carry all the traffic from all origin nodes to all destination nodes

$$C_L = \sum_{i=1}^{N} \sum_{j=i+1}^{N} L_{ij} \left(2\gamma_0^{OLT} + 2\gamma_1^{OLT} \tau W_{ij} + N_{ij}^{R} c^{R} \right) \tag{6.2}$$

where

- $i \rightarrow$ Index for start node of a physical link
- $j \rightarrow$ Index for end node of a physical link
- $N \rightarrow$ Total number of nodes, N $\in \mathbb{N}$
- $L_{ij} \rightarrow$ Binary variable indicating if link between the nodes i and j is used, $L_{ij} \in 0, 1$

- $\gamma_0^{OLT} \rightarrow$ OLT cost in monetary units (e.g. euros, or dollars)
- $\gamma_1^{OLT} \rightarrow$ Transponder cost in monetary units (e.g. euros, or dollars)
- $\tau \rightarrow$ Line bit-rate
- $W_{ij} \rightarrow$ Number of optical channels in link i j
- $N_{ij}^R \rightarrow$ Number of optical amplifiers in link i j
- $c^R \rightarrow$ Optical amplifiers cost in monetary units (e.g. euros, or dollars)

The line bit-rate that is used in this report has the value of 100. It represents the separation between regeneration stages in km. On the other hand, the nodes' cost, C_N, in monetary units (e.g. euros, or dollars), is calculated by the equation 6.3

$$C_N = C_{EXC} + C_{OXC} \tag{6.3}$$

where

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

As all the nodes have an electrical part and an optical part, it is necessary to calculate both with their respective formulas and sum the results. The electrical nodes' cost, C_{EXC}, in monetary units (e.g. euros, or dollars), is given by the equation 6.4

$$C_{EXC} = \sum_{n=1}^{N} N_{exc,n} \left(\gamma_{e0} + \sum_{c=-1}^{B} \gamma_{e1,c} P_{exc,c,n} \right) \tag{6.4}$$

where

- $N \rightarrow$ Total number of nodes, N $\in \mathbb{N}$
- $N_{exc,n} \rightarrow$ Binary variable indicating if node n is used, $N_{exc,n} \in 0, 1$
- $\gamma_{e0} \rightarrow$ EXC cost in monetary units (e.g. euros, or dollars)
- $\gamma_{e1,c} \rightarrow$ EXC port cost in monetary units (e.g. euros, or dollars) with bit-rate B and with a given transceiver reach
- $P_{exc,c,n} \rightarrow$ Number of ports of the electrical switch
- $B \rightarrow$ A natural number corresponding to the maximum index of short-reach ports, see table below

Index	Bit rate
-1	100 Gbits/s line bit-rate (long-reach port)
0	1.25 Gbits/s tributary bit-rate (short-reach port)
1	2.5 Gbits/s tributary bit-rate (short-reach port)
2	10 Gbits/s tributary bit-rate (short-reach port)
3	40 Gbits/s tributary bit-rate (short-reach port)
4	100 Gbits/s tributary bit-rate (short-reach port)

Tabela 6.1: Table with index and your corresponding bit rate

The constitution of the electrical node part can be seen in the Integer Linear Programming section 5.2. Finally, the optical nodes' cost, C_{OXC}, in monetary units (e.g. euros, or dollars), is given by the equation 6.5

$$C_{OXC} = \sum_{n=1}^{N} N_{oxc,n} \left(\gamma_{o0} + \gamma_{o1} P_{oxc,n} \right) \tag{6.5}$$

where

- $N \rightarrow$ Total number of nodes, N $\in \mathbb{N}$
- $N_{oxc,n} \rightarrow$ Binary variable indicating if node n is used, $N_{oxc,n} \in 0, 1$
- $\gamma_{o0} \rightarrow$ OXC cost in monetary units (e.g. euros, or dollars)
- $\gamma_{o1} \rightarrow$ OXC port cost in monetary units (e.g. euros, or dollars)
- $P_{oxc,n} \rightarrow$ Number of ports of the optical switch

The constitution of the optical node part can be seen in the Integer Linear Programming section 5.3. To obtain the best possible value, it will be necessary to minimize the cost of the CAPEX mentioned above so that we can obtain the objective function 6.1.

$$minimize \quad \left\{ \quad C_C \quad \right\}$$

After all the formulas needed to calculate the CAPEX of a network are demonstrated above, it is also essential to have pre-defined the costs of the network equipments. In the table 6.2 it is shown the cost, in euros, of all the equipments with their symbols used in the respective formulas.

Equipment	Symbol	Cost
OLT without transponders	γ_0^{OLT}	15000 €
Transponder	γ_1^{OLT}	5000 €/Gb
Unidirectional Optical Amplifier	c^R	4000 €
EXC	γ_{e0}	10000 €
OXC	γ_{o0}	20000 €
EXC Port for line ports	$\gamma_{e1,-1}$	1000 €/Gb/s
EXC Port for ODU0	$\gamma_{e1,0}$	8 €/Gb/s
EXC Port for ODU1	$\gamma_{e1,1}$	6 €/Gb/s
EXC Port for ODU2	$\gamma_{e1,2}$	3 €/Gb/s
EXC Port for ODU3	$\gamma_{e1,3}$	1.5 €/Gb/s
EXC Port for ODU4	$\gamma_{e1,4}$	1 €/Gb/s
OXC Port	γ_{o1}	2500 €/porto

Tabela 6.2: Table with costs

6.1.1 Opaque without Survivability

Student Name	:	Pedro Coelho (01/03/2018 -)
Goal	:	Implement the Heuristic model for the opaque transport mode without survivability.

Model description

In the opaque transport mode (link-by-link approach), the lightpath entering any intermediate node is necessarily terminated, i.e., there are performed OEO (optical-electrical-optical) conversions at every intermediate node since the origin to the destination node. These conversions are used for every wavelength at every node.
Contrary to the opaque with dedicated 1+1 protection technique, the opaque without survivability technique does not have a backup path, so if there is a network failure it is more likely to suffer large data losses, which consequently leads to higher network costs. However, the CAPEX will be significantly lower, because that not includes a secondary path that will increase several network elements.
After the creation of the matrices and the network topology, it is necessary to apply the routing and grooming algorithms created. In the end, a report algorithm will be applied to obtain the best CAPEX result for the network in question.
Firstly, in the opaque transport mode, the optical node cost is 0 because all the ports in the network are electrical. Consequently, to calculate the nodes' cost in this transport mode it only has to be considered the electrical nodes' cost:

- $N_{OXC,n}$ = 0, $\forall$ n
- $N_{EXC,n}$ = 1, $\forall$ n that process traffic

As previously mentioned, equation 6.6 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e., the number of line ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} w_{nj} \tag{6.6}$$

where w_{nj} is the number of optical channels between node n and node j.

As previously mentioned, equation 6.7 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e., the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{6.7}$$

where $D_{nd,c}$ are the client demands between nodes n and d with bit rate c.

In this case there is the following particularity:

- When n=j, the value of client demands is always zero, i.e, $D_{nn,c} = 0$.

The function, to be minimized, is the expression 6.1.

This heuristic approach consists in four algorithms made in Java in a programming software called Eclipse and testing them in an open-source network program called Net2Plan. In the Net2Plan guide section 10.1 there is a brief explanation of the algorithms and a demonstration on how to use and test them in this network planner. The logical topology and the grooming algorithms are going to be explained below with more details because they have more substantial differences between the three transport modes used in this report.

Topologies

A network topology represents how the links and the nodes of the network interconnect with each other. These connections are made in the physical (real) and the logical (virtual) topologies and the algorithm creates the logical topology on another layer. The final and resulting physical and optical topologies depend on the method used in each of the transport modes.

In the opaque transport mode the physical and logical topologies are the same, so it is needed to add a new layer from the lower layer (default layer). The respective demands are saved in the new upper layer and those demands from the lower layer are then removed. The lower layer is the physical layer of the network and it is now created a new upper layer which is the logical layer of the network and represents the logical topology of the opaque transport mode.

The allowed topologies, physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 6.1.1 for the three traffic scenarios.

Grooming

After a network topology is created, it is now time to set the grooming algorithm. This algorithm aggregates the traffic into the network, i.e., in the optical channels that are interconnected between end nodes. This aggregation is made by creating bidirectional routes based on the shortest path type (hops or km). In this report it is used the shortest path type in hops.

In the opaque transport mode the grooming algorithm starts with going through all the demands, create routes (primary paths) and then set the traffic into those routes. One important aspect is that these routes are created based on the shortest path method, comparing all the routes with each other and the final resulting route is the shortest one. As we also have a dedicated 1+1 protection scheme, if the network has this feature, the algorithm will compare the routes again and it will create new routes (backup paths) if they are the next shortest path routes comparing to the previous ones and then set the traffic into those routes. The final resulting backup path routes are used to prevent network failures. Despite of the fact the network will be much more secure, the network CAPEX will increase more than the double, due to the creation of primary and backup paths. The traffic that is carried into the network will be the sum of all the created paths. Knowing the value of the total traffic and the wavelength capacity of all links, it is possible to calculate the number of wavelengths in each link.

It is shown in the next page below a fluxogram with the description of the algorithms and the steps performed to obtain the final results in the opaque transport mode.

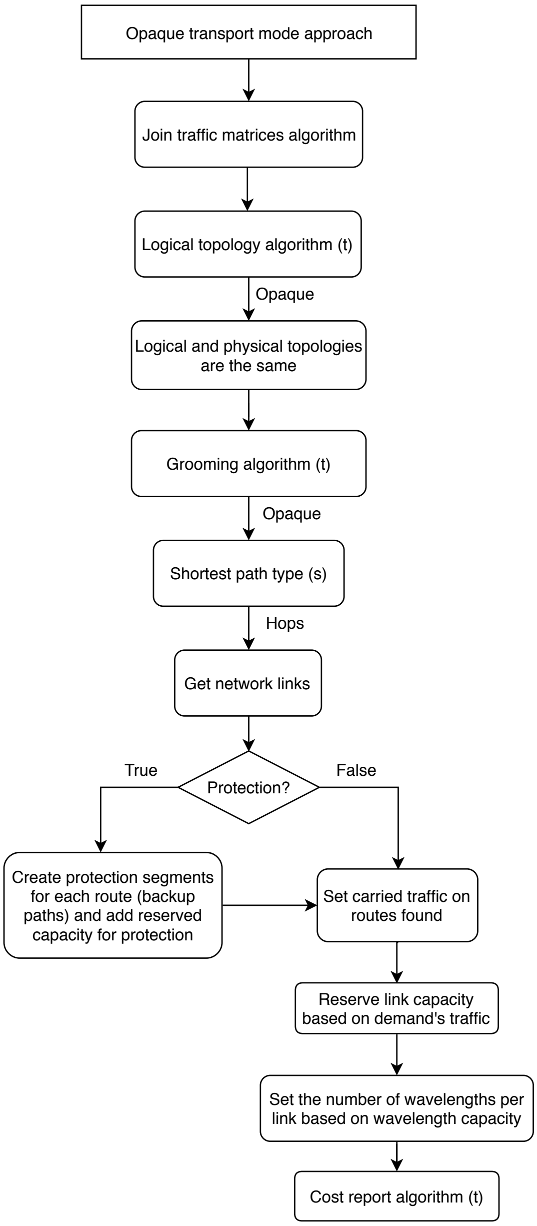


Figura 6.1: Fluxogram with opaque transport mode approach.

Result description

It is already known all the necessary formulas to obtain the CAPEX value for the reference network 10.1. As described in the subsection of the network traffic 4.2, it is necessary to obtain three different values of CAPEX for the low (0.5 Tbit/s), medium (5 Tbit/s) and high (10 Tbit/s) traffic. It is used a network software program called Net2Plan which can design the traffic matrices, create all the network topologies, simulate the algorithms into the network implemented in the programming software called Eclipse and analyze the results obtained.
In this chapter will be demonstrated the results by Vasco's heuristics from 2016. In each of the three traffic scenarios, it will be shown the network topologies followed by the table with the CAPEX value of the network.

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.1. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

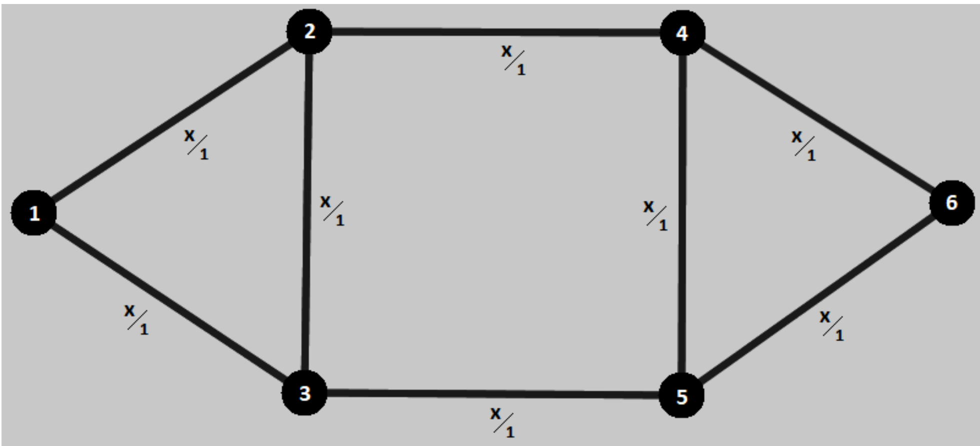


Figura 6.2: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

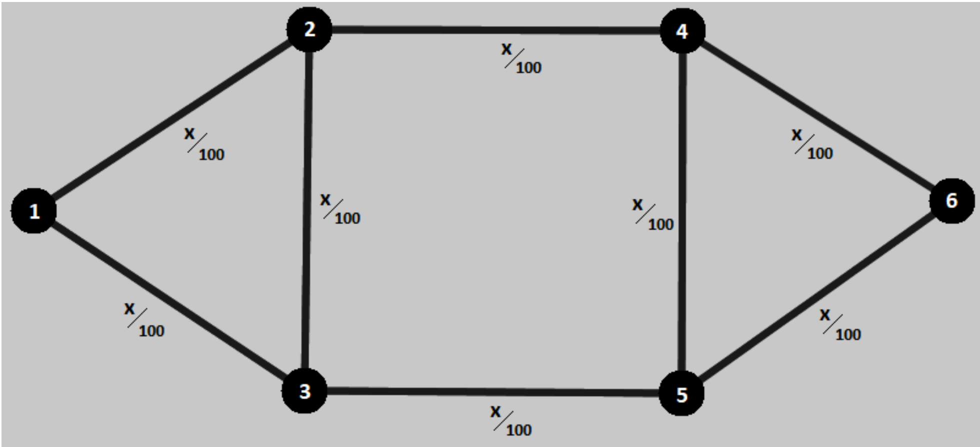


Figura 6.3: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

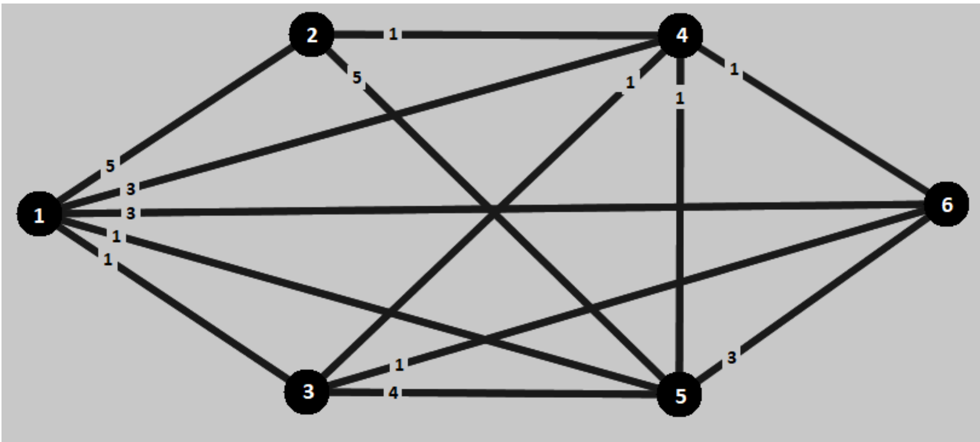


Figura 6.4: ODU0 logical topology defined by the ODU0 traffic matrix.

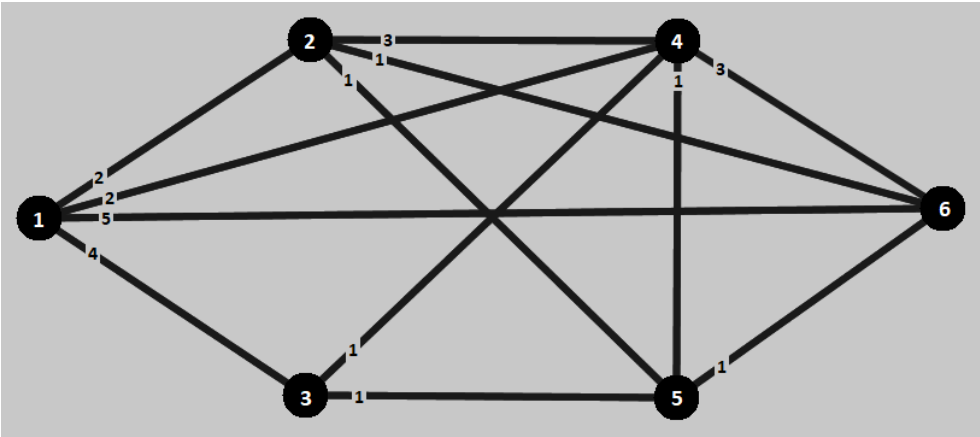


Figura 6.5: ODU1 logical topology defined by the ODU1 traffic matrix.

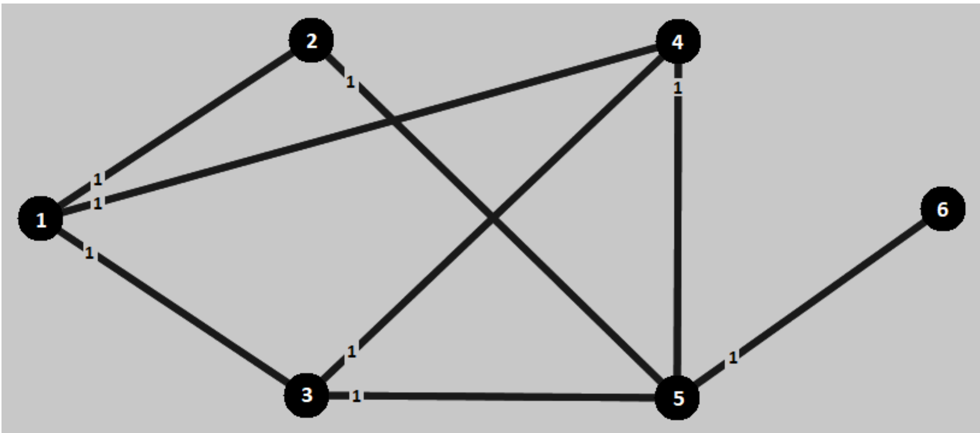


Figura 6.6: ODU2 logical topology defined by the ODU2 traffic matrix.

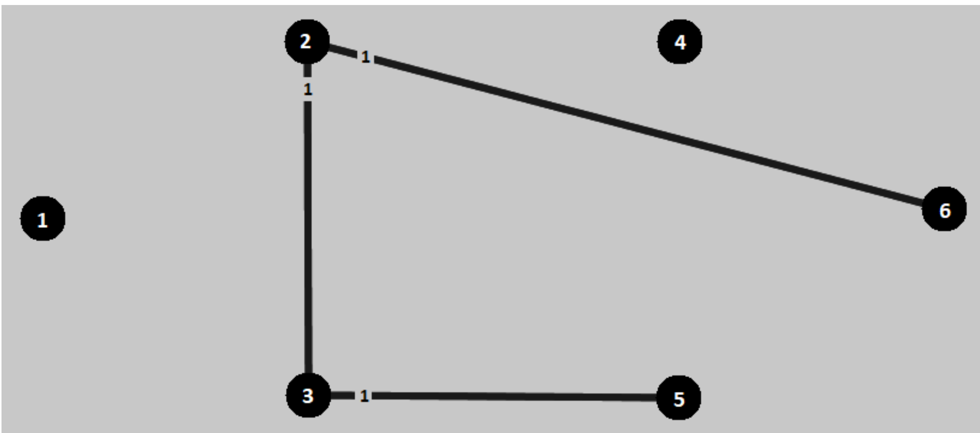


Figura 6.7: ODU3 logical topology defined by the ODU3 traffic matrix.

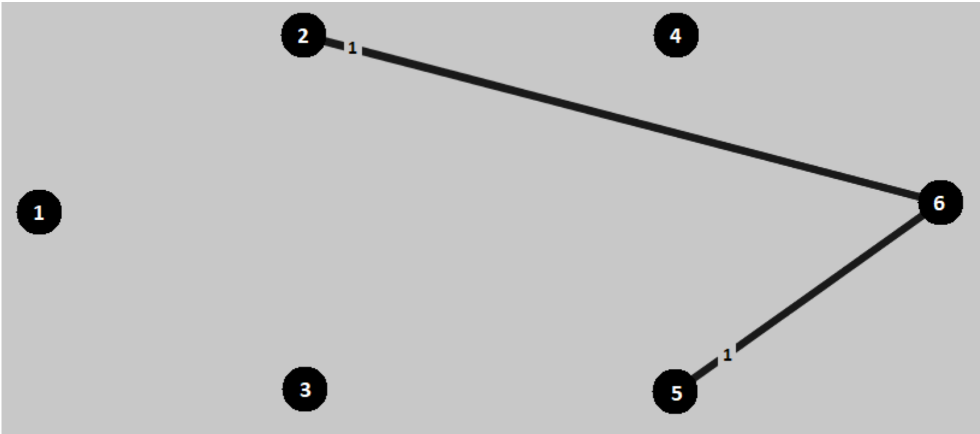


Figura 6.8: ODU4 logical topology defined by the ODU4 traffic matrix.

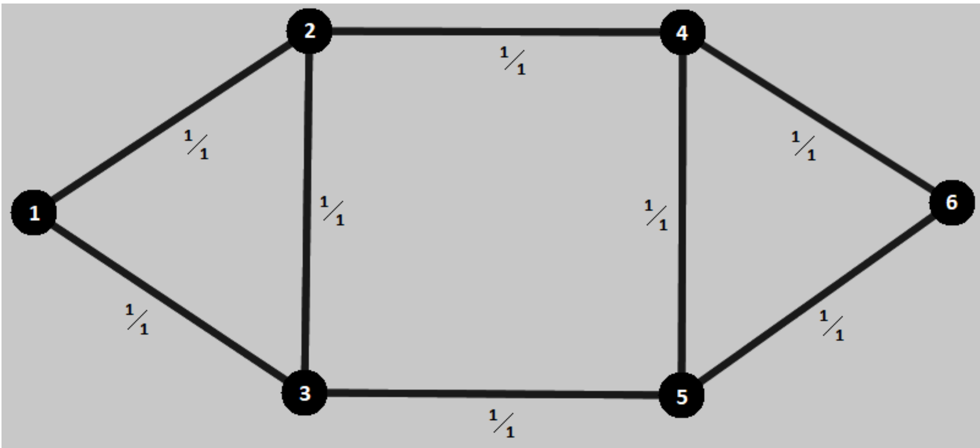


Figura 6.9: Physical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.3.

All the values calculated in the previous table were obtained through the equations 6.2 and 6.3 referred to in section 6.1, but for a more detailed analysis we created table 6.4 where we can see how all the parameters are calculated individually.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	12 020 000 €
	100 Gbits/s Transceivers		23	5 000 €/Gbit/s	11 500 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	2 362 590 €
		ODU0 Ports	60	10 €/port	600 €	
		ODU1 Ports	50	15 €/port	750 €	
		ODU2 Ports	16	30 €/port	480 €	
		ODU3 Ports	6	60 €/port	360 €	
		ODU4 Ports	4	100 €/port	400 €	
		Line Ports	23	100 000 €/port	2 300 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						14 382 590 €

Tabela 6.3: Table with detailed description of CAPEX of Vasco's 2016 results.

	Equation used to calculate the cost
OLTs	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}\gamma_0^{OLT}$
Transceivers	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}w_{ij}\gamma_1^{OLT}\tau$
Amplifiers	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}N_{ij}^{R}c^{R}$
EXCs	$\sum_{n=1}^{N} N_{exc,n}\gamma_{e0}$
ODU0	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,0}\gamma_{e1,0}$
ODU1	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,1}\gamma_{e1,1}$
ODU2	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,2}\gamma_{e1,2}$
ODU3	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,3}\gamma_{e1,3}$
ODU4	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,4}\gamma_{e1,4}$
Line	$\sum_{n=1}^{N}\sum_{j=1}^{N} N_{exc,n}w_{nj}\gamma_{e1,-1}$
OXCs	For opaque transport mode this parameter is always zero.
P_{oxc}	For opaque transport mode this parameter is always zero.
CAPEX	The final cost is calculated by summing all previous results.

Tabela 6.4: Table with description of calculation

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.2. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

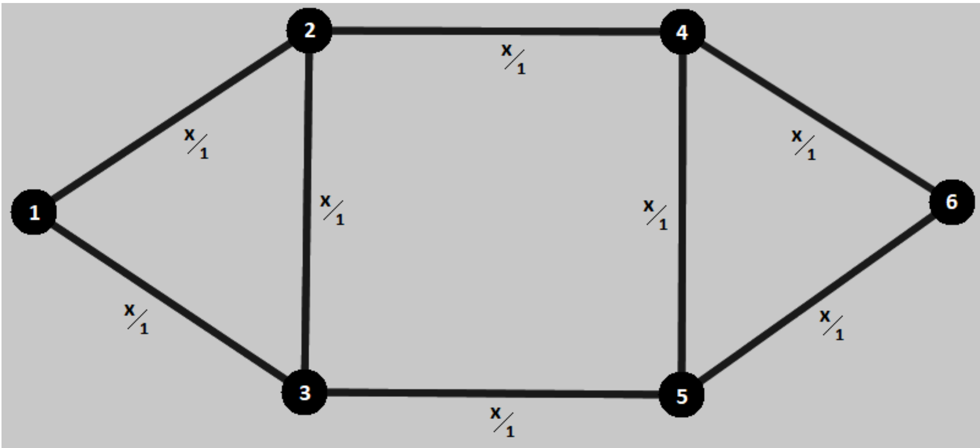


Figura 6.10: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

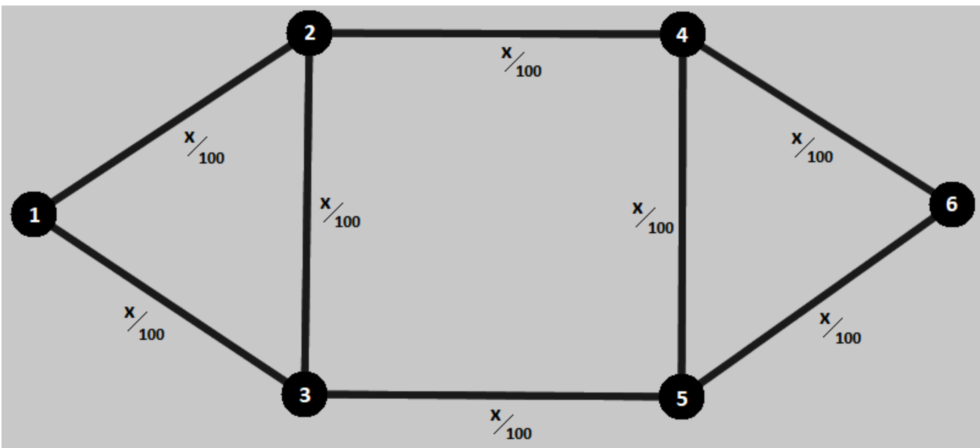


Figura 6.11: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

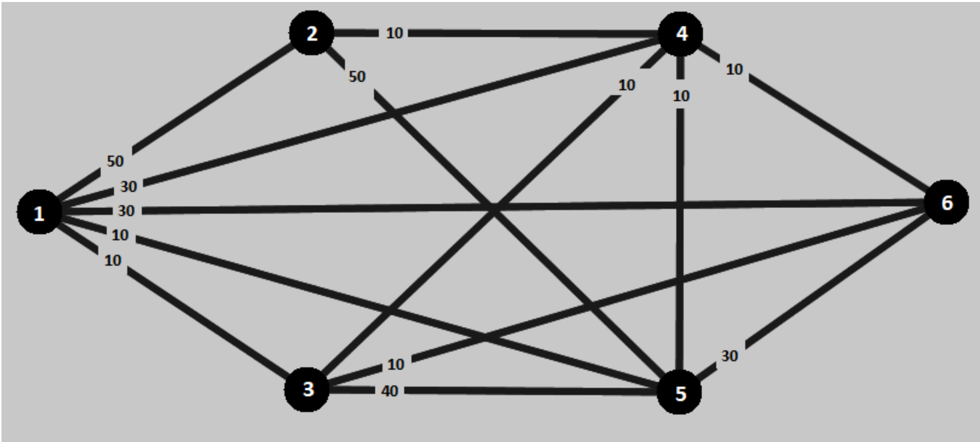


Figura 6.12: ODU0 logical topology defined by the ODU0 traffic matrix.

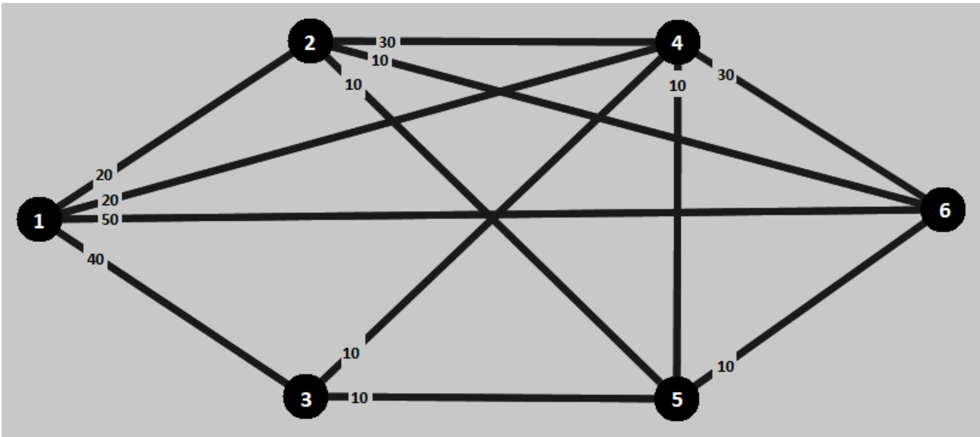


Figura 6.13: ODU1 logical topology defined by the ODU1 traffic matrix.

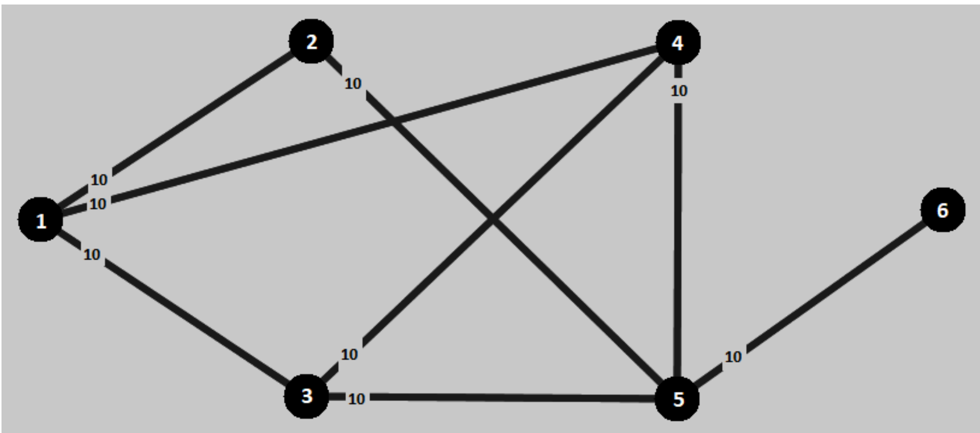


Figura 6.14: ODU2 logical topology defined by the ODU2 traffic matrix.

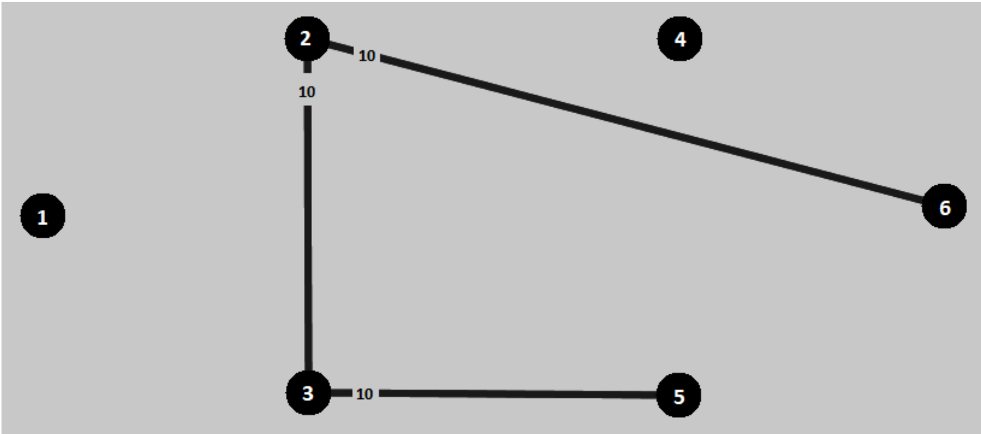


Figura 6.15: ODU3 logical topology defined by the ODU3 traffic matrix.

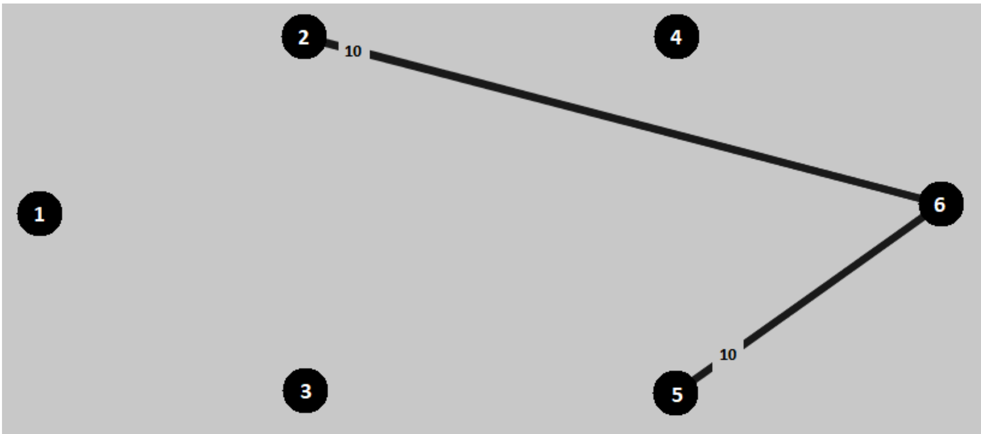


Figura 6.16: ODU4 logical topology defined by the ODU4 traffic matrix.

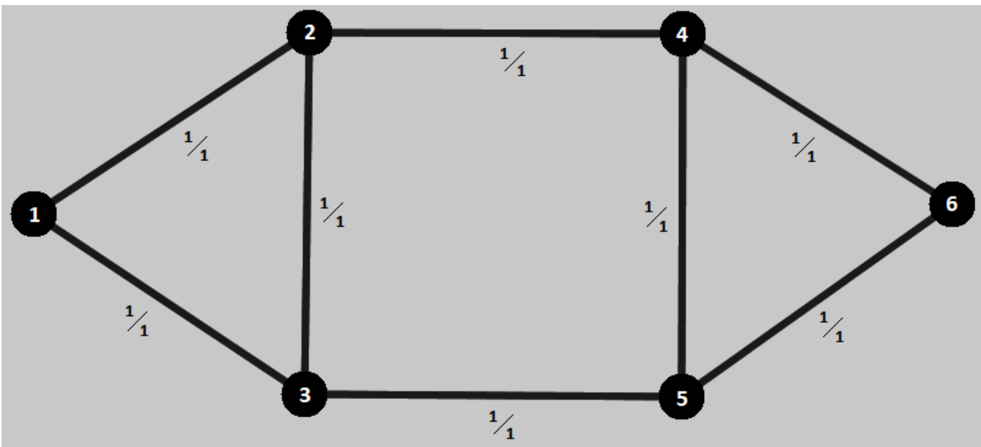


Figura 6.17: Physical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.5. In table 6.4 mentioned in previous scenario we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	77 020 000 €
	100 Gbits/s Transceivers		153	5 000 €/Gbit/s	76 500 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	15 385 900 €
		ODU0 Ports	600	10 €/port	6 000 €	
		ODU1 Ports	500	15 €/port	7 500 €	
		ODU2 Ports	160	30 €/port	4 800 €	
		ODU3 Ports	60	60 €/port	3 600 €	
		ODU4 Ports	40	100 €/port	4 000 €	
		Line Ports	153	100 000 €/port	15 300 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						92 405 900 €

Tabela 6.5: Table with detailed description of CAPEX of Vasco's 2016 results.

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.3. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

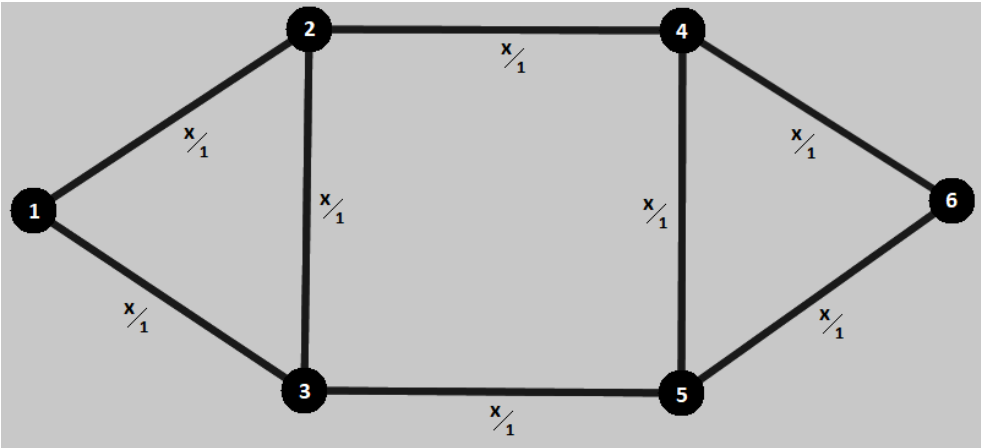


Figura 6.18: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

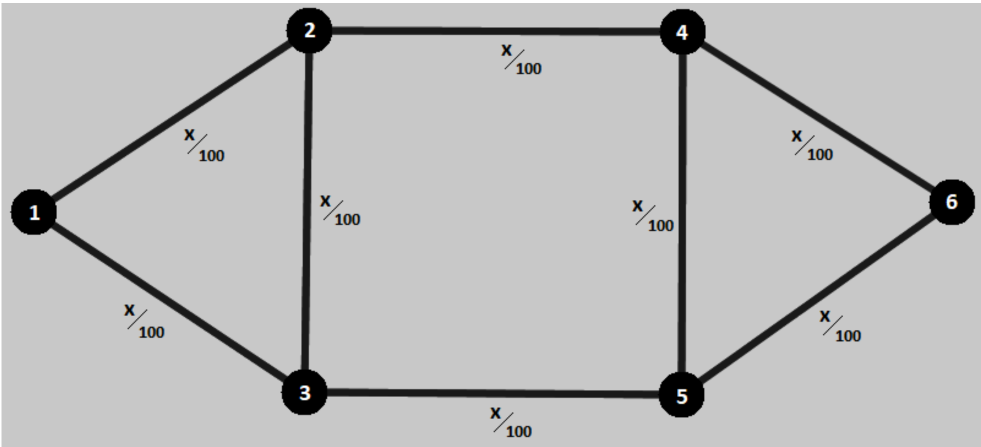


Figura 6.19: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

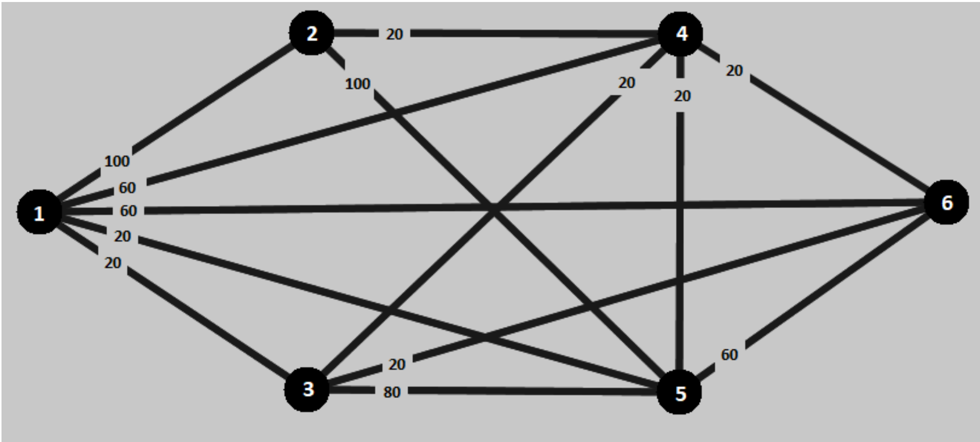


Figura 6.20: ODU0 logical topology defined by the ODU0 traffic matrix.

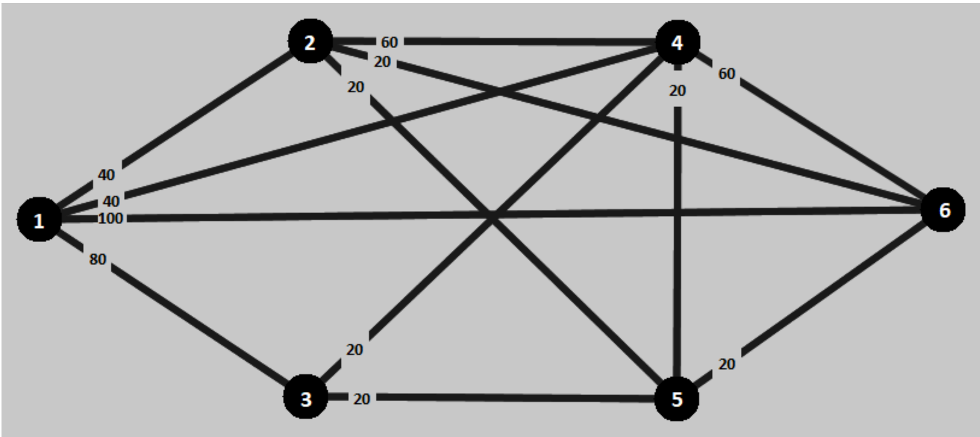


Figura 6.21: ODU1 logical topology defined by the ODU1 traffic matrix.

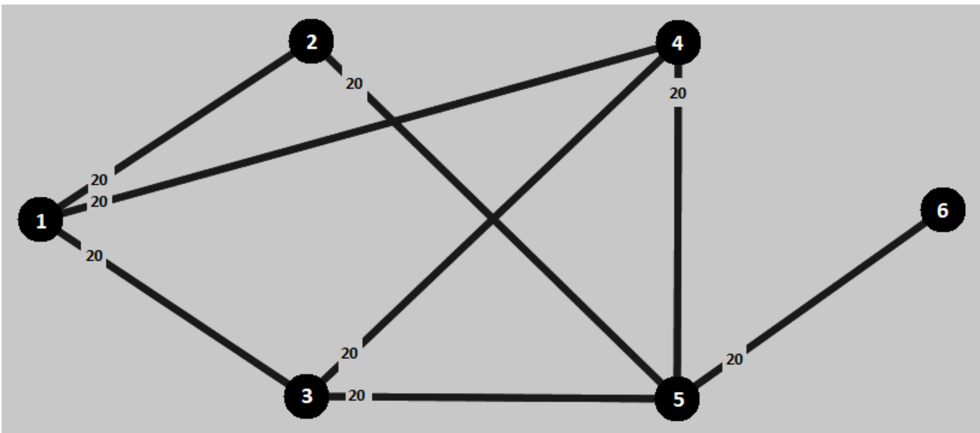


Figura 6.22: ODU2 logical topology defined by the ODU2 traffic matrix.

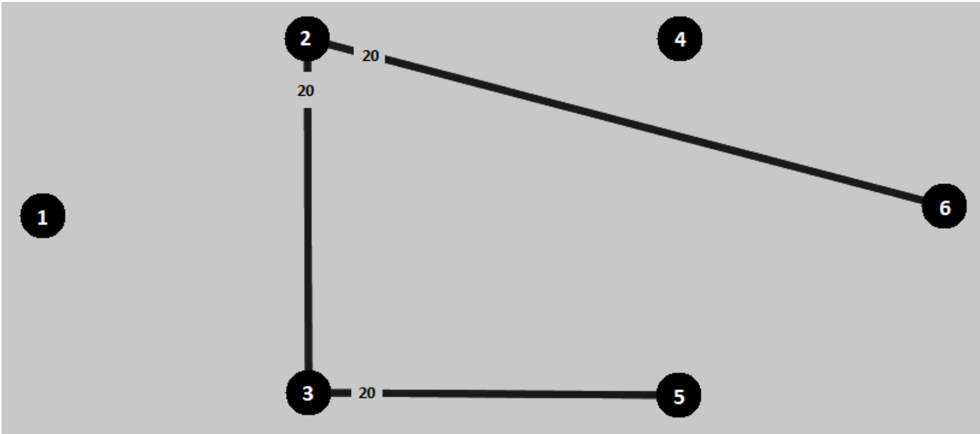


Figura 6.23: ODU3 logical topology defined by the ODU3 traffic matrix.

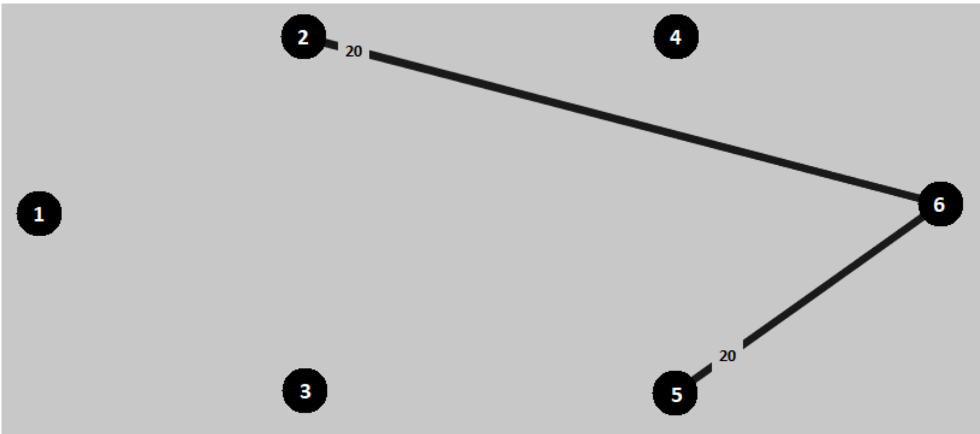


Figura 6.24: ODU4 logical topology defined by the ODU4 traffic matrix.

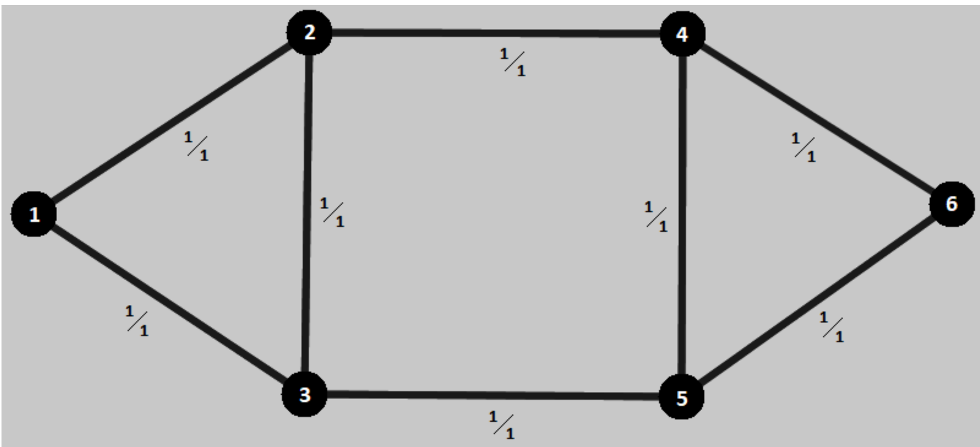


Figura 6.25: Physical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.6. In table 6.4 mentioned in previous scenario we can see how all the values were calculated.

<table>
<tr><th colspan="7">CAPEX of the Network</th></tr>
<tr><th colspan="3"></th><th>Quantity</th><th>Unit Price</th><th>Cost</th><th>Total</th></tr>
<tr><td rowspan="3">Link Cost</td><td colspan="2">OLTs</td><td>16</td><td>15 000 €</td><td>240 000 €</td><td rowspan="3">149 020 000 €</td></tr>
<tr><td colspan="2">100 Gbits/s Transceivers</td><td>297</td><td>5 000 €/Gbit/s</td><td>148 500 000 €</td></tr>
<tr><td colspan="2">Amplifiers</td><td>70</td><td>4 000 €</td><td>280 000 €</td></tr>
<tr><td rowspan="9">Node Cost</td><td rowspan="7">Electrical</td><td>EXCs</td><td>6</td><td>10 000 €</td><td>60 000 €</td><td rowspan="9">29 814 200 €</td></tr>
<tr><td>ODU0 Ports</td><td>1 200</td><td>10 €/port</td><td>12 000 €</td></tr>
<tr><td>ODU1 Ports</td><td>1 000</td><td>15 €/port</td><td>15 000 €</td></tr>
<tr><td>ODU2 Ports</td><td>320</td><td>30 €/port</td><td>9 600 €</td></tr>
<tr><td>ODU3 Ports</td><td>120</td><td>60 €/port</td><td>7 200 €</td></tr>
<tr><td>ODU4 Ports</td><td>80</td><td>100 €/port</td><td>8 000 €</td></tr>
<tr><td>Line Ports</td><td>297</td><td>100 000 €/port</td><td>29 700 000 €</td></tr>
<tr><td rowspan="2">Optical</td><td>OXCs</td><td>0</td><td>20 000 €</td><td>0 €</td></tr>
<tr><td>Ports</td><td>0</td><td>2 500 €/port</td><td>0 €</td></tr>
<tr><td colspan="6">Total Network Cost</td><td>178 834 200 €</td></tr>
</table>

Tabela 6.6: Table with detailed description of CAPEX of Vasco's 2016 results.

Conclusions

Once we have obtained the results for all the scenarios we will now draw some conclusions about these results. For a better analysis of the results will be created the table 6.7 with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

	Low Traffic	Medium Traffic	High Traffic
Traffic (Gbit/s)	500	5 000	10 000
Bidirectional Links used	8	8	8
Number of Line ports	23	153	297
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	23	153	297
Link Cost	12 020 000 €	77 020 000 €	149 020 000 €
Node Cost	2 362 590 €	15 385 900 €	29 814 200 €
CAPEX	**14 382 590 €**	**92 405 900 €**	**178 834 200 €**
CAPEX/Gbit/s	**28 765 €/Gbit/s**	**18 481 €/Gbit/s**	**17 883 €/Gbit/s**

Tabela 6.7: Table with different value of CAPEX for this case.

Looking at the previous table we can make some comparisons between the several scenario:

- Comparing the low traffic with the others we can see that despite having an increase of factor ten (medium traffic) and factor twenty (high traffic), the same increase does not occur in the final cost (it is lower);

  This happens because the number of the transceivers is lower than expected which leads by carrying the traffic with less network components and, consequently, the network CAPEX is lower;

- Comparing the medium traffic with the high traffic we can see that the increase of the factor is double and in the final cost this factor is very close but still inferior;

  This happens because the number of the transceivers is also lower but very close to the expected;

- Comparing the CAPEX cost per bit we can see that in the low traffic the cost is higher than the medium and high traffic, which in these two cases the value is very similar;

  This happens because the lower the traffic, the higher CAPEX/bit will be. We can see that in medium and high traffic the results tend to be one closer value.

Opens Issues

The creation of this model for any scenario, started with some considerations and some open issues being:

- Allow blocking.

  The presented model assume that the solution is possible or impossible, does not support a partial solution where some demands are not routed (are blocked);

- Allow multiple transmission system.

  The presented model for each link only supports one transmission system;

- Allowing multi-path routing.

  The presented model for all demands sharing the same node pairs have to follow the same path.

6.1.2 Opaque with 1+1 Protection

Student Name	:	Pedro Coelho (01/03/2018 -)
Goal	:	Implement the heuristic model for the opaque transport mode with 1 plus 1 protection.

Model description

The impact of failure in WDM (Wavelength Division Multiplexing) networks is caused by extremely high volume of traffic carried. In a high speed network like the WDM, a failure of a network element may cause failure of various optical channels that leads to large data and revenue losses, which can interrupt communication services.
In this protection scheme, the primary and backup path carry the traffic end-to-end, i.e., there is a need to have a backup path (the unaffected path) in case of a network failure. Then, the receiver will decide which one of the two incoming traffic it is going to pick, if the primary or the backup path.
Although it is the fastest protection scheme, it is also the most expensive, because it normally uses more than the double of the capacity of the primary path. This happens because the backup path is typically longer than the primary.
After the creation of the matrices and the network topology, it is necessary to apply the routing and grooming algorithms created. In the end, a report algorithm will be applied to obtain the best CAPEX result for the network in question.
Firstly, in the opaque transport mode, the optical node cost is 0 because all the ports in the network are electrical. Consequently, to calculate the nodes' cost in this transport mode it only has to be considered the electrical nodes' cost:

- $N_{OXC,n}$ = 0, $\forall$ n
- $N_{EXC,n}$ = 1, $\forall$ n that process traffic

As previously mentioned, equation 6.8 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e., the number of line ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} w_{nj} \tag{6.8}$$

where w_{nj} is the number of optical channels between node n and node j.

As previously mentioned, equation 6.9 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e., the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{6.9}$$

where $D_{nd,c}$ are the client demands between nodes n and d with bit rate c.

In this case there is the following particularity:

- When n=j, the value of client demands is always zero, i.e, $D_{nn,c} = 0$.

The function, to be minimized, is the expression 6.1.

Result description

It is already known all the necessary formulas to obtain the CAPEX value for the reference network 10.1. As described in the subsection of the network traffic 4.2, it is necessary to obtain three different values of CAPEX for the low (0.5 Tbit/s), medium (5 Tbit/s) and high (10 Tbit/s) traffic. It is used a network software program called Net2Plan which can design the traffic matrices, create all the network topologies, simulate the algorithms into the network implemented in the programming software called Eclipse and analyze the results obtained.
In this chapter will be demonstrated the results by Vasco's heuristics from 2016. In each of the three traffic scenarios, it will be shown the network topologies followed by the table with the CAPEX value of the network.

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.1. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

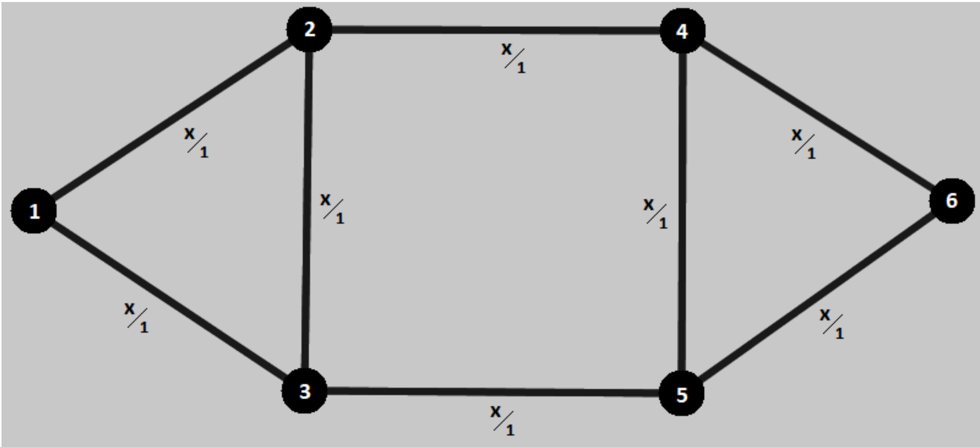


Figura 6.26: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

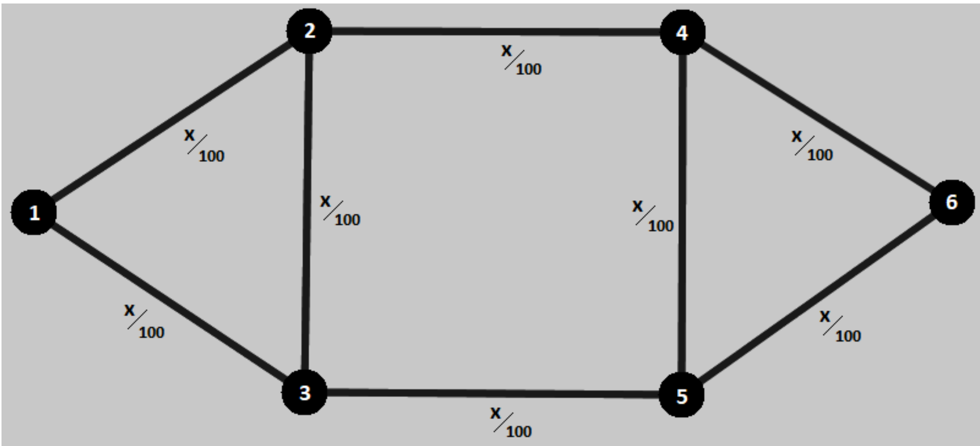


Figura 6.27: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

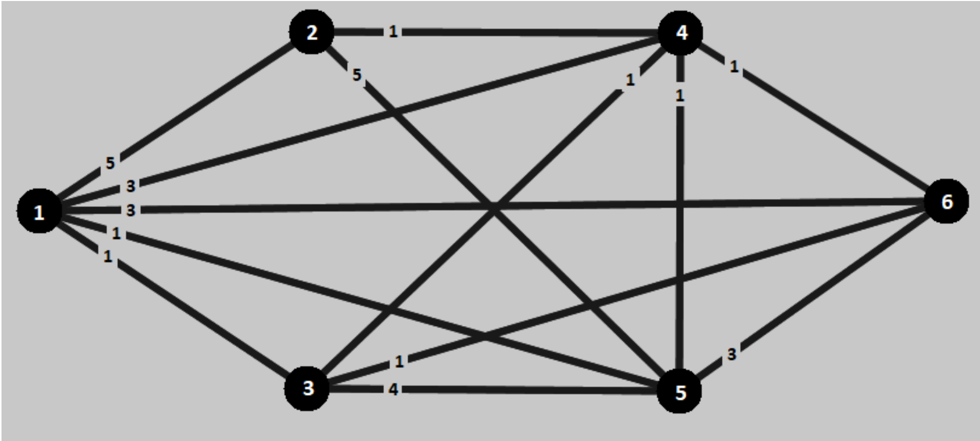


Figura 6.28: ODU0 logical topology defined by the ODU0 traffic matrix.

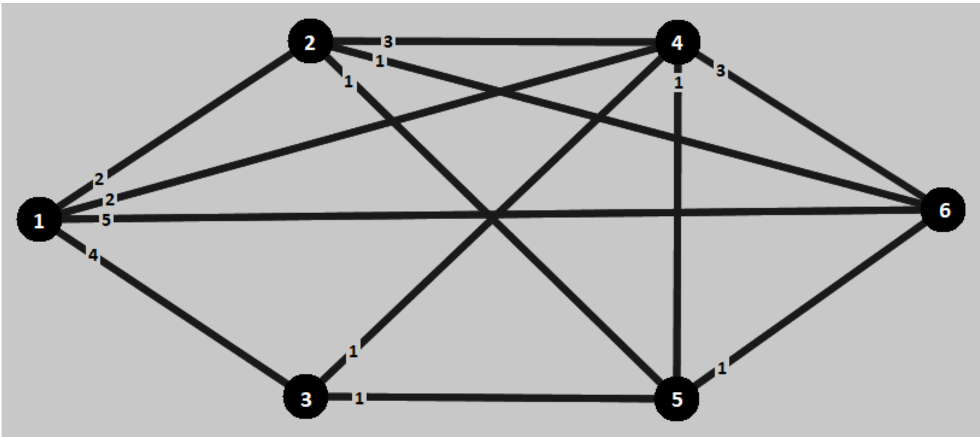


Figura 6.29: ODU1 logical topology defined by the ODU1 traffic matrix.

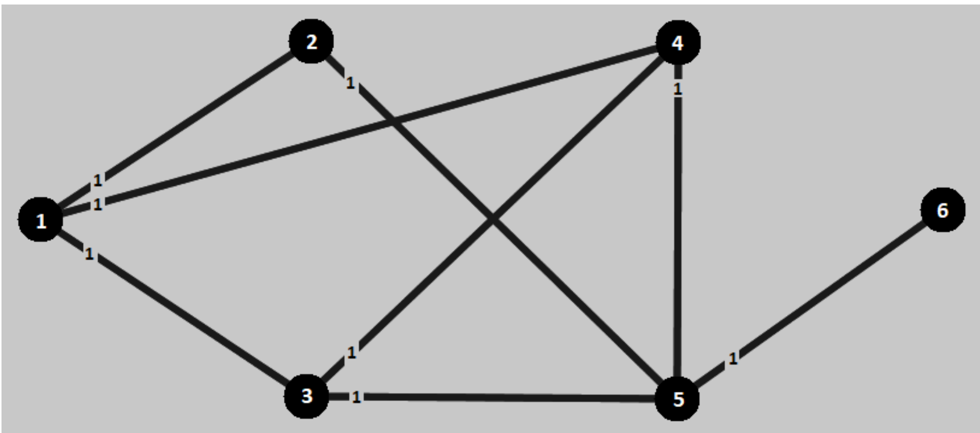


Figura 6.30: ODU2 logical topology defined by the ODU2 traffic matrix.

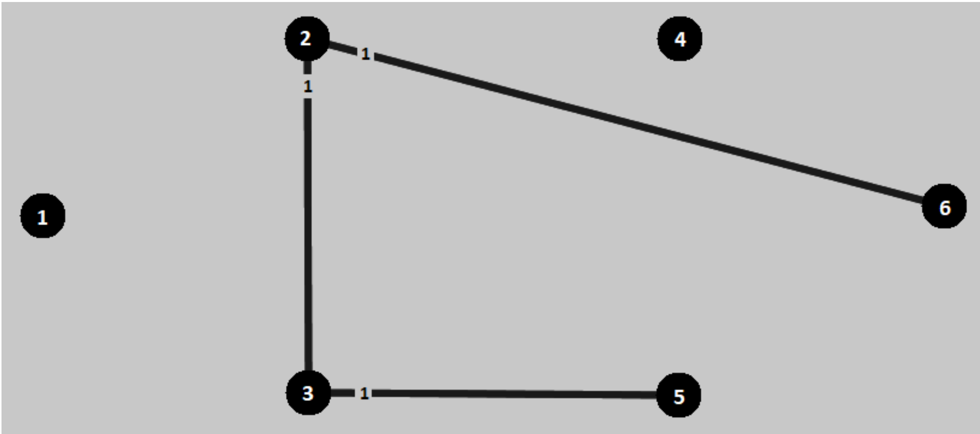


Figura 6.31: ODU3 logical topology defined by the ODU3 traffic matrix.

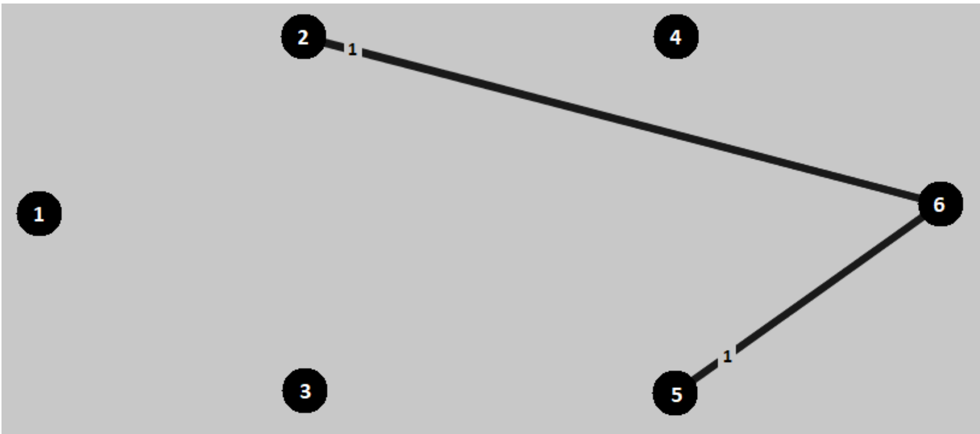


Figura 6.32: ODU4 logical topology defined by the ODU4 traffic matrix.

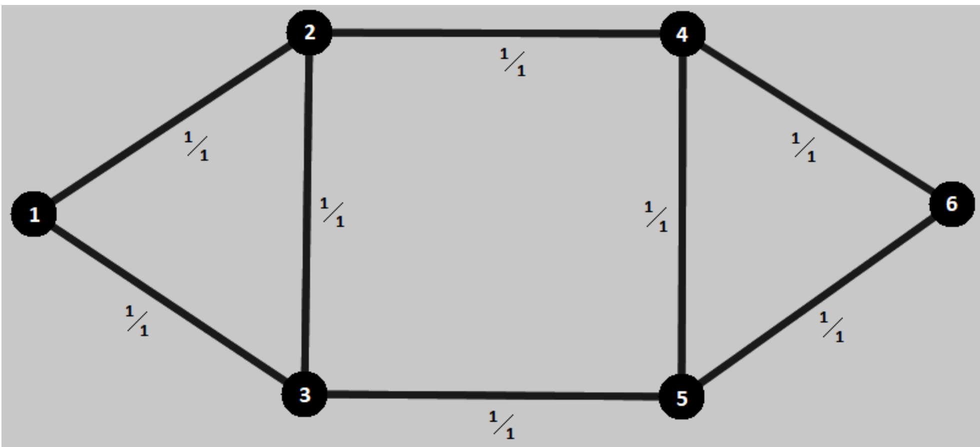


Figura 6.33: Physical topology after dimensioning.

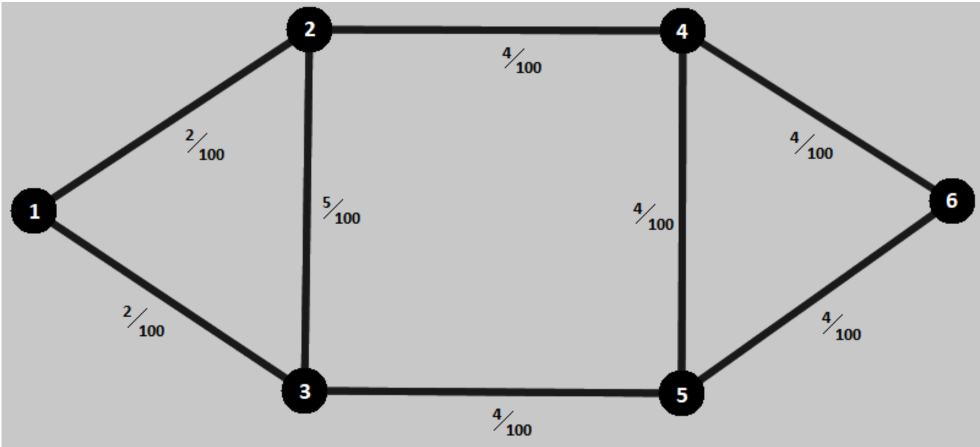


Figura 6.34: Optical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.8. In table 6.4 mentioned in previous model we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	23 520 000 €
	100 Gbits/s Transceivers		46	5 000 €/Gbit/s	23 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	4 662 590 €
		ODU0 Ports	60	10 €/port	600 €	
		ODU1 Ports	50	15 €/port	750 €	
		ODU2 Ports	16	30 €/port	480 €	
		ODU3 Ports	6	60 €/port	360 €	
		ODU4 Ports	4	100 €/port	400 €	
		Line Ports	46	100 000 €/port	4 600 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						28 182 590 €

Tabela 6.8: Table with detailed description of CAPEX of Vasco's 2016 results.

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.2. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

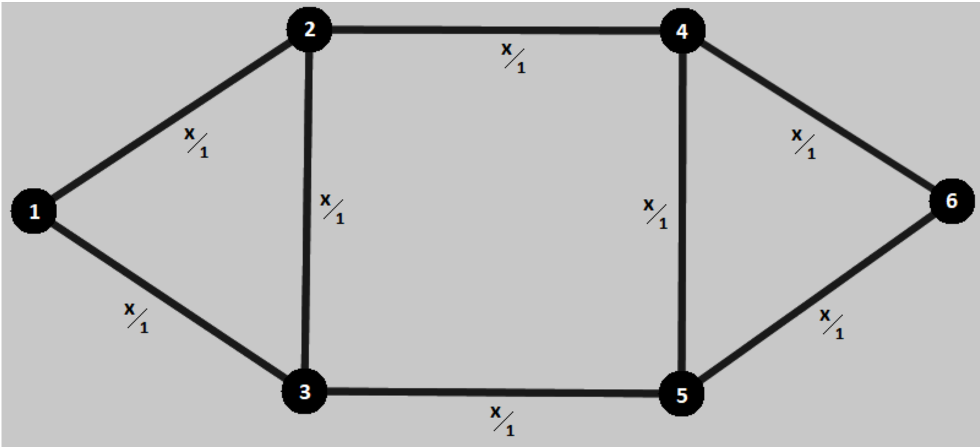


Figura 6.35: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

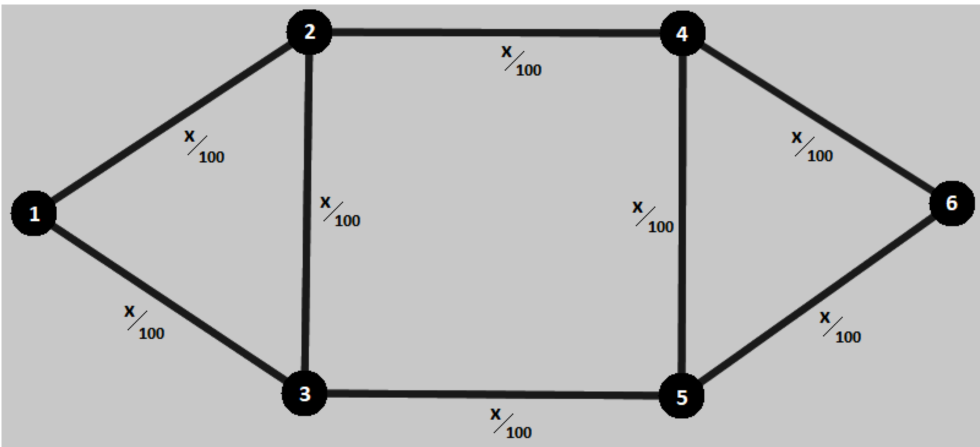


Figura 6.36: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

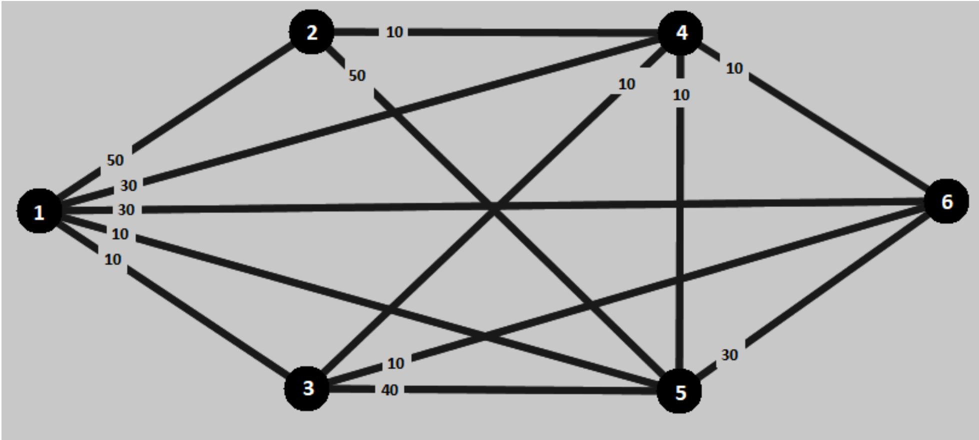


Figura 6.37: ODU0 logical topology defined by the ODU0 traffic matrix.

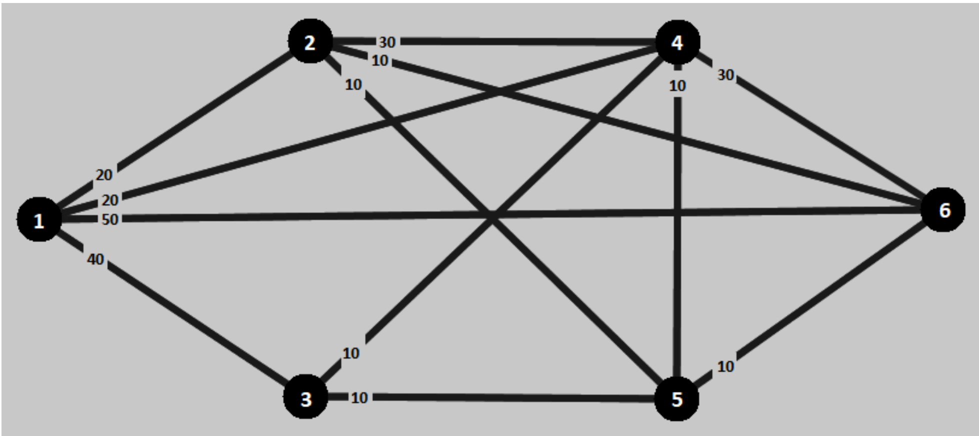


Figura 6.38: ODU1 logical topology defined by the ODU1 traffic matrix.

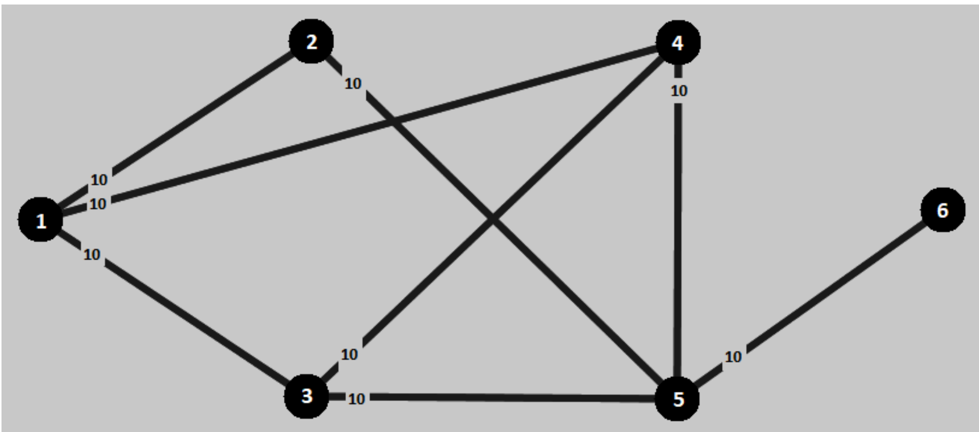


Figura 6.39: ODU2 logical topology defined by the ODU2 traffic matrix.

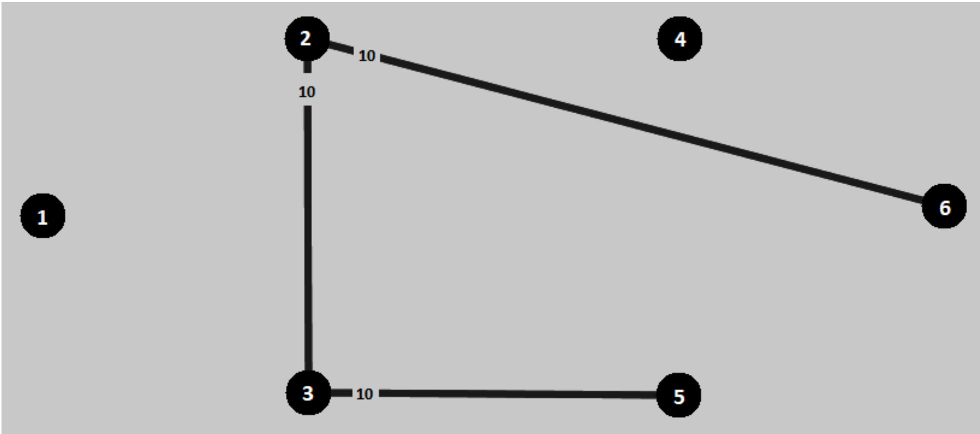


Figura 6.40: ODU03 logical topology defined by the ODU3 traffic matrix.

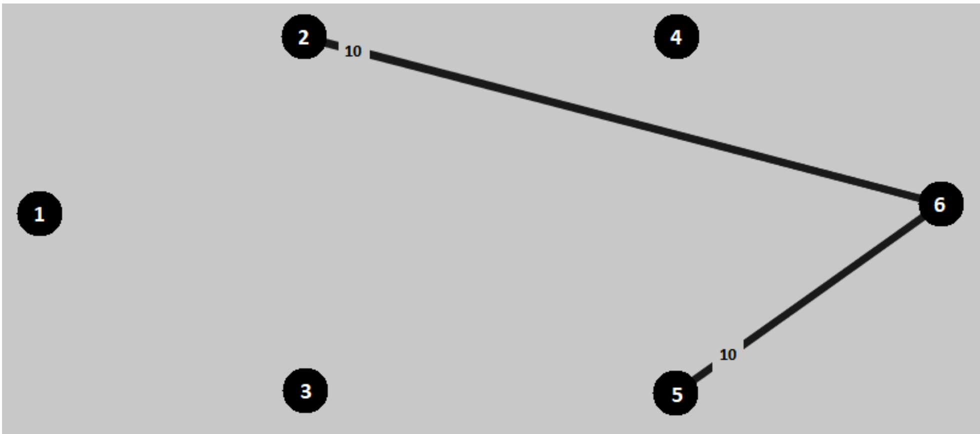


Figura 6.41: ODU4 logical topology defined by the ODU4 traffic matrix.

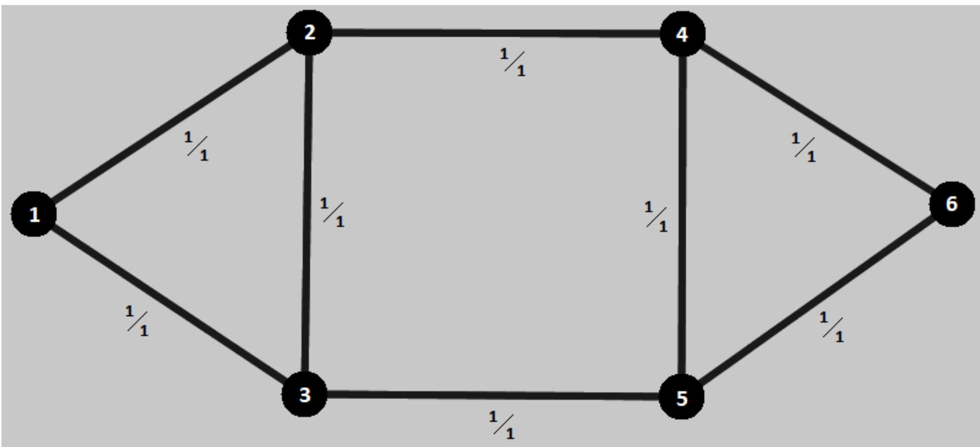


Figura 6.42: Physical topology after dimensioning.

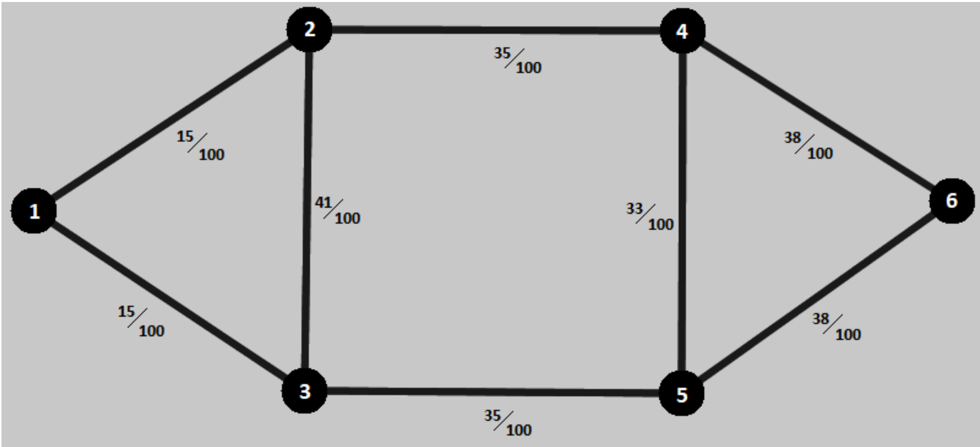


Figura 6.43: Optical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.9. In table 6.4 mentioned in previous model we can see how all the values were calculated.

CAPEX of the Network							
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	199 520 000 €
	100 Gbits/s Transceivers		398	5 000 €/Gbit/s	199 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	39 885 900 €
		ODU0 Ports	600	10 €/port	6 000 €	
		ODU1 Ports	500	15 €/port	7 500 €	
		ODU2 Ports	160	30 €/port	4 800 €	
		ODU3 Ports	60	60 €/port	3 600 €	
		ODU4 Ports	40	100 €/port	4 000 €	
		Line Ports	398	100 000 €/port	50 000 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						239 405 900 €

Tabela 6.9: Table with detailed description of CAPEX of Vasco's 2016 results.

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.3. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

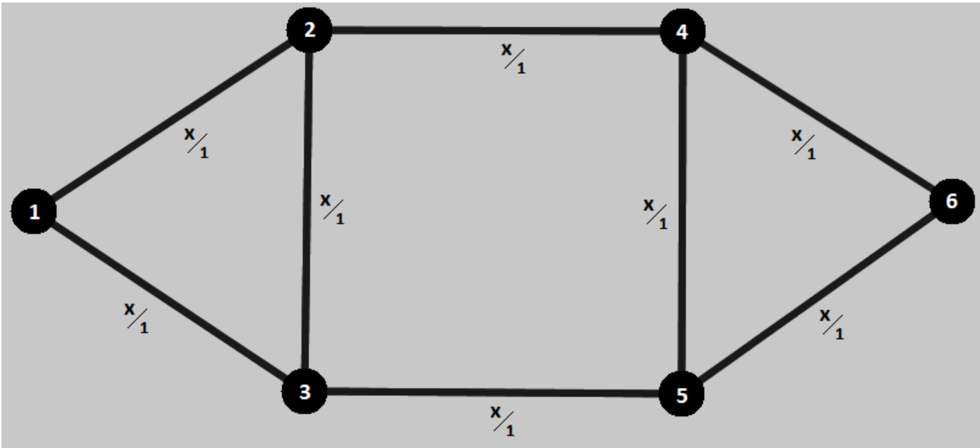


Figura 6.44: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

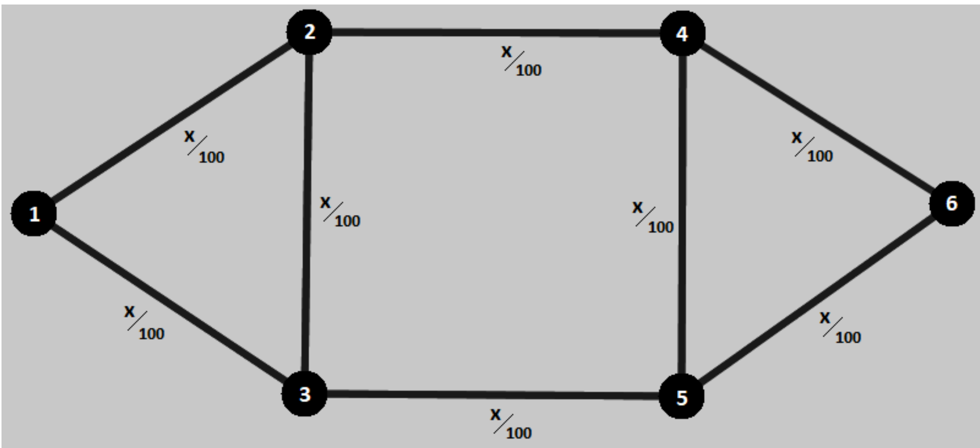


Figura 6.45: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

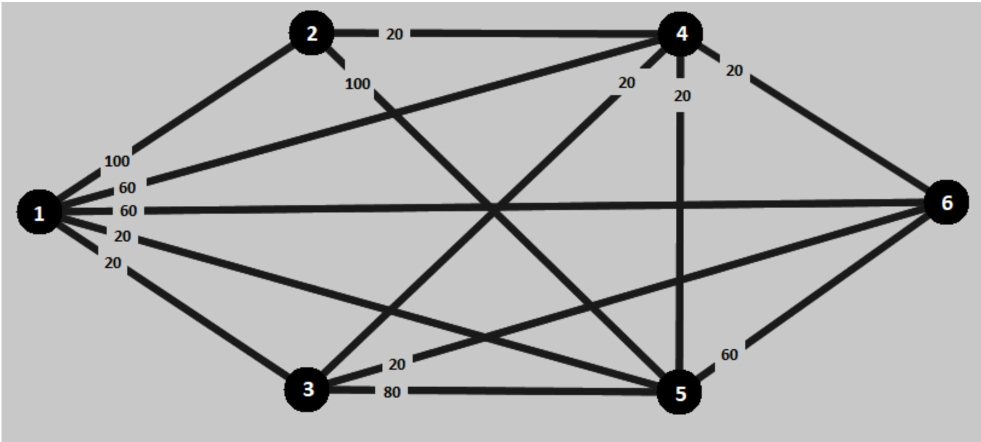


Figura 6.46: ODU0 logical topology defined by the ODU0 traffic matrix.

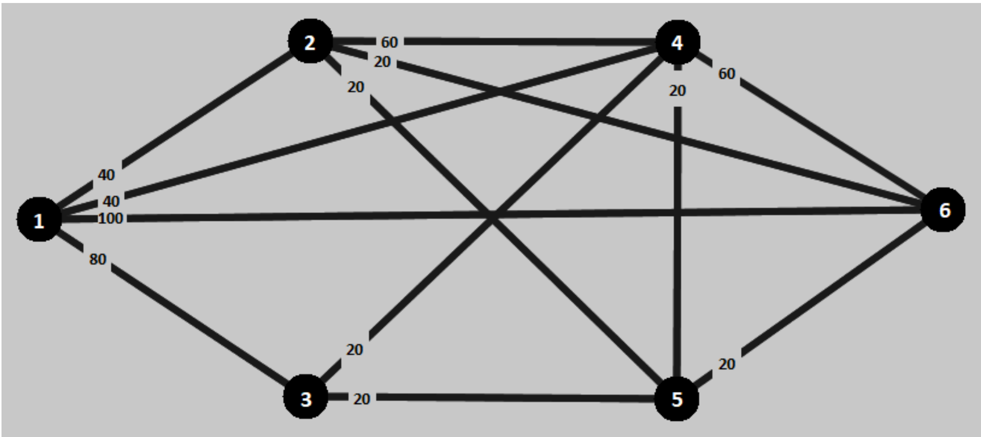


Figura 6.47: ODU1 logical topology defined by the ODU1 traffic matrix.

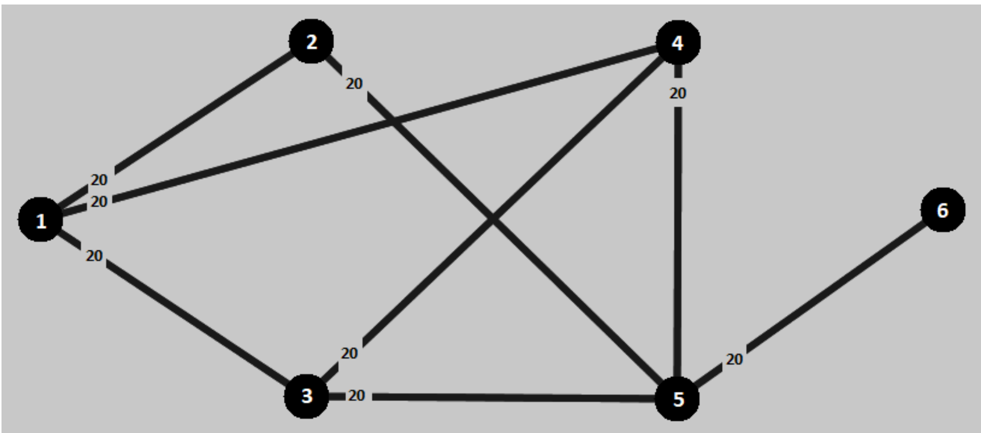


Figura 6.48: ODU2 logical topology defined by the ODU2 traffic matrix.

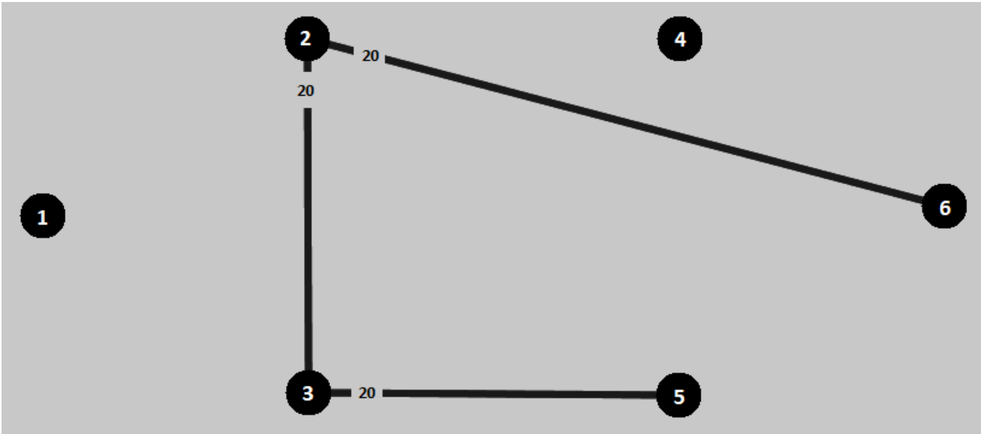


Figura 6.49: ODU3 logical topology defined by the ODU3 traffic matrix.

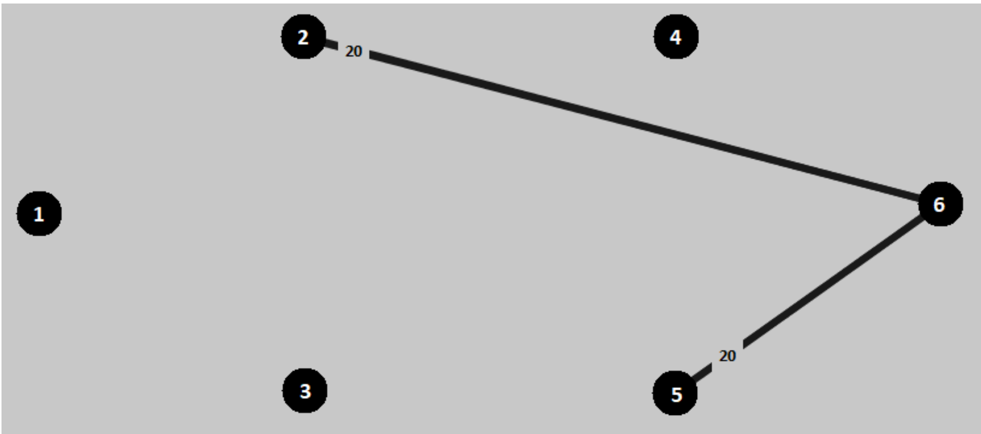


Figura 6.50: ODU4 logical topology defined by the ODU4 traffic matrix.

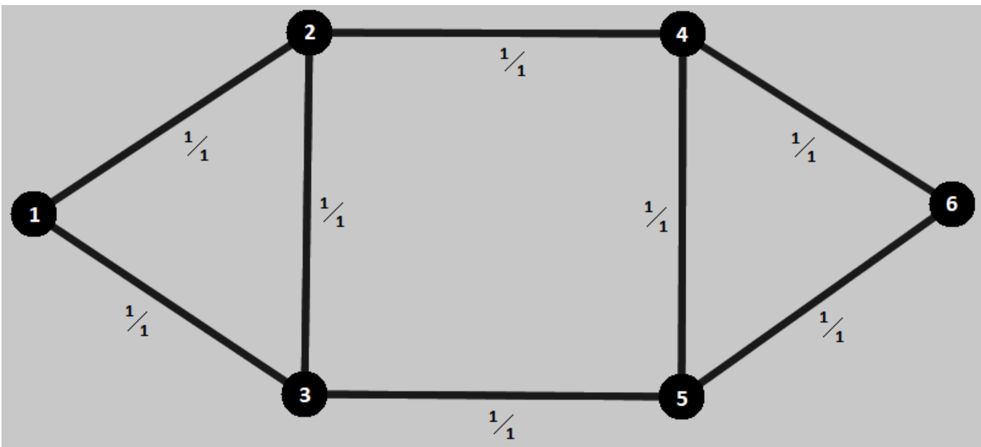


Figura 6.51: Physical topology after dimensioning.

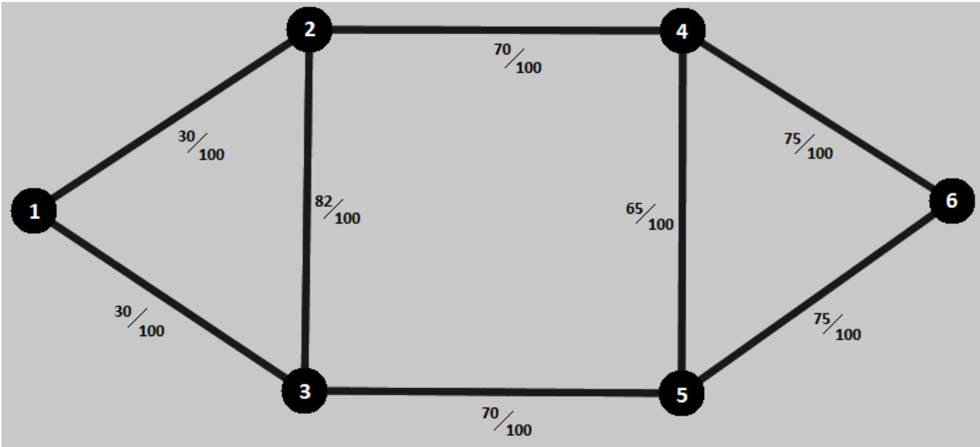


Figura 6.52: Optical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.10. In table 6.4 mentioned in previous model we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	397 520 000 €
	100 Gbits/s Transceivers		794	5 000 €/Gbit/s	397 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	79 514 200 €
		ODU0 Ports	1 200	10 €/port	12 000 €	
		ODU1 Ports	1 000	15 €/port	15 000 €	
		ODU2 Ports	320	30 €/port	9 600 €	
		ODU3 Ports	120	60 €/port	7 200 €	
		ODU4 Ports	80	100 €/port	8 000 €	
		Line Ports	794	100 000 €/port	99 400 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						477 034 200 €

Tabela 6.10: Table with detailed description of CAPEX of Vasco's 2016 results.

Conclusions

Once we have obtained the results for all the scenarios for opaque without survivability and opaque with 1+1 protection we will now draw some conclusions about these results. For a better analysis of the results will be created the table 6.11 with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

	Low Traffic	Medium Traffic	High Traffic
CAPEX without survivability	14 382 590 €	92 405 900 €	178 834 200 €
CAPEX/Gbit/s without survivability	28 765 €/Gbit/s	18 481 €/Gbit/s	17 883 €/Gbit/s
Traffic (Gbit/s)	500	5 000	10 000
Bidirectional Links used	8	8	8
Number of Line ports	46	398	794
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	46	398	794
Link Cost	23 520 000 €	199 520 000 €	397 520 000 €
Node Cost	4 662 590 €	39 885 900 €	79 514 200 €
CAPEX	**28 182 590 €**	**239 405 900 €**	**477 034 200 €**
CAPEX/Gbit/s	**56 365 €/Gbit/s**	**47 881 €/Gbit/s**	**47 703 €/Gbit/s**

Tabela 6.11: Table with different value of CAPEX for this case.

Looking at the previous table we can make some comparisons between the opaque with 1+1 protection scenario:

- Comparing the low traffic with the others we can see that despite having an increase of factor ten (medium traffic) and factor twenty (high traffic), the same increase does not occur in the final cost (it is lower);

  This happens because the number of the transceivers is lower than expected which leads by carrying the traffic with less network components and, consequently, the network CAPEX is lower;

- Comparing the medium traffic with the high traffic we can see that the increase of the factor is double and in the final cost this factor is very close but still inferior;

  This happens because the number of the transceivers is also lower but very close to the expected;

- Comparing the CAPEX cost per bit we can see that in the low traffic the cost is higher than the medium and high traffic, which in these two cases the value is very similar;

  This happens because the lower the traffic, the higher CAPEX/bit will be. We can see that in medium and high traffic the results tend to be one closer value.

We can also make some comparisons between the opaque without survivability and opaque with 1+1 protection scenarios:

- We can see that in the opaque with 1+1 protection the CAPEX cost for all the three traffic is more than the double;

  This happens because in the opaque with 1+1 protection there is a need of having a primary and a backup path, in case of a network failure, and the backup path is typically longer and normally uses more than the double of the capacity of the primary;

- The number of the network components and the CAPEX cost are directly proportional to the traffic value. The higher the traffic value, the higher the network CAPEX cost;

  This happens because if the traffic value is higher, the network components have to be in more quantity to carry all the traffic end-to-end, both in the primary and backup paths;

- Comparing the CAPEX cost per bit we can see that has a similar case in both of the two scenarios. In the low traffic the cost is higher than the medium and high traffic, which in these two cases the value is very similar;

  This happens because the lower the traffic, the higher CAPEX/bit will be. We can see that in medium and high traffic the results tend to be one closer value.

Opens Issues

The creation of this model for any scenario, started with some considerations and some open issues being:

- Allow blocking.

  The presented model assume that the solution is possible or impossible, does not support a partial solution where some demands are not routed (are blocked);

- Allow multiple transmission system.

  The presented model for each link only supports one transmission system;

- Allowing multi-path routing.

  In the presented model all demands sharing the same end nodes have to follow the same path.

6.1.3 Transparent without Survivability

Student Name	:	Pedro Coelho (01/03/2018 -)
Goal	:	Implement the heuristic model for the transparent transport mode without survivability.

Model description

In the transparent transport mode (single-hop approach), the signals travel through the network in the optical domain between lightpaths. One advantage of this transport mode is that these networks require optical switching. This enables the realization of ongoing optical connections throughout several links without OEO (optical-electrical-optical) conversions. However, there are performed some conversions in some intermediate nodes.
Transparent optical connections creates lightpaths which require the assignment of a wavelength that will be used to be exchanged by wavelength converters in order to optimize the network and minimize the total CAPEX.
After the creation of the matrices and the network topology, it is necessary to apply the routing and grooming algorithms created. In the end, a report algorithm will be applied to obtain the best CAPEX result for the network in question.
We also must take into account the following particularity of this mode of transport:

- $N_{OXC,n}$ = 1, $\forall$ n that process traffic
- $N_{EXC,n}$ = 1, $\forall$ n that process traffic

The minimization of the network CAPEX is made through the equation 6.1 where in this case for the cost of nodes we have in consideration the electric cost 6.4 and the optical cost 6.5.

In this case the value of $P_{exc,c,n}$ is obtained by equation 6.10 for short-reach and by the equation 6.11 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 6.12.

The equation 6.10 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{6.10}$$

where $D_{nd,c}$ are the client demands between nodes n and d with bit rate c.

In this case there is the following particularity:

- When n=d the value of client demands is always zero, i.e, $D_{nn,c} = 0$

As previously mentioned, the equation 6.11 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e. the number of add ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} f_{nj}^{od} \tag{6.11}$$

where f_{nj}^{od} is the number of optical channels between node n and node j for all demand pairs (od).

The equation 6.12 refers to the number of line ports and the number of adding ports of node n which can be calculated as

$$P_{oxc,n} = \sum_{j=1}^{N} 2f_{nj}^{od} + \sum_{j=1}^{N} \lambda_{nj} \tag{6.12}$$

where f_{nj}^{od} refers to the number of line ports for all demand pairs (od) and λ_{nj} refers to the number of adding ports.

The function, to be minimized, is the expression 6.1.

This heuristic approach consists in four algorithms made in Java in a programming software called Eclipse and testing them in an open-source network program called Net2Plan. In the Net2Plan guide section 10.1 there is a brevious explanation of the algorithms and a demonstration on how to use and test them in this network planner. The logical topology and the grooming algorithms are going to be explained below with more details because they have more substantial differences between the three transport modes used in this report.

Logical topology

A network topology represents how the links and the nodes of the network interconnect with each other. These connections are made in the physical (real) and the logical (virtual) topologies and the algorithm creates the logical topology on another layer. The final and resulting physical and optical topologies depend on the method used in each of the transport modes.

In the transparent transport mode each node connects to each other creating direct links between all nodes in the network. Going through all nodes, if a node has a different index from other node, then creates a shortest and direct link between them. These additions of links between nodes are made in the new upper layer of the network. The respective demands are saved in the new upper layer and those demands from the lower layer are then removed. The lower layer is the physical layer of the network and it is now created a new upper layer which is the logical layer of the network and represents the logical topology of the transparent transport mode.

The allowed topologies, physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 6.1.1 for the three traffic scenarios.

Grooming

After a network topology is created, it is now time to set the grooming algorithm. This algorithm aggregates the traffic into the network, i.e., in the optical channels that are interconnected between end nodes. This aggregation is made by creating bidirectional routes based on the shortest path type (hops or km). In this report it is used the shortest path type in hops.

In the transparent transport mode the grooming algorithm is similar with the one used in opaque transport mode. It starts with going through all the nodes which have different index between them (end nodes), create routes (primary paths) and then set the traffic into those routes. In all direct links between end nodes is reserved a link capacity based on the previous traffic aggregation. One important aspect is that these routes are created based on the shortest path method, comparing all the routes with each other and the final resulting route is the shortest one. As we also have a dedicated 1+1 protection scheme, if the network has this feature, the algorithm will compare the routes again and it will create new routes (backup paths) if they are the next shortest path routes comparing to the previous ones and then set the traffic into those routes. The traffic that is carried into the network will be the sum of all the created paths. Knowing the value of the total traffic and the wavelength capacity of all links, it is possible to calculate the number of wavelengths in each link.

It is shown in the next page below a fluxogram with the description of the algorithms and the steps performed to obtain the final results in the opaque transport mode.

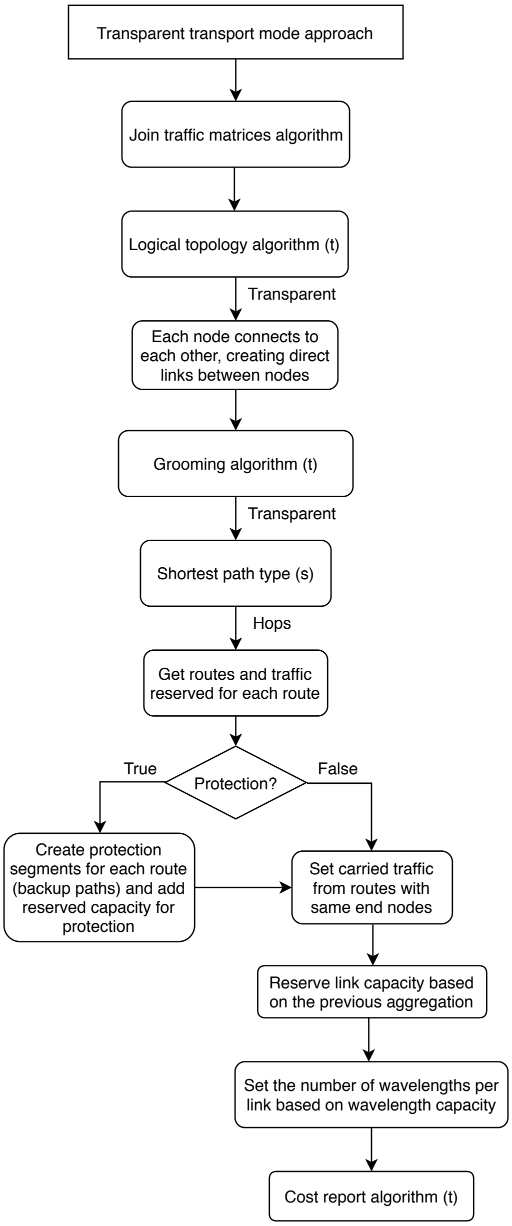


Figura 6.53: Fluxogram with transparent transport mode approach.

Result description

It is already known all the necessary formulas to obtain the CAPEX value for the reference network 10.1. As described in the subsection of the network traffic 4.2, it is necessary to obtain three different values of CAPEX for the low (0.5 Tbit/s), medium (5 Tbit/s) and high (10 Tbit/s) traffic. It is used a network software program called Net2Plan which can design the traffic matrices, create all the network topologies, simulate the algorithms into the network implemented in the programming software called Eclipse and analyze the results obtained.
In this chapter will be demonstrated the results by Vasco's heuristics from 2016. In each of the three traffic scenarios, it will be shown the network topologies followed by the table with the CAPEX value of the network.

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.1. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

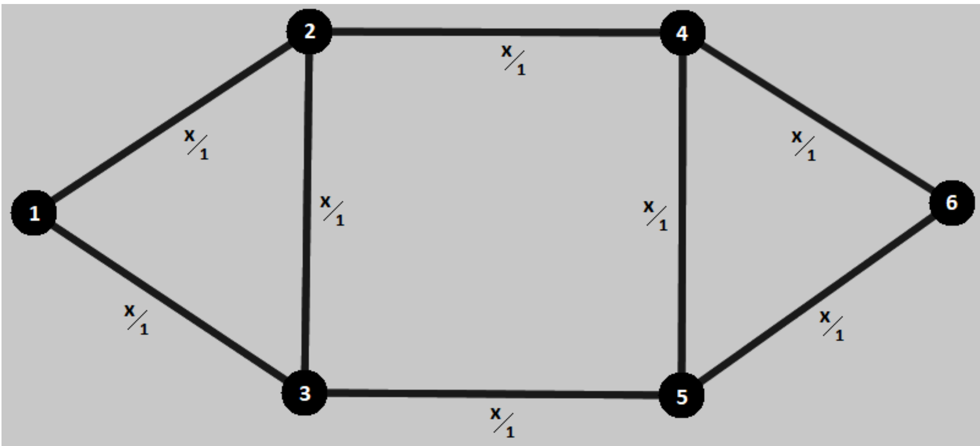


Figura 6.54: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

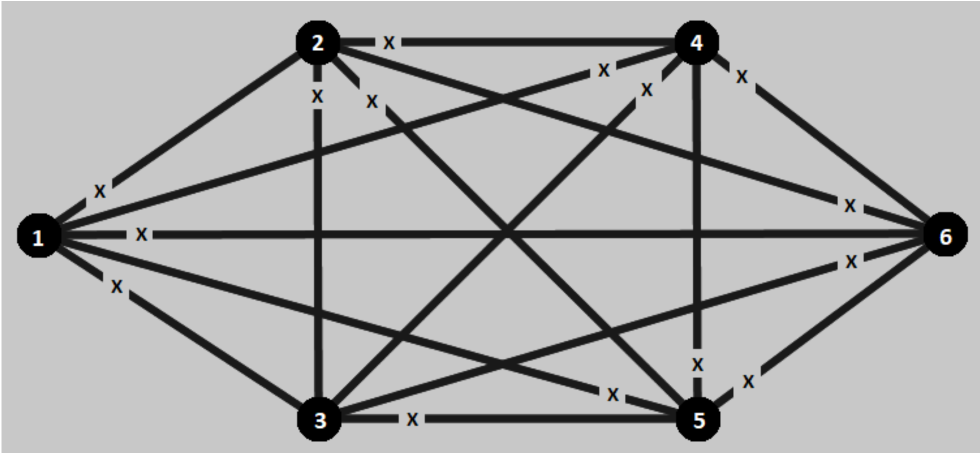


Figura 6.55: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

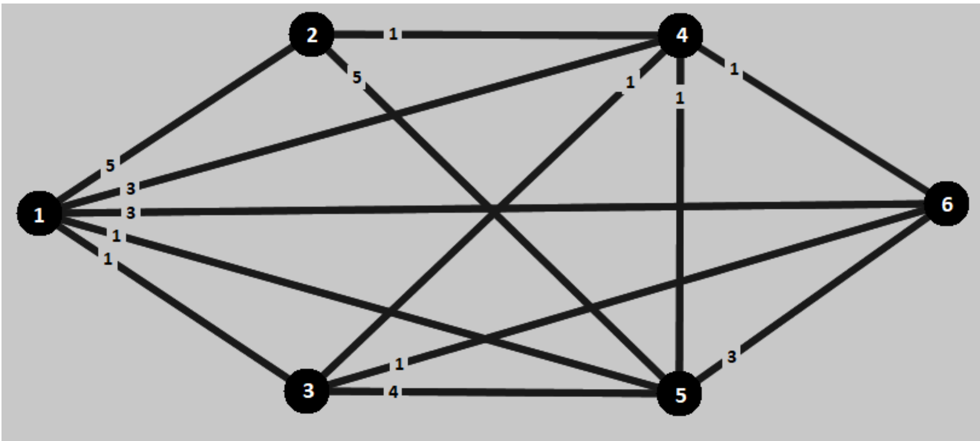


Figura 6.56: ODU0 logical topology defined by the ODU0 traffic matrix.

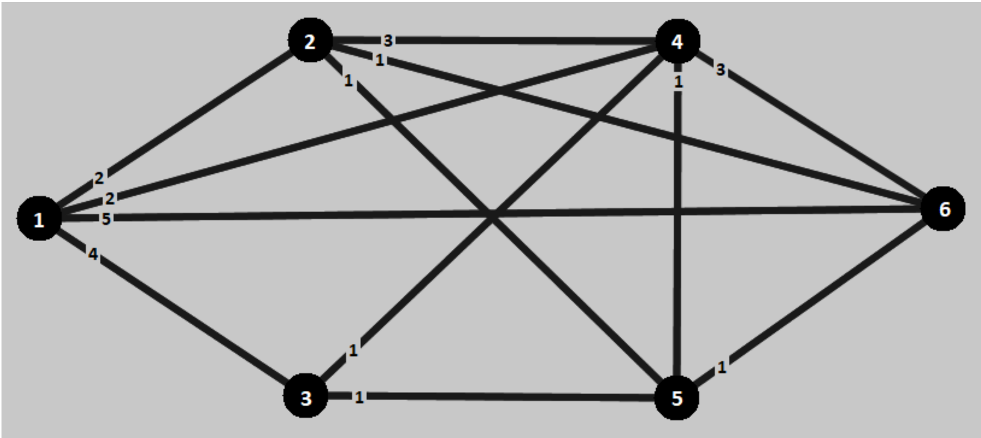


Figura 6.57: ODU1 logical topology defined by the ODU1 traffic matrix.

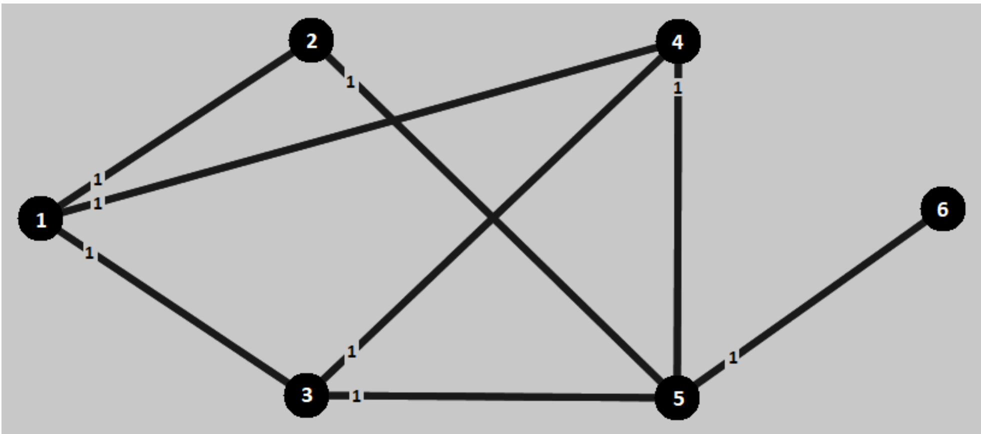


Figura 6.58: ODU2 logical topology defined by the ODU2 traffic matrix.

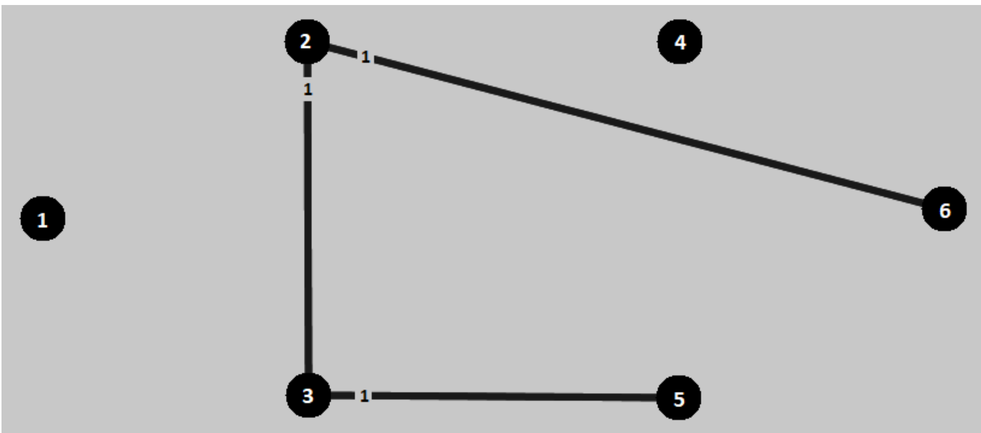


Figura 6.59: ODU3 logical topology defined by the ODU3 traffic matrix.

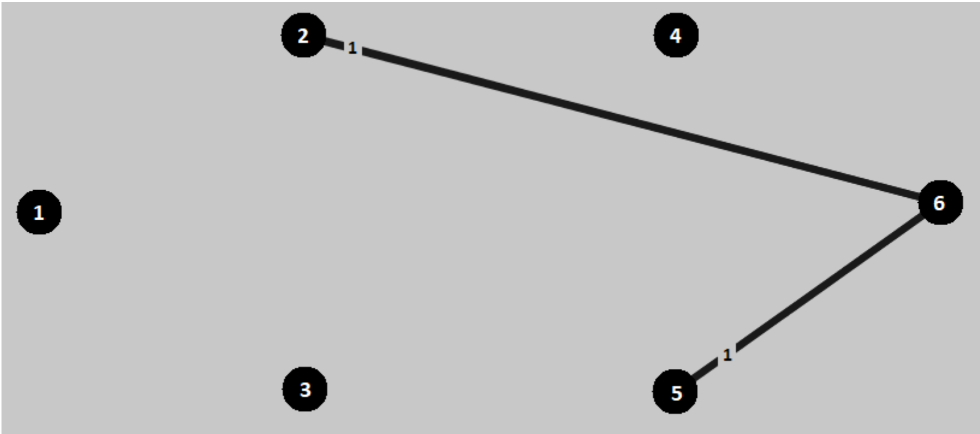


Figura 6.60: ODU4 logical topology defined by the ODU4 traffic matrix.

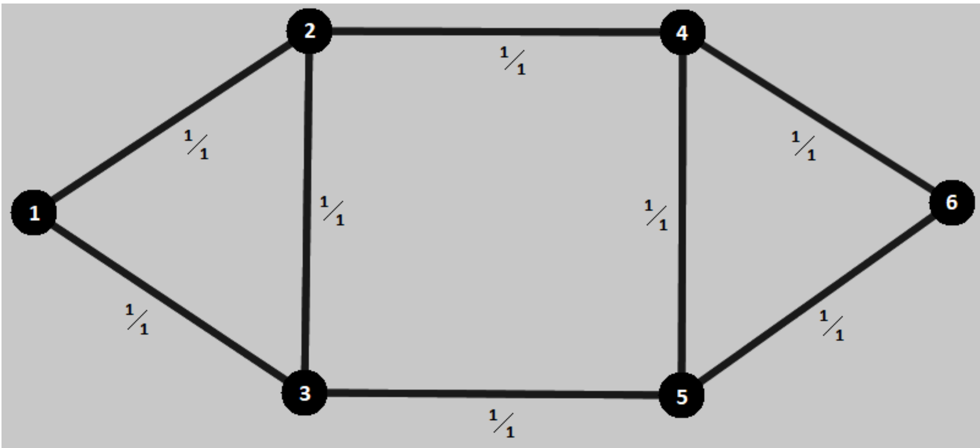


Figura 6.61: Physical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.12.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	52 520 000 €
	100 Gbits/s Transceivers		52	5 000 €/Gbit/s	26 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	3 927 590 €
		ODU0 Ports	60	10 €/port	600 €	
		ODU1 Ports	50	15 €/port	750 €	
		ODU2 Ports	16	30 €/port	480 €	
		ODU3 Ports	6	60 €/port	360 €	
		ODU4 Ports	4	100 €/port	400 €	
		Transponders	34	100 000 €/port	3 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	104	2 500 €/port	260 000 €	
		Add Ports	34	2 500 €/port	85 000 €	
Total Network Cost						56 447 590 €

Tabela 6.12: Table with detailed description of CAPEX of Vasco's 2016 results.

All the values calculated in the previous table were obtained through the equations 6.2 and 6.3 referred to in section 6.1, but for a more detailed analysis we created table 6.13 where we can see how all the parameters are calculated individually.

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.2. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

	Equation used to calculate the cost
OLTs	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}\gamma_0^{OLT}$
Transceivers	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}f_{ij}^{od}\gamma_1^{OLT}\tau$
Amplifiers	$2\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}N_{ij}^{R}c^{R}$
EXCs	$\sum_{n=1}^{N} N_{exc,n}\gamma_{e0}$
ODU0 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,0}\gamma_{e1,0}$
ODU1 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,1}\gamma_{e1,1}$
ODU2 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,2}\gamma_{e1,2}$
ODU3 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,3}\gamma_{e1,3}$
ODU4 Port	$\sum_{n=1}^{N}\sum_{d=1}^{N} N_{exc,n}D_{nd,4}\gamma_{e1,4}$
LR Transponders	$\sum_{n=1}^{N}\sum_{j=1}^{N} N_{exc,n}\lambda_{od}\gamma_{e1,-1}$
OXCs	$\sum_{n=1}^{N} N_{oxc,n}\gamma_{o0}$
Add Port	$\sum_{n=1}^{N}\sum_{j=1}^{N} N_{oxc,n}\lambda_{od}\gamma_{o1}$
Line Port	$\sum_{n=1}^{N}\sum_{j=1}^{N} N_{oxc,n}f_{ij}^{od}\gamma_{o1}$
CAPEX	The final cost is calculated by summing all previous results.

Tabela 6.13: Table with description of calculation

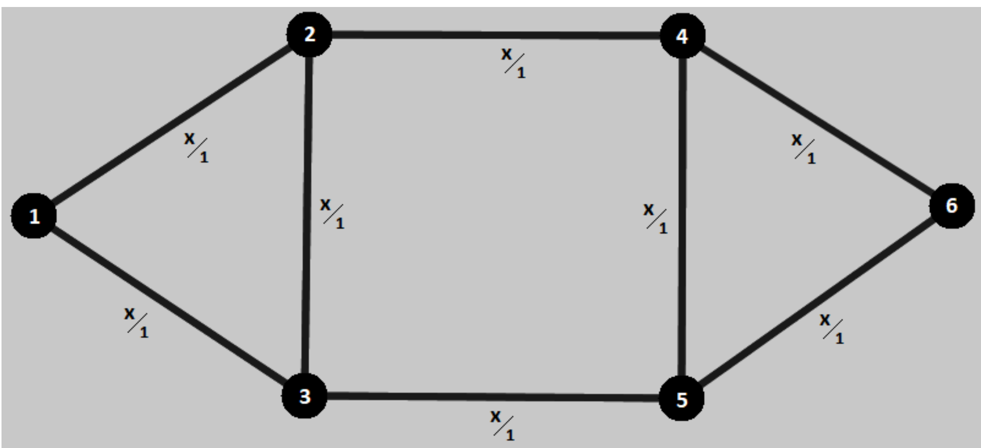


Figura 6.62: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional

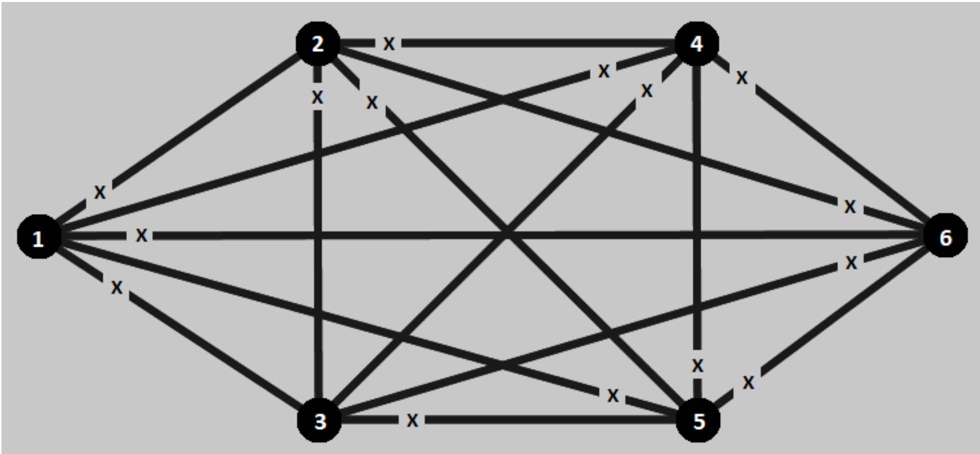


Figura 6.63: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

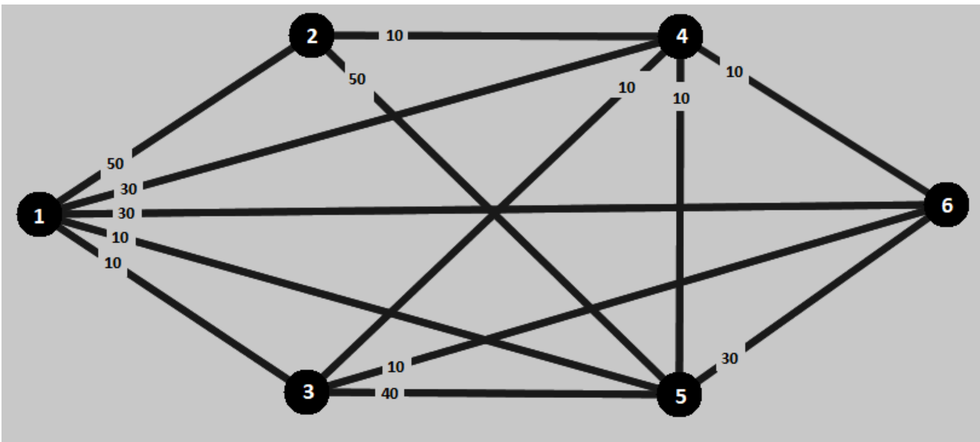


Figura 6.64: ODU0 logical topology defined by the ODU0 traffic matrix.

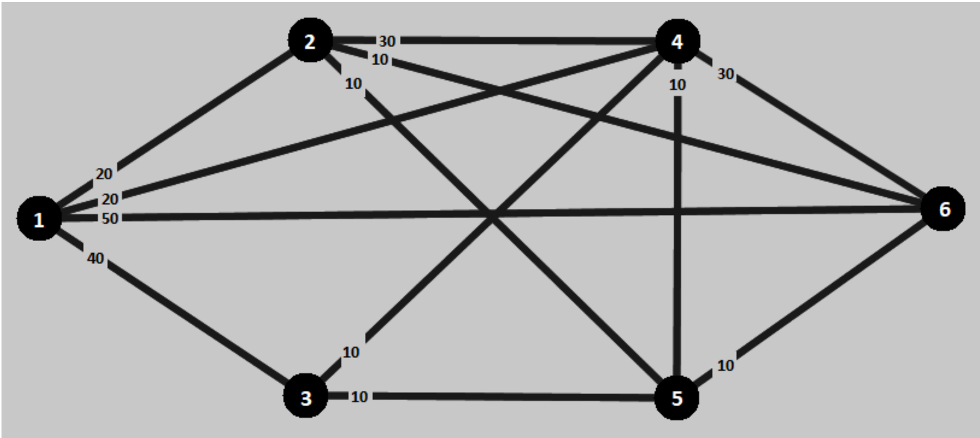


Figura 6.65: ODU1 logical topology defined by the ODU1 traffic matrix.

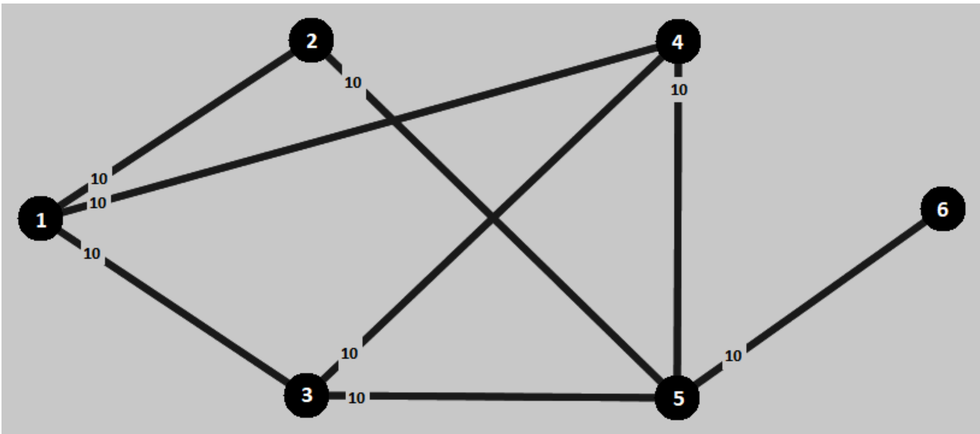


Figura 6.66: ODU2 logical topology defined by the ODU2 traffic matrix.

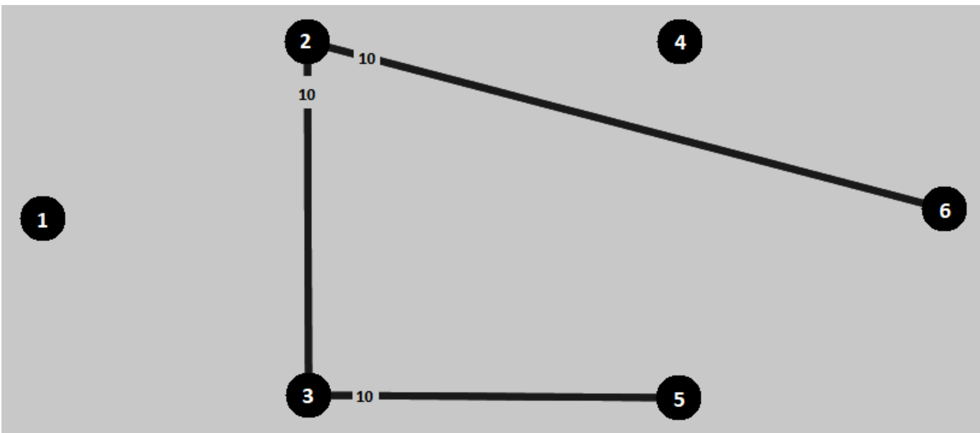


Figura 6.67: ODU3 logical topology defined by the ODU3 traffic matrix.

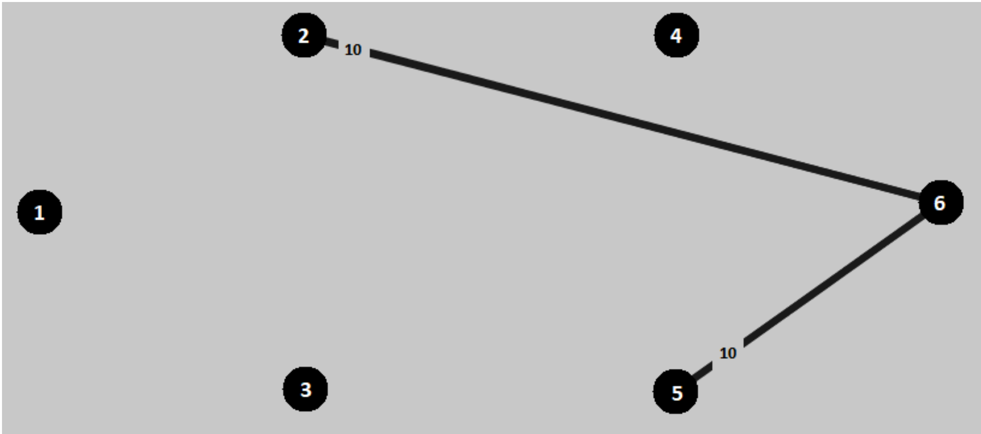


Figura 6.68: ODU4 logical topology defined by the ODU4 traffic matrix.

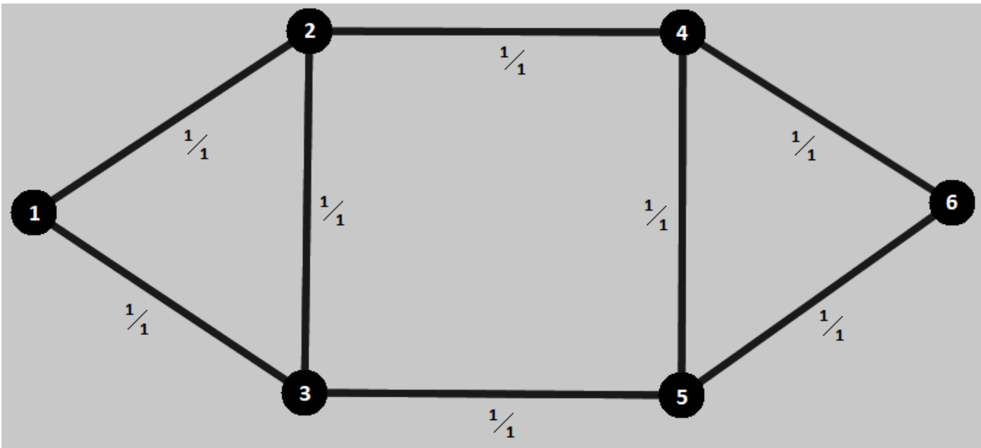


Figura 6.69: Physical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.14. In table 6.13 mentioned in previous scenario we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	168 520 000 €
	100 Gbits/s Transceivers		168	5 000 €/Gbit/s	84 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	12 730 900 €
		ODU0 Ports	600	10 €/port	6 000 €	
		ODU1 Ports	500	15 €/port	7 500 €	
		ODU2 Ports	160	30 €/port	4 800 €	
		ODU3 Ports	60	60 €/port	3 600 €	
		ODU4 Ports	40	100 €/port	4 000 €	
		Transponders	114	100 000 €/port	11 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	336	2 500 €/port	840 000 €	
		Add Ports	114	2 500 €/port	285 000 €	
Total Network Cost						181 250 900 €

Tabela 6.14: Table with detailed description of CAPEX of Vasco's 2016 results.

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.3. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

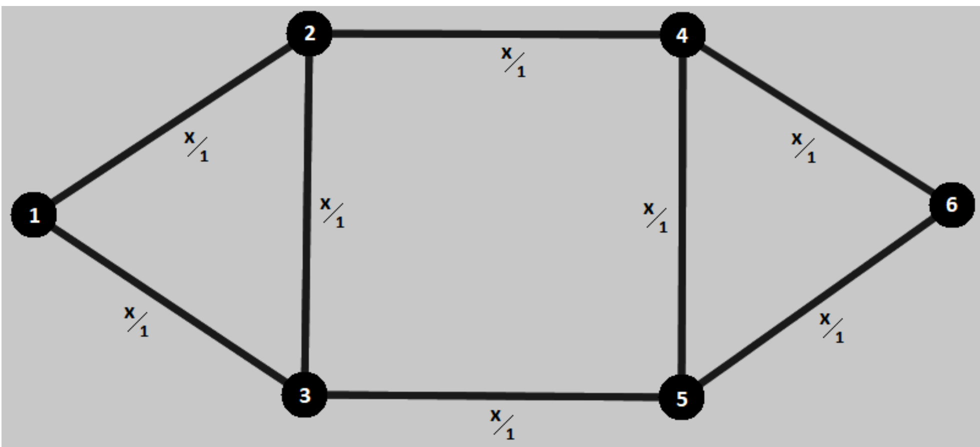


Figura 6.70: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

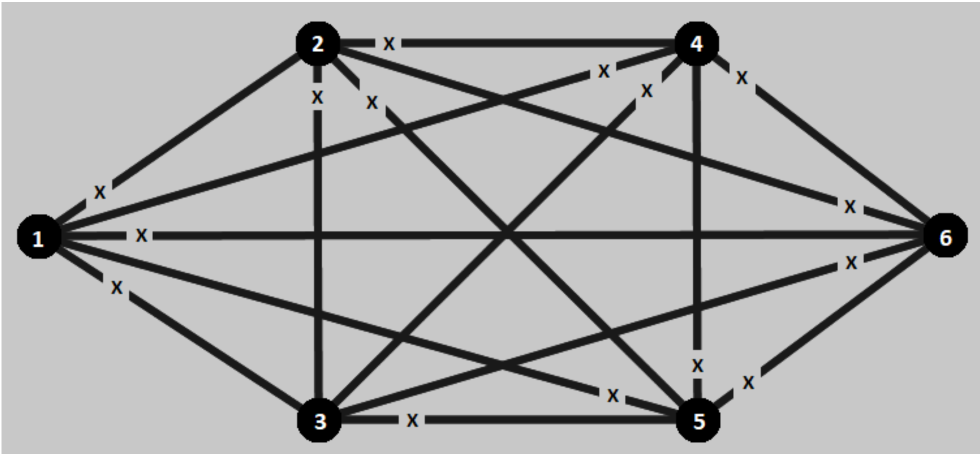


Figura 6.71: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

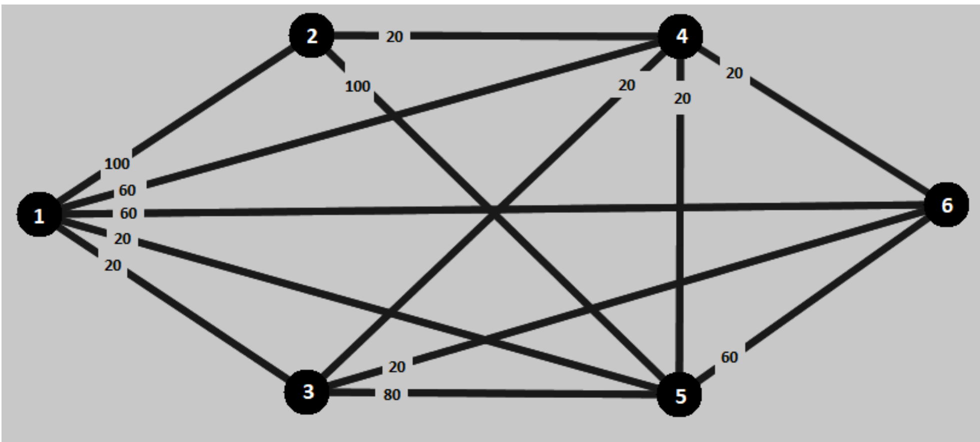


Figura 6.72: ODU0 logical topology defined by the ODU0 traffic matrix.

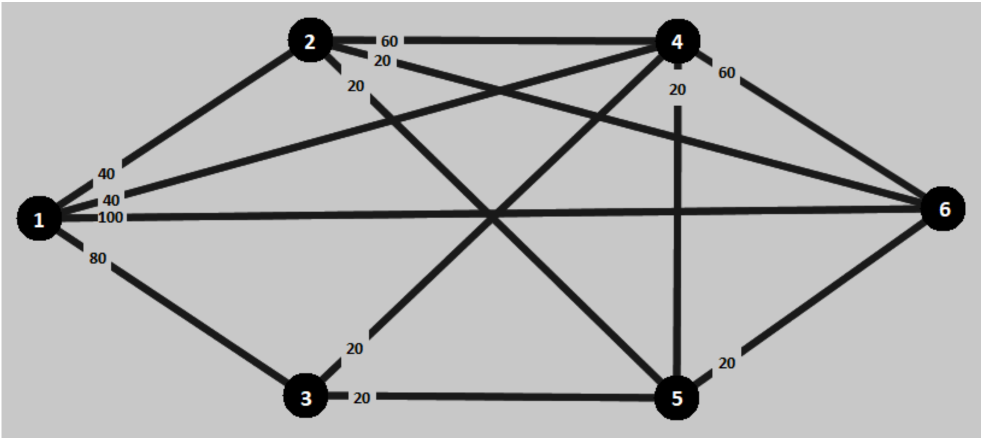


Figura 6.73: ODU1 logical topology defined by the ODU1 traffic matrix.

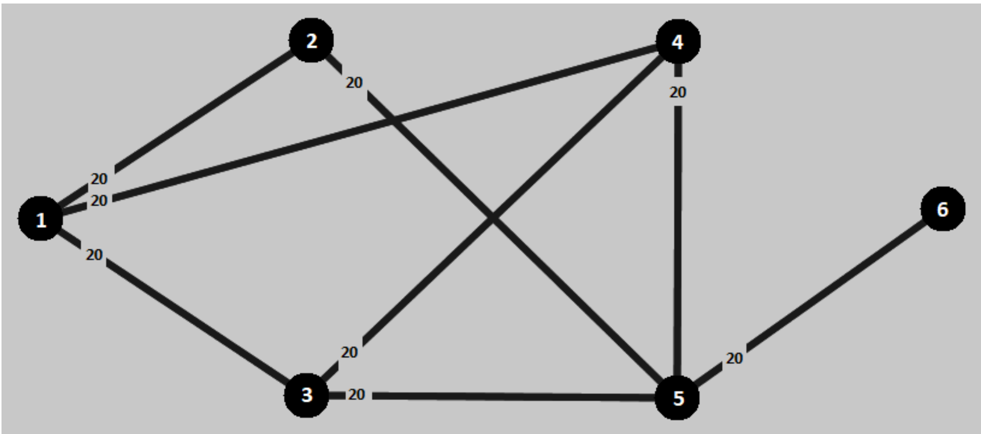


Figura 6.74: ODU2 logical topology defined by the ODU2 traffic matrix.

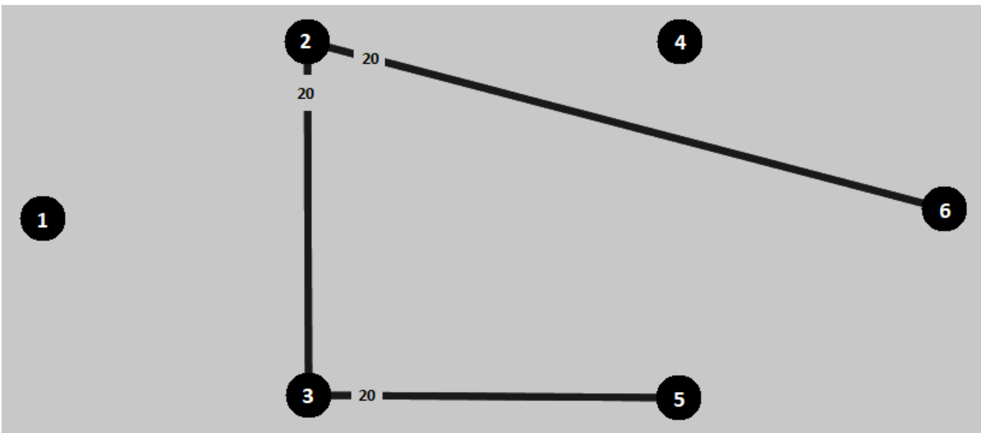


Figura 6.75: ODU3 logical topology defined by the ODU3 traffic matrix.

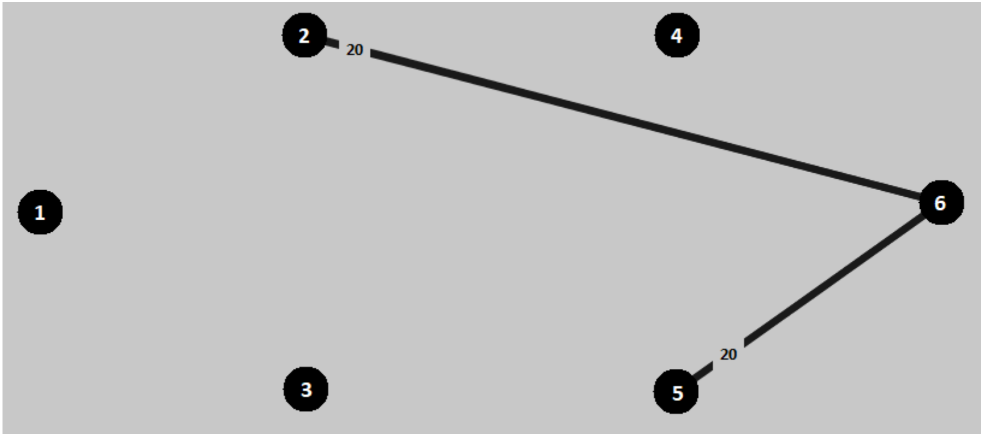


Figura 6.76: ODU4 logical topology defined by the ODU4 traffic matrix.

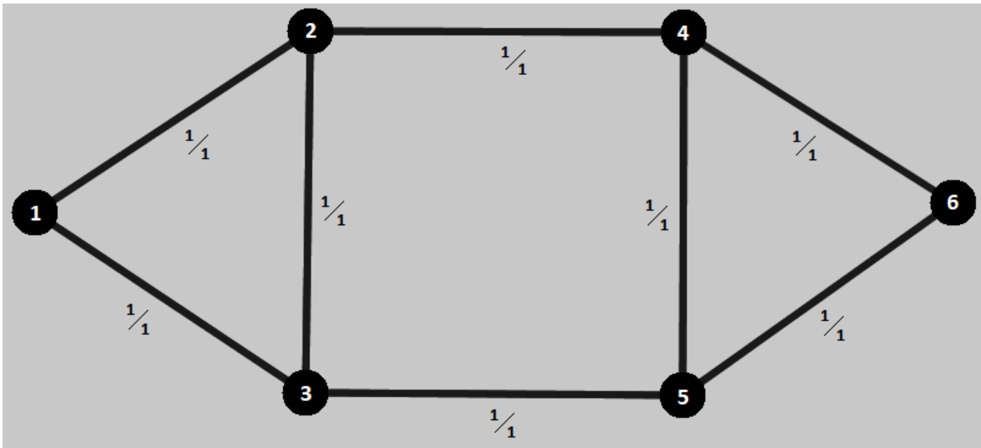


Figura 6.77: Physical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.15. In table 6.13 mentioned in previous scenario we can see how all the values were calculated.

<table>
<tr><td colspan="7">CAPEX of the Network</td></tr>
<tr><td colspan="3"></td><td>Quantity</td><td>Unit Price</td><td>Cost</td><td>Total</td></tr>
<tr><td rowspan="3">Link Cost</td><td colspan="2">OLTs</td><td>16</td><td>15 000 €</td><td>240 000 €</td><td rowspan="3">314 520 000 €</td></tr>
<tr><td colspan="2">100 Gbits/s Transceivers</td><td>314</td><td>5 000 €/Gbit/s</td><td>157 000 000 €</td></tr>
<tr><td colspan="2">Amplifiers</td><td>70</td><td>4 000 €</td><td>280 000 €</td></tr>
<tr><td rowspan="10">Node Cost</td><td rowspan="7">Electrical</td><td>EXCs</td><td>6</td><td>10 000 €</td><td>60 000 €</td><td rowspan="10">23 736 800 €</td></tr>
<tr><td>ODU0 Ports</td><td>1 200</td><td>10 €/port</td><td>12 000 €</td></tr>
<tr><td>ODU1 Ports</td><td>1 000</td><td>15 €/port</td><td>15 000 €</td></tr>
<tr><td>ODU2 Ports</td><td>320</td><td>30 €/port</td><td>9 600 €</td></tr>
<tr><td>ODU3 Ports</td><td>120</td><td>60 €/port</td><td>7 200 €</td></tr>
<tr><td>ODU4 Ports</td><td>80</td><td>100 €/port</td><td>8 000 €</td></tr>
<tr><td>Transponders</td><td>214</td><td>100 000 €/port</td><td>21 400 000 €</td></tr>
<tr><td rowspan="3">Optical</td><td>OXCs</td><td>6</td><td>20 000 €</td><td>120 000 €</td></tr>
<tr><td>Line Ports</td><td>628</td><td>2 500 €/port</td><td>1 570 000 €</td></tr>
<tr><td>Add Ports</td><td>214</td><td>2 500 €/port</td><td>535 000 €</td></tr>
<tr><td colspan="6">Total Network Cost</td><td>338 256 800 €</td></tr>
</table>

Tabela 6.15: Table with detailed description of CAPEX of Vasco's 2016 results.

Conclusions

Once we have obtained the results for all the scenarios we will now draw some conclusions about these results. For a better analysis of the results will be created the table 6.16 with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

	Low Traffic	Medium Traffic	High Traffic
Traffic (Gbit/s)	500	5 000	10 000
Bidirectional Links used	8	8	8
Number of Add ports	34	114	214
Number of Line ports	104	336	628
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	104	336	628
Link Cost	52 520 000 €	168 520 000 €	314 520 000 €
Node Cost	3 927 590 €	12 730 900 €	23 736 800 €
CAPEX	**56 447 590 €**	**181 250 900 €**	**338 256 800 €**
CAPEX/Gbit/s	**112 895 €/Gbit/s**	**36 250 €/Gbit/s**	**33 825 €/Gbit/s**

Tabela 6.16: Table with different value of CAPEX for this case.

Looking at the previous table we can make some comparisons between the several scenario:

- Comparing the low traffic with the others we can see that despite having an increase of factor ten (medium traffic) and factor twenty (high traffic), the same increase does not occur in the final cost (it is lower);

  This happens because the number of the transceivers is lower than expected which leads by carrying the traffic with less network components and, consequently, the network CAPEX is lower;

- Comparing the medium traffic with the high traffic we can see that the increase of the factor is double and in the final cost this factor is very close but still inferior;

  This happens because the number of the transceivers is also lower but very close to the expected;

- Comparing the CAPEX cost per bit we can see that in the low traffic the cost is higher than the medium and high traffic, which in these two cases the value is similar, but still inferior in the higher traffic;

  This happens because the lower the traffic, the higher CAPEX/bit will be. We can see that in medium and high traffic the results tend to be one closer and lower value.

Opens Issues

The creation of this model for any scenario, started with some considerations and some open issues being:

- Allow blocking.

  The presented model assume that the solution is possible or impossible, does not support a partial solution where some demands are not routed (are blocked);

- Allow multiple transmission system.

  The presented model for each link only supports one transmission system.

6.1.4 Transparent with 1+1 Protection

Student Name	:	Pedro Coelho (01/03/2018 -)
Goal	:	Implement the heuristic model for the transparent transport mode with 1 plus 1 protection.

Model description

Contrary to the transparent without survivability transport mode, the transparent with 1+1 protection technique has a backup path, so if there is a network failure it is more likely to not suffer large data losses. The backup paths are always different from the primary ones and they prevent that the information going through optical channels could be lost in these occasions. However, the CAPEX will be significantly higher (more than the double), because that includes a secondary path that will increase several network elements.
After the creation of the matrices and the network topology, it is necessary to apply the routing and grooming algorithms created. In the end, a report algorithm will be applied to obtain the best CAPEX result for the network in question.
We also must take into account the following particularity of this mode of transport:

- $N_{OXC,n}$ = 1, $\forall$ n that process traffic
- $N_{EXC,n}$ = 1, $\forall$ n that process traffic

The minimization of the network CAPEX is made through the equation 6.1 where in this case for the cost of nodes we have in consideration the electric cost 6.4 and the optical cost 6.5.

In this case the value of $P_{exc,c,n}$ is obtained by equation 6.13 for short-reach and by the equation 6.14 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 6.15.

The equation 6.13 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{6.13}$$

where $D_{nd,c}$ are the client demands between nodes n and d with bit rate c.

In this case there is the following particularity:

- When n=d the value of client demands is always zero, i.e, $D_{nn,c} = 0$

As previously mentioned, the equation 6.14 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e. the number of add ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} f_{nj}^{od} \tag{6.14}$$

where f_{nj}^{od} is the number of optical channels between node n and node j for all demand pairs (od).

The equation 6.15 refers to the number of line ports and the number of adding ports of node n which can be calculated as

$$P_{oxc,n} = \sum_{j=1}^{N} 2f_{nj}^{od} + \sum_{j=1}^{N} \lambda_{nj} \tag{6.15}$$

where f_{nj}^{od} refers to the number of line ports for all demand pairs (od) and λ_{nj} refers to the number of adding ports.

The function, to be minimized, is the expression 6.1.

Result description

It is already known all the necessary formulas to obtain the CAPEX value for the reference network 10.1. As described in the subsection of the network traffic 4.2, it is necessary to obtain three different values of CAPEX for the low (0.5 Tbit/s), medium (5 Tbit/s) and high (10 Tbit/s) traffic. It is used a network software program called Net2Plan which can design the traffic matrices, create all the network topologies, simulate the algorithms into the network implemented in the programming software called Eclipse and analyze the results obtained.
In this chapter will be demonstrated the results by Vasco's heuristics from 2016. In each of the three traffic scenarios, it will be shown the network topologies followed by the table with the CAPEX value of the network.

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.1. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

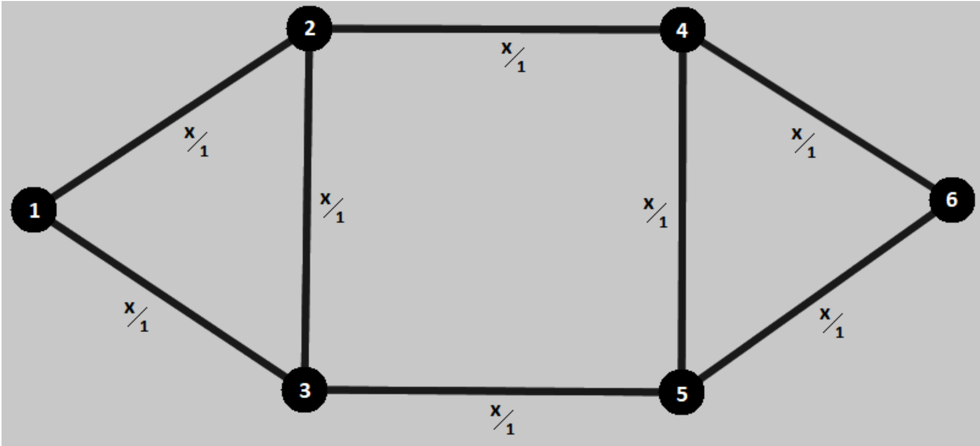


Figura 6.78: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

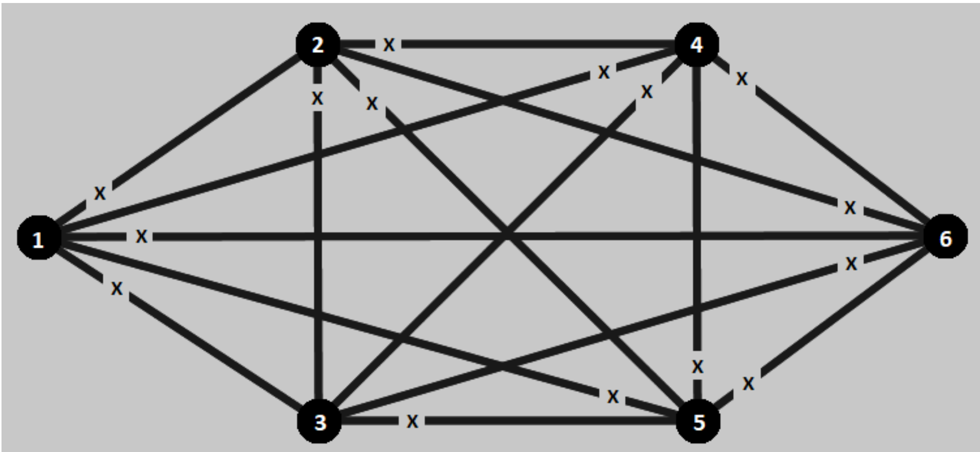


Figura 6.79: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

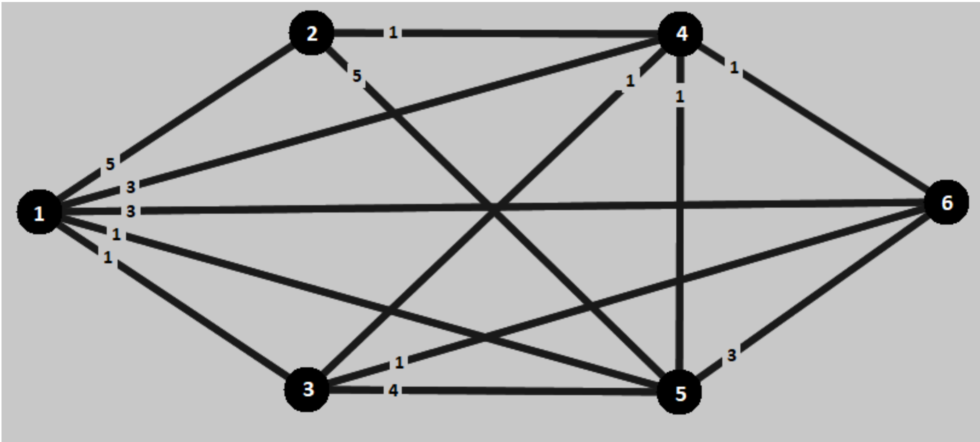


Figura 6.80: ODU0 logical topology defined by the ODU0 traffic matrix.

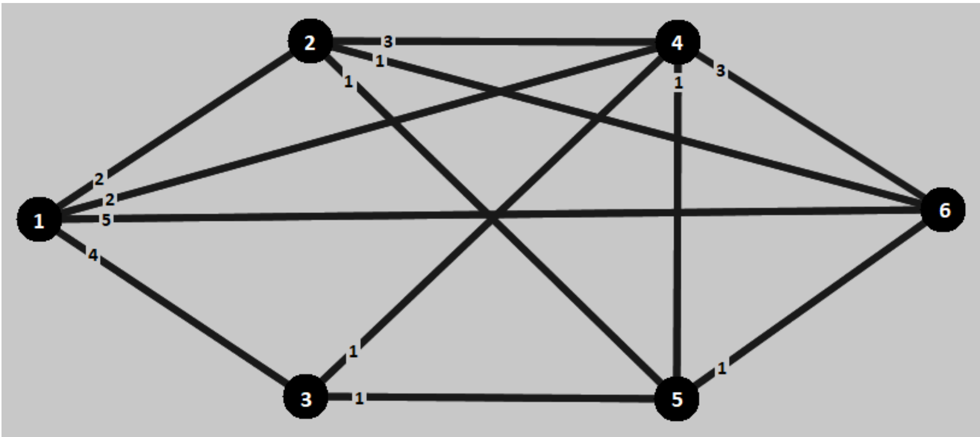


Figura 6.81: ODU1 logical topology defined by the ODU1 traffic matrix.

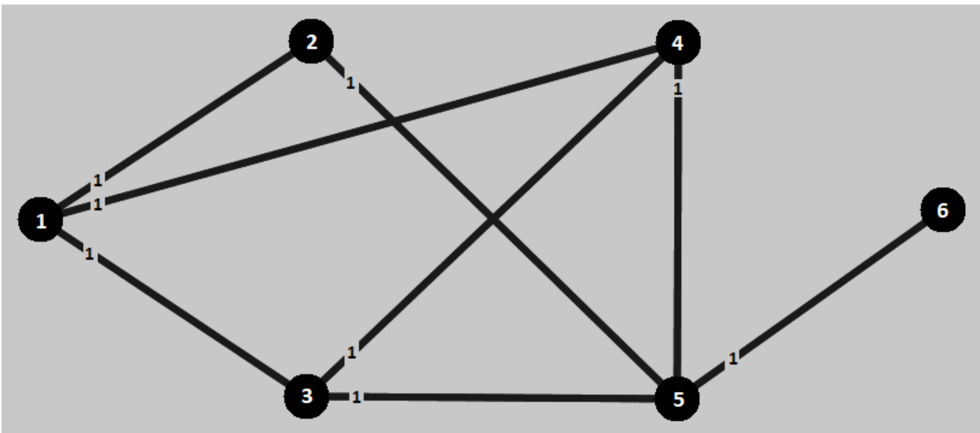


Figura 6.82: ODU2 logical topology defined by the ODU2 traffic matrix.

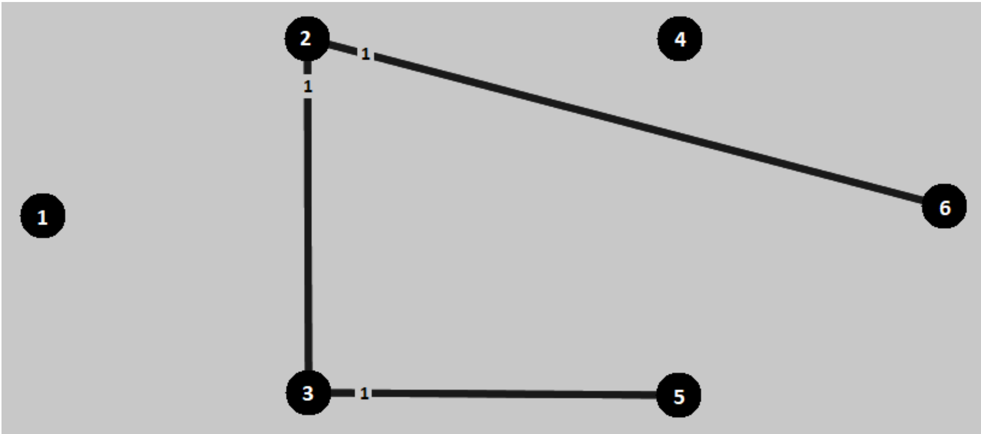


Figura 6.83: ODU3 logical topology defined by the ODU3 traffic matrix.

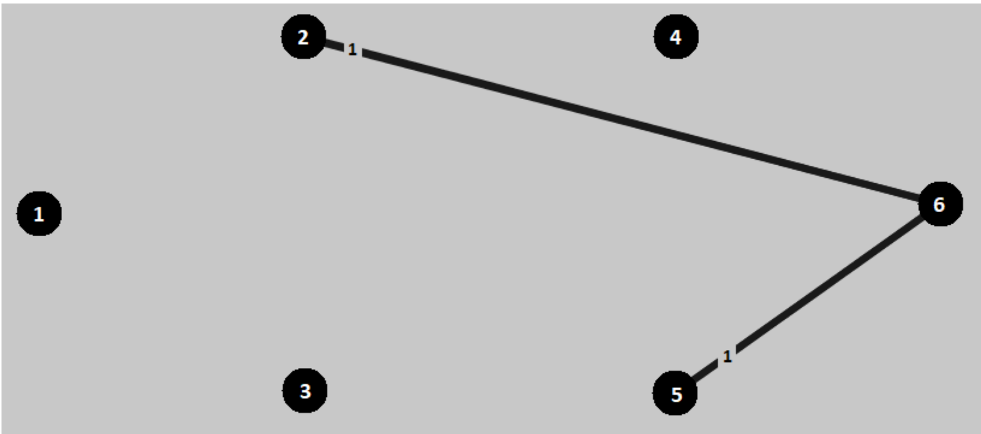


Figura 6.84: ODU4 logical topology defined by the ODU4 traffic matrix.

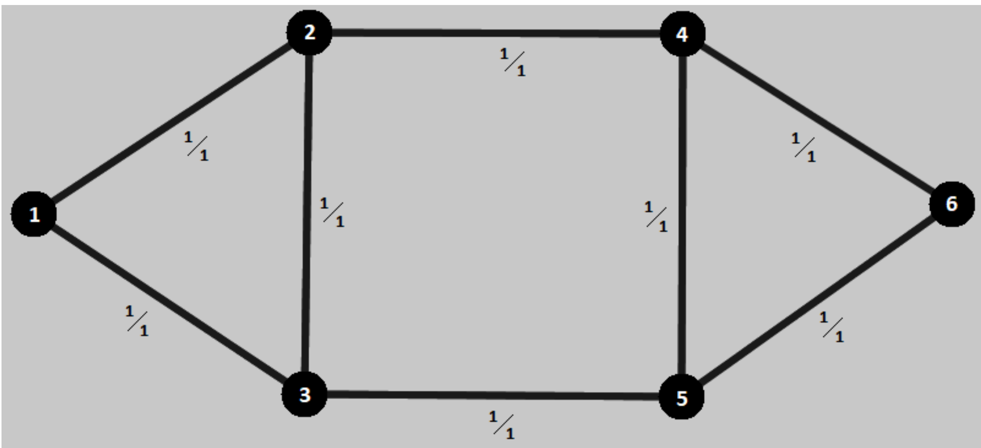


Figura 6.85: Physical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.17. In table 6.13 mentioned in previous model we can see how all the values were calculated.

<table>
<tr><th colspan="7">CAPEX of the Network</th></tr>
<tr><th colspan="3"></th><th>Quantity</th><th>Unit Price</th><th>Cost</th><th>Total</th></tr>
<tr><td rowspan="3">Link Cost</td><td colspan="2">OLTs</td><td>16</td><td>15 000 €</td><td>240 000 €</td><td rowspan="3">136 520 000 €</td></tr>
<tr><td colspan="2">100 Gbits/s Transceivers</td><td>136</td><td>5 000 €/Gbit/s</td><td>68 000 000 €</td></tr>
<tr><td colspan="2">Amplifiers</td><td>70</td><td>4 000 €</td><td>280 000 €</td></tr>
<tr><td rowspan="10">Node Cost</td><td rowspan="7">Electrical</td><td>EXCs</td><td>6</td><td>10 000 €</td><td>60 000 €</td><td rowspan="10">4 347 590 €</td></tr>
<tr><td>ODU0 Ports</td><td>60</td><td>10 €/port</td><td>600 €</td></tr>
<tr><td>ODU1 Ports</td><td>50</td><td>15 €/port</td><td>750 €</td></tr>
<tr><td>ODU2 Ports</td><td>16</td><td>30 €/port</td><td>480 €</td></tr>
<tr><td>ODU3 Ports</td><td>6</td><td>60 €/port</td><td>360 €</td></tr>
<tr><td>ODU4 Ports</td><td>4</td><td>100 €/port</td><td>400 €</td></tr>
<tr><td>Transponders</td><td>34</td><td>100 000 €/port</td><td>3 400 000 €</td></tr>
<tr><td rowspan="3">Optical</td><td>OXCs</td><td>6</td><td>20 000 €</td><td>120 000 €</td></tr>
<tr><td>Line Ports</td><td>272</td><td>2 500 €/port</td><td>680 000 €</td></tr>
<tr><td>Add Ports</td><td>34</td><td>2 500 €/port</td><td>85 000 €</td></tr>
<tr><td colspan="6">Total Network Cost</td><td>140 867 590 €</td></tr>
</table>

Tabela 6.17: Table with detailed description of CAPEX of Vasco's 2016 results.

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.2. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

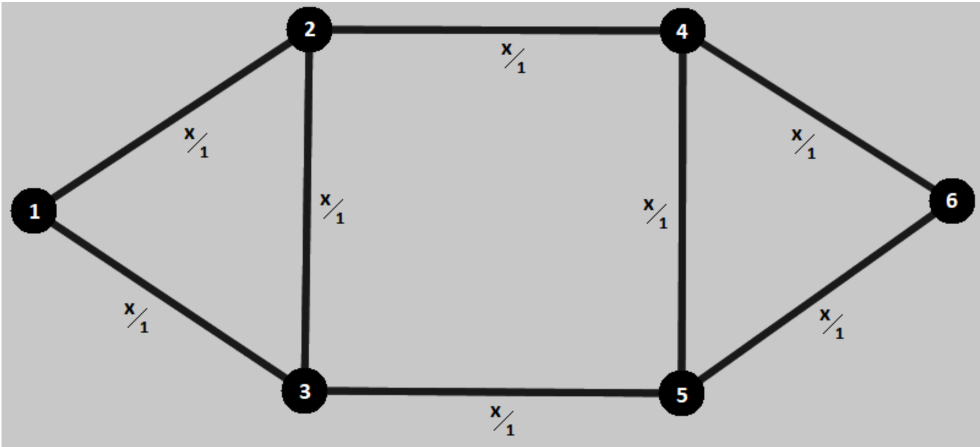


Figura 6.86: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

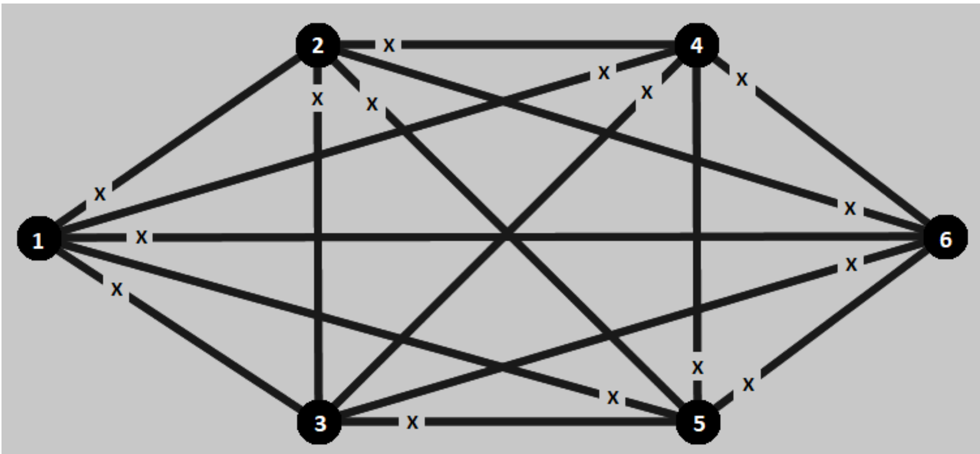


Figura 6.87: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

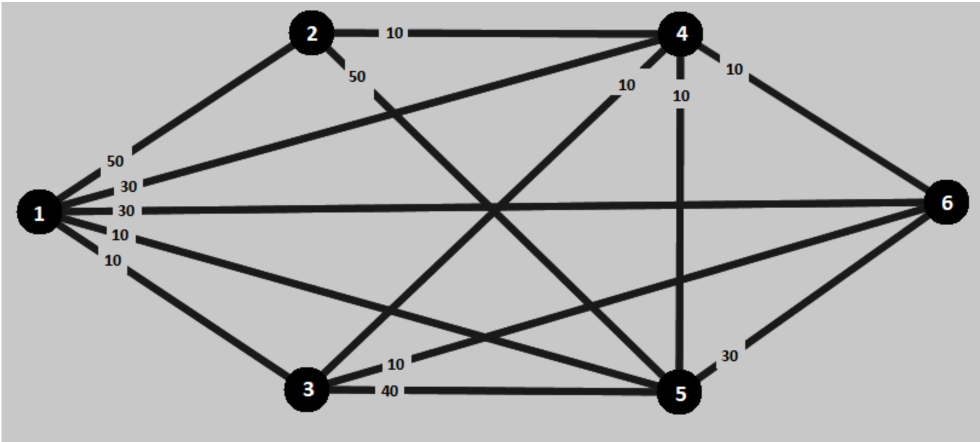


Figura 6.88: ODU0 logical topology defined by the ODU0 traffic matrix.

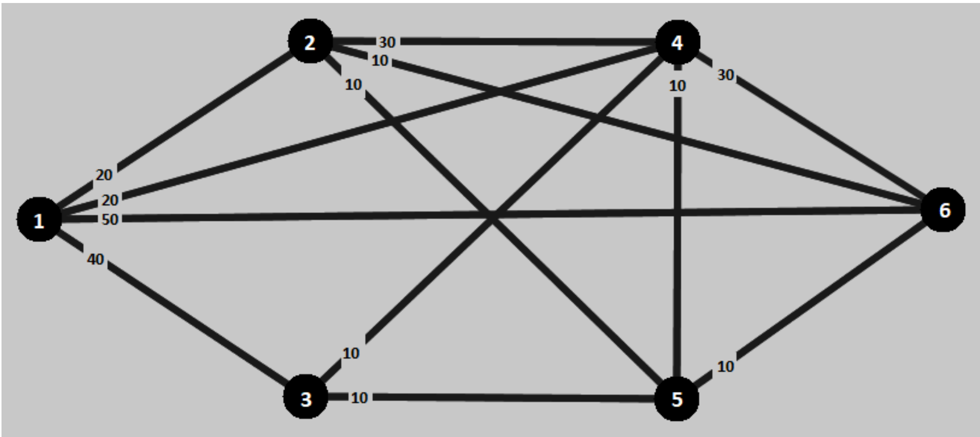


Figura 6.89: ODU1 logical topology defined by the ODU1 traffic matrix.

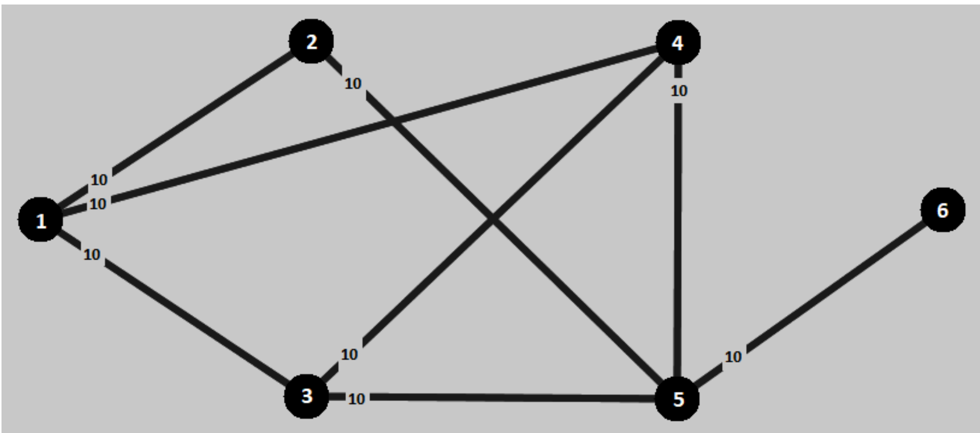


Figura 6.90: ODU2 logical topology defined by the ODU2 traffic matrix.

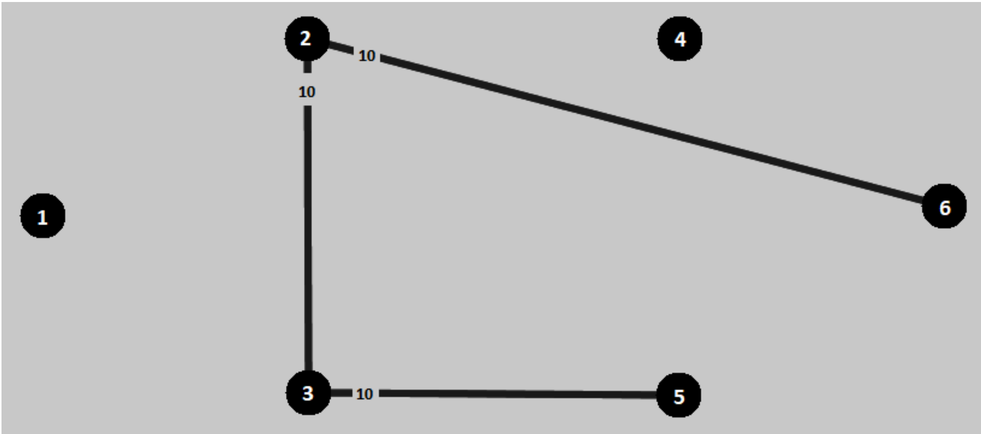


Figura 6.91: ODU3 logical topology defined by the ODU3 traffic matrix.

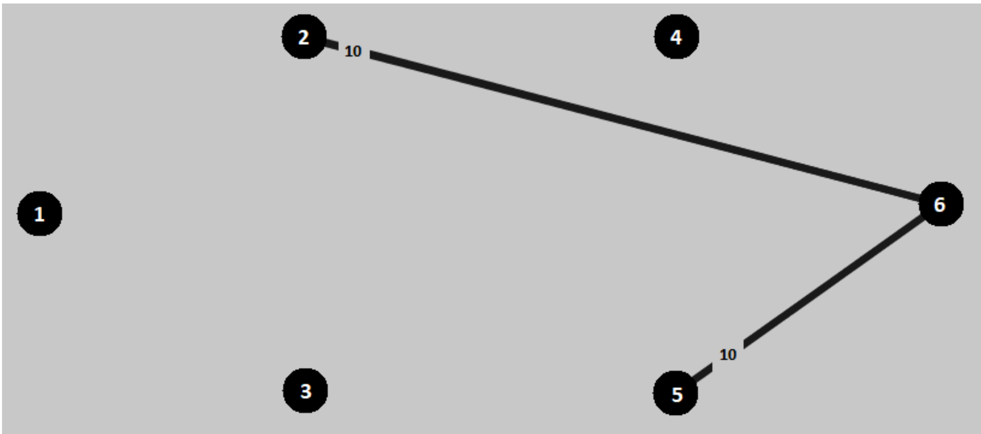


Figura 6.92: ODU4 logical topology defined by the ODU4 traffic matrix.

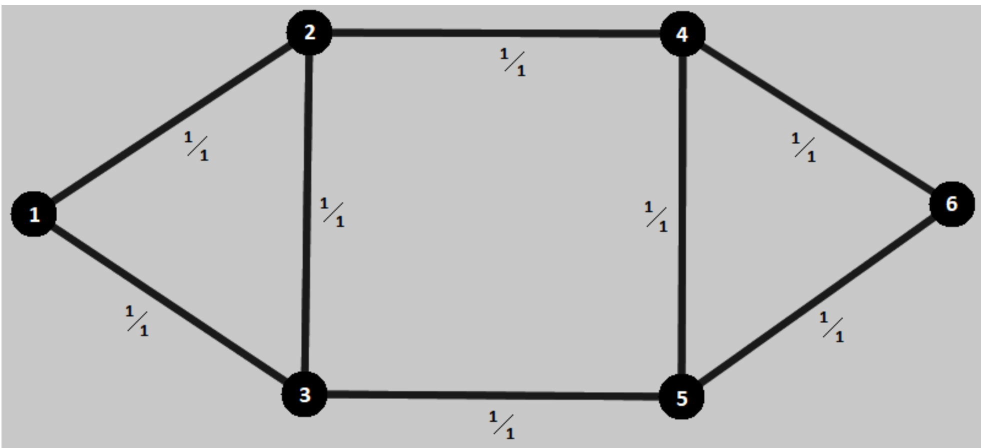


Figura 6.93: Physical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.18. In table 6.13 mentioned in previous model we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	452 520 000 €
	100 Gbits/s Transceivers		452	5 000 €/Gbit/s	226 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	14 150 900 €
		ODU0 Ports	600	10 €/port	6 000 €	
		ODU1 Ports	500	15 €/port	7 500 €	
		ODU2 Ports	160	30 €/port	4 800 €	
		ODU3 Ports	60	60 €/port	3 600 €	
		ODU4 Ports	40	100 €/port	4 000 €	
		Transponders	114	100 000 €/port	11 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	904	2 500 €/port	2 260 000 €	
		Add Ports	114	2 500 €/port	285 000 €	
Total Network Cost						466 670 900 €

Tabela 6.18: Table with detailed description of CAPEX of Vasco's 2016 results.

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.3. In a first phase we will show the various existing topologies of the network. The first are the allowed topologies, physical and optical topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

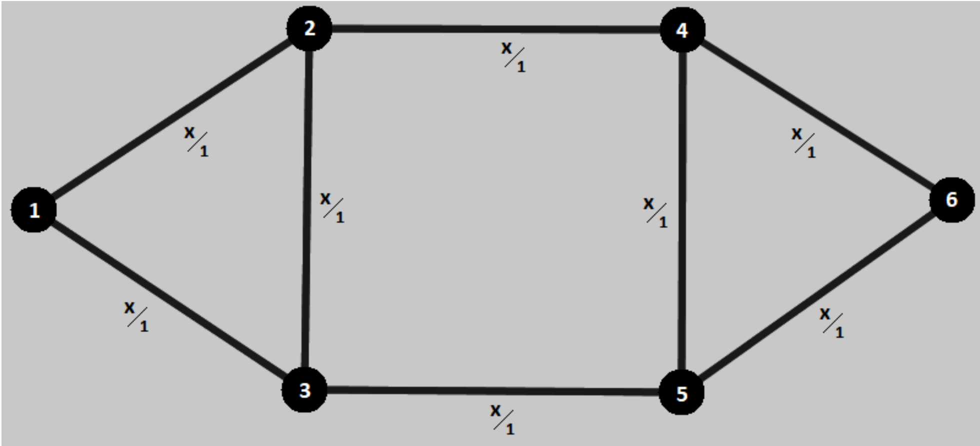


Figura 6.94: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

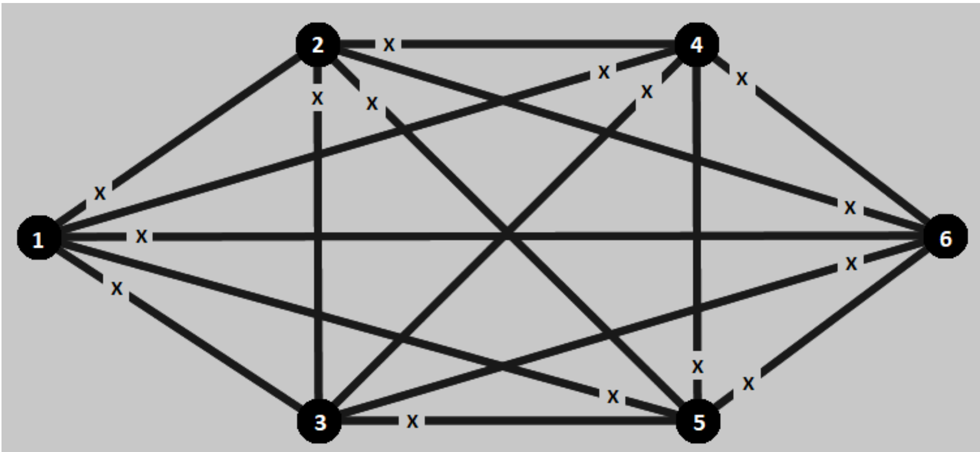


Figura 6.95: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

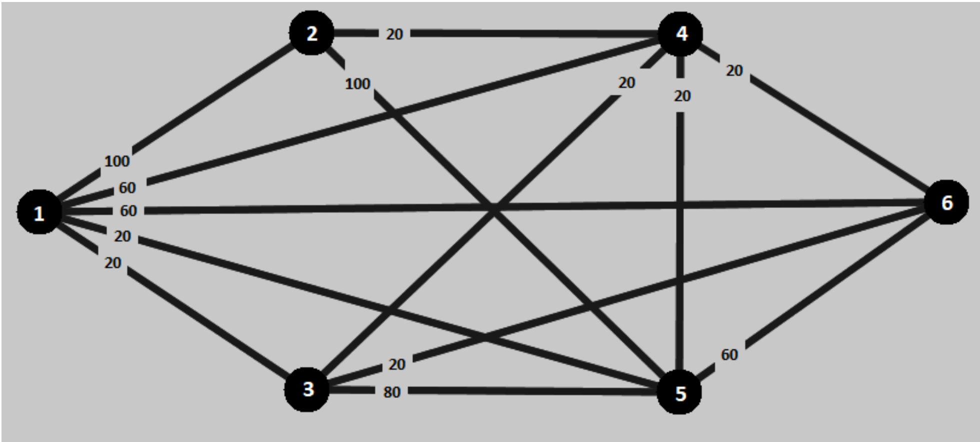


Figura 6.96: ODU0 logical topology defined by the ODU0 traffic matrix.

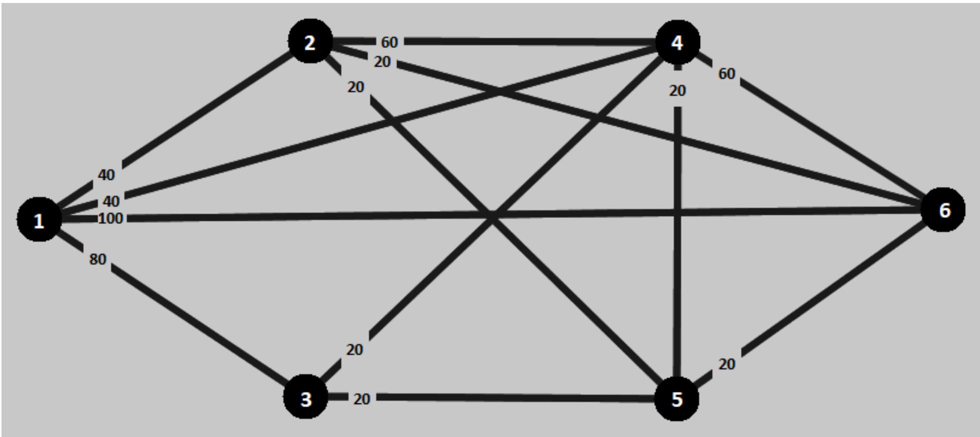


Figura 6.97: ODU1 logical topology defined by the ODU1 traffic matrix.

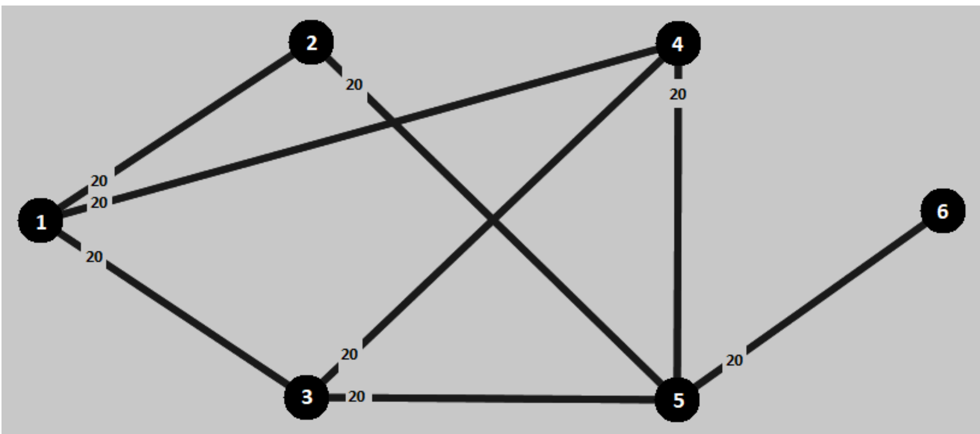


Figura 6.98: ODU2 logical topology defined by the ODU2 traffic matrix.

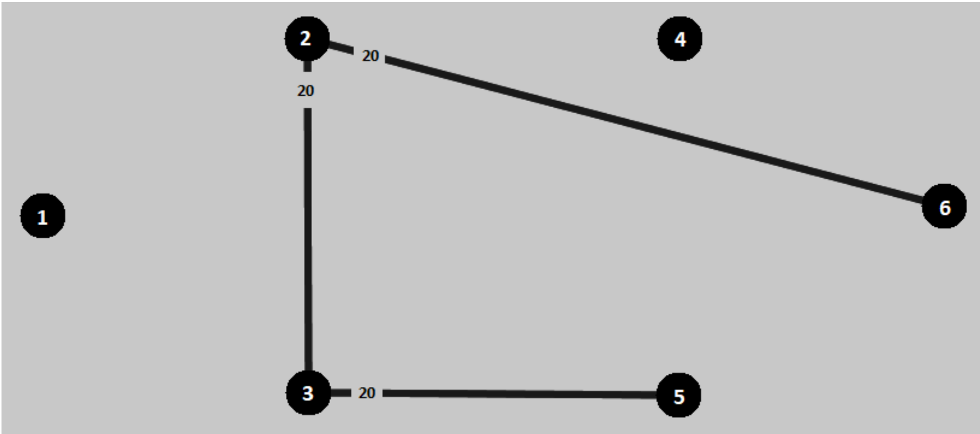


Figura 6.99: ODU3 logical topology defined by the ODU3 traffic matrix.

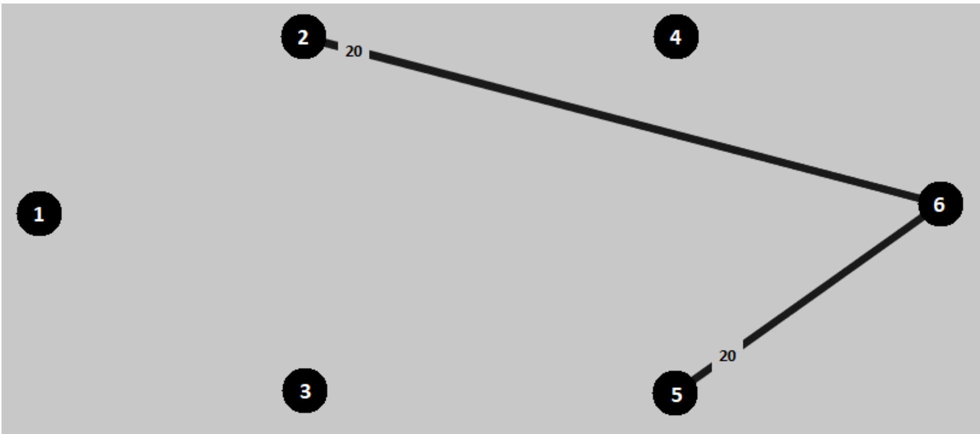


Figura 6.100: ODU4 logical topology defined by the ODU4 traffic matrix.

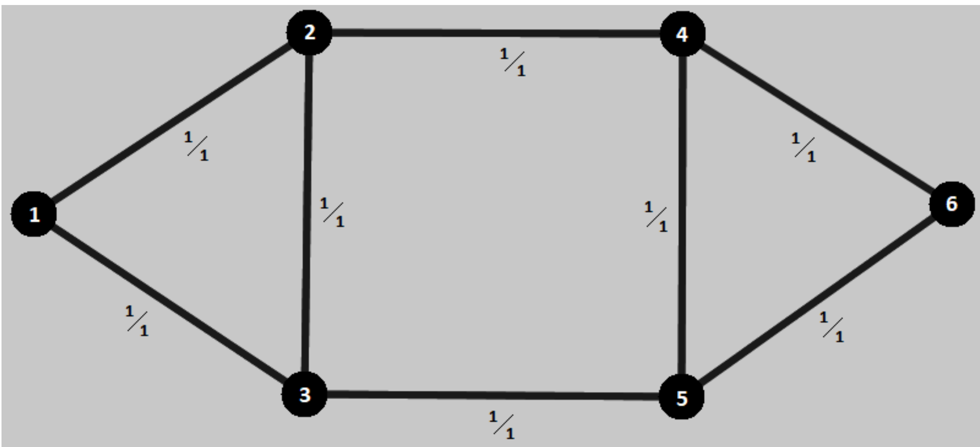


Figura 6.101: Physical topology after dimensioning.

Following all the steps mentioned in the 10.1, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 6.19. In table 6.13 mentioned in previous model we can see how all the values were calculated.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	848 520 000 €
	100 Gbits/s Transceivers		848	5 000 €/Gbit/s	424 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	26 406 800 €
		ODU0 Ports	1 200	10 €/port	12 000 €	
		ODU1 Ports	1 000	15 €/port	15 000 €	
		ODU2 Ports	320	30 €/port	9 600 €	
		ODU3 Ports	120	60 €/port	7 200 €	
		ODU4 Ports	80	100 €/port	8 000 €	
		Transponders	214	100 000 €/port	21 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	1 696	2 500 €/port	4 240 000 €	
		Add Ports	214	2 500 €/port	535 000 €	
Total Network Cost						874 926 800 €

Tabela 6.19: Table with detailed description of CAPEX of Vasco's 2016 results.

Conclusions

Once we have obtained the results for all the scenarios for transparent without survivability and transparent with 1+1 protection we will now draw some conclusions about these results. For a better analysis of the results will be created the table **??** with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

	Low Traffic	Medium Traffic	High Traffic
CAPEX without survivability	56 447 590 €	181 250 900 €	338 256 800 €
CAPEX/Gbit/s without survivability	112 895 €/Gbit/s	36 250 €/Gbit/s	33 825 €/Gbit/s
Traffic (Gbit/s)	500	5 000	10 000
Bidirectional Links used	8	8	8
Number of Add ports	34	114	214
Number of Line ports	272	904	1 696
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	272	904	1 696
Link Cost	136 520 000 €	452 520 000 €	848 520 000 €
Node Cost	4 347 590 €	14 150 900 €	26 406 800 €
CAPEX	**140 867 590 €**	**466 670 900 €**	**874 926 800 €**
CAPEX/Gbit/s	**281 735 €/Gbit/s**	**93 334 €/Gbit/s**	**87 492 €/Gbit/s**

Tabela 6.20: Table with different value of CAPEX for this case.

Looking at the previous table we can make some comparisons between the transparent with 1+1 protection scenario:

- Comparing the low traffic with the others we can see that despite having an increase of factor ten (medium traffic) and factor twenty (high traffic), the same increase does not occur in the final cost (it is lower);

  This happens because the number of the transceivers is lower than expected which leads by carrying the traffic with less network components and, consequently, the network CAPEX is lower;

- Comparing the medium traffic with the high traffic we can see that the increase of the factor is double and in the final cost this factor is very close but still inferior;

  This happens because the number of the transceivers is also lower but very close to the expected;

- Comparing the CAPEX cost per bit we can see that in the low traffic the cost is higher than the medium and high traffic, which in these two cases the value is similar, but still inferior in the higher traffic;

  This happens because the lower the traffic, the higher CAPEX/bit will be. We can see that in medium and high traffic the results tend to be one closer and lower value.

We can also make some comparisons between the transparent without survivability and transparent with 1+1 protection scenarios:

- We can see that in the transparent with 1+1 protection the CAPEX cost for all the three traffic is more than the double;

This happens because in the transparent with 1+1 protection there is a need of having a primary and a backup path, in case of a network failure, and the backup path is typically longer;

- Comparing the CAPEX cost per bit we can see that has a similar case in both of the two scenarios. In the low traffic the cost is higher than the medium and high traffic, which in these two cases the value is similar;

  This happens because the lower the traffic, the higher CAPEX/bit will be. We can see that in medium and high traffic the results tend to be one closer and lower value.

Opens Issues

The creation of this model for any scenario, started with some considerations and some open issues being:

- Allow blocking.

  The presented model assume that the solution is possible or impossible, does not support a partial solution where some demands are not routed (are blocked);

- Allow multiple transmission system.

  The presented model for each link only supports one transmission system.

6.1.5 Translucent without Survivability

Student Name	:	Pedro Coelho (March 01, 2018 -)
Goal	:	Implement the heuristic model for the translucent transport mode without survivability.

Model description

Result description

6.1.6 Translucent with 1+1 Protection

Student Name	:	Pedro Coelho (March 01, 2018 -)
Goal	:	Implement the heuristic model for the translucent transport mode with 1 plus 1 protection.

Model description

Result description

Capítulo 7

Analytical Models

The focus of the current section is to propose and describe a model for the analytical calculation of the network CAPEX, based on the three modes of transport (opaque, transparent and translucent) without survivability and protection.
In the section 7.1, it is described how the CAPEX is calculated in a general way. In the following subsections it is proposed in detail the restrictions of the three previously mentioned models without survivability and with protection as well as a detailed report of the results obtained for each case.

7.1 CAPEX

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement of the analytical model to obtain the best possible CAPEX of a given network.

The cost of a telecommunications network can be divided into CAPEX and OPEX. CAPEX is the amount of money needed to set up and install a particular network. OPEX is the amount of money needed to run this network as well as its maintenance and operation over time. In this section we will only focus on CAPEX, that is, the costs of installing a particular network. As we know the telecommunications networks are made up of links and nodes, so it is possible to define the CAPEX as being the sum of the cost of links and cost of nodes. This can be said that the value of CAPEX is given by the equation 7.1.

$$C_C = C_L + C_N \tag{7.1}$$

- $C_C \rightarrow$ CAPEX cost
- $C_L \rightarrow$ Link cost
- $C_N \rightarrow$ Node cost

For this calculation first let's focus on the cost of the links. Where to calculate the cost of the Links we will use the equation 7.2.

$$C_L = \left(2 \times L \times \gamma_0^{OLT}\right) + \left(2 \times L \times \gamma_1^{OLT} \times \tau \times < w >\right) + \left(N^R \times c^R\right) \tag{7.2}$$

- $C_L \rightarrow$ Links cost
- $\gamma_0^{OLT} \rightarrow$ OLT cost in euros
- $L \rightarrow$ Number of unidirectional links
- $\gamma_1^{OLT} \rightarrow$ Transponder cost in euros
- $< w > \rightarrow$ Average number of optical channels
- $\tau \rightarrow$ Traffic per port
- $N^R \rightarrow$ Total number of optical amplifiers
- $c^R \rightarrow$ Optical amplifiers cost in euros

Looking at the equation 7.2 we can see that we already have practically all the values of the variables used. Assuming that τ is 100 Gbits/s is thus only missing the number of optical amplifiers and the number of optical channels where they can be calculated by equation 7.3 and 7.4 respectively.

$$N^R = \sum_{l=1}^{L} \left(\left\lceil \frac{len_l}{span} \right\rceil - 1 \right) \tag{7.3}$$

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

$$< w >= \left(\frac{\lceil D\times < h > \rceil}{L} \right) \times (1+ < k >) \tag{7.4}$$

- $< w > \rightarrow$ Average number of optical channels
- $D \rightarrow$ Number of bidirectional demands
- $L \rightarrow$ Number of Links
- $< k > \rightarrow$ Survivability coefficient

where:

$$D = \left(\frac{1}{2} \right) \times (1 + \xi) \times \left(\frac{T_1}{\tau} \right) \tag{7.5}$$

- $D \rightarrow$ Number of bidirectional demands
- $\xi \rightarrow$ Coefficient
- $T_1 \rightarrow$ Total unidirectional traffic
- $\tau \rightarrow$ Traffic per port

The next step is to take into account the cost of the nodes, but for this we must first know how a node is constituted. The nodes have an electrical part and an optical part so we can conclude that the cost of the nodes is given by the sum of these two parts thus obtaining the equation 7.6.

$$C_N = C_{EXC} + C_{OXC} \tag{7.6}$$

To know the electric cost of the nodes that is given by equation 7.7.

$$C_{exc} = N \times (\gamma_{e0} + (\gamma_{e1} \times \tau\times < P_{exc} >)) \tag{7.7}$$

- $C_{exc} \rightarrow$ Electrical ports cost
- $N \rightarrow$ Number of nodes
- $\gamma_{e0} \rightarrow$ EXC cost in euros
- $\gamma_{e1} \rightarrow$ EXC port cost in euros
- $\tau \rightarrow$ Traffic per port
- $< P_{exc} > \rightarrow$ Average number of ports of the electrical switch

In relation to the optical part to know the optical cost of the nodes that is given by equation 7.8.

$$C_{oxc} = N \times (\gamma_{o0} + (\gamma_{o1} \times < P_{oxc} >)) \tag{7.8}$$

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

We have to take into account that the calculated value for the variable $< P_{exc} >$ and $< P_{oxc} >$ will depend on the mode of transport used (opaque, transparent or translucent) but later on it will be explained how these values are calculated for each specific transport mode. Finally, for this we will also have to take into account the cost of the equipment used that can be consulted in table 7.1.

Equipment	Cost
OLT without transponders	15000 €
Transponder	5000 €/Gb
Optical Amplifier	4000 €
EXC	10000 €
OXC	20000 €
EXC Port	1000 €/Gb/s
OXC Port	2500 €/porto

Tabela 7.1: Table with costs

7.1.1 Opaque without Survivability

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the analytical model for the opaque transport mode without survivability.

Model description

Before carrying out the detailed description we must take into account the following peculiarities of this mode of transport:

- C_{oxc} = 0
- ξ = 1
- $< k >$ = 0

The first particularity exists because in this mode of transport there is no optical cost, in the case of the second we are assuming that the coefficient has value 1 and finally in the last particularity we are assuming that the survivability coefficient is zero because it is without survivability.

Finally looking at the equation 7.7 we can see that we already have practically all the values with the exception of the average number of ports the electrical switch,$< P_{exc} >$, that can be calculated as

$$< P_{exc} >=< d > \times[1 + (1+ < k >) \times < h >] \tag{7.9}$$

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

The variable $< d >$ is calculated through the equation 7.10.

$$< d >= \frac{2 \times D}{N} \tag{7.10}$$

Result description

We already have all the necessary formulas to obtain the CAPEX value for the reference network 10.1. As described in the subsection of network traffic 4.2, we have three values of network traffic (low, medium and high traffic) so we have to obtain three different CAPEX.

Low Traffic Scenario:
In this scenario we have to take into account the traffic calculated in 4.2.1.

Using equation 7.5:

$D = \frac{1}{2} * (1 + 1) * (\frac{1000}{100})$ $\quad\quad$ $D = 10$

Replacing in equation 7.4:

$< w > = (\frac{10*1.533}{8}) * (1 + 0)$ $\quad\quad$ $< w > = 2$

Using equation 7.3:

$N^R = (\frac{460}{100}\text{-}1) + (\frac{640}{100}\text{-}1) + (\frac{75}{100}\text{-}1) + (\frac{684}{100} \text{-}1) + (\frac{890}{100}\text{-}1) + (\frac{103}{100}\text{-}1) + (\frac{761}{100}\text{-}1) + (\frac{361}{100}\text{-}1)$

$N^R = 35$

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 2) + (35 * 4 000)

C_L = **16 380 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d > = \frac{2*10}{6}$ $\quad\quad$ $< d > = 3.333$

Replacing in equation 7.9:

$< P_{exc} >$ = 3.333 * [1 + (1 + 0) * 1.533] $\quad\quad$ $< P_{exc} >$ = 8.4425

Finally, replacing all in equation 7.7 the Node Cost is:

$C_N = C_{exc}$ = 6 * (10 000 + (1 000 * 100 * 8.4425))

C_N = **5 125 500 €**

The CAPEX is:
$CAPEX$ = 16 380 000 + 5 125 500

$CAPEX$ = **21 505 500 €**

Medium Traffic Scenario
In this scenario we have to take into account the traffic calculated in 4.2.2.

Using equation 7.5:

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

replacing in equation 7.4:

$< w >$ = ($\frac{100*1.533}{8}$) * (1 + 0) $< w >$ = 19.25

Using equation 7.3:

N^R = ($\frac{460}{100}$-1) + ($\frac{640}{100}$-1) + ($\frac{75}{100}$-1) + ($\frac{684}{100}$ -1) + ($\frac{890}{100}$-1) + ($\frac{103}{100}$-1) + ($\frac{761}{100}$-1) + ($\frac{361}{100}$-1)

N^R = 35

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 19.25) + (35 * 4 000)

C_L = **154 380 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d >$ = $\frac{2*100}{6}$ $< d >$ = 33.333

Replacing in equation 7.9:

$< P_{exc} >$ = 33.333 * [1 + (1 + 0) * 1.533] $< P_{exc} >$ = 84.4325

Finally, replacing all in equation 7.7 the Node Cost is:

C_N = C_{exc} = 6 * (10 000 + (1 000 * 100 * 84.4325))

C_N = **50 719 500 €**

The CAPEX is:
$CAPEX$ = 154 380 000 + 50 719 500

$CAPEX$ = **211 099 500 €**

High Traffic Scenario
In this scenario we have to take into account the traffic calculated in 4.2.3.

Using equation 7.5:

$D = \frac{1}{2} * (1 + 1) * (\frac{20000}{100})$ $\qquad$ $D = 200$

replacing in equation 7.4:

$< w > = (\frac{200*1.533}{8}) * (1 + 0)$ $\qquad$ $< w > = 38.375$

Using equation 7.3:

$N^R = (\frac{460}{100}\text{-}1) + (\frac{640}{100}\text{-}1) + (\frac{75}{100}\text{-}1) + (\frac{684}{100} \text{-}1) + (\frac{890}{100}\text{-}1) + (\frac{103}{100}\text{-}1) + (\frac{761}{100}\text{-}1) + (\frac{361}{100}\text{-}1)$

$N^R = 35$

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 38.375) + (35 * 4 000)

C_L = **307 380 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d > = \frac{2*200}{6}$ $\qquad$ $< d > = 66.667$

Replacing in equation 7.9:

$< P_{exc} >$ = 66.667 * [1 + (1 + 0) * 1.533] $\qquad$ $< P_{exc} >$ = 168.8675

Finally, replacing all in equation 7.7 the Node Cost is:

$C_N = C_{exc}$ = 6 * (10 000 + (1 000 * 100 * 168.8675))

C_N = **101 380 500 €**

The CAPEX is:
$CAPEX$ = 307 380 000 + 101 380 500

$CAPEX$ = **408 760 500 €**

7.1.2 Opaque with 1+1 Protection

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the analytical model for the opaque transport mode with 1 plus 1 protection.

Model description

Before carrying out the detailed description we must take into account the following peculiarities of this mode of transport:

- $C_{oxc} = 0$
- $\xi = 1$
- $< k > = < kp >$

The first particularity exists because in this mode of transport there is no optical cost, in the case of the second we are assuming that the coefficient has value 1 and finally in the last particularity we are assuming that the survivability coefficient is $< kp >$ because it is with protection 1+1 where

$$< kp >= \frac{< h' >}{< h >} \tag{7.11}$$

Finally looking at the equation 7.7 we can see that we already have practically all the values with the exception of the average number of ports the electrical switch,$< P_{exc} >$, that can be calculated as

$$< P_{exc} >=< d > \times[1 + (1+ < k >) \times < h >] \tag{7.12}$$

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

Result description

We already have all the necessary formulas to obtain the CAPEX value for the reference network 10.1. As described in the subsection of network traffic 4.2, we have three values of network traffic (low, medium and high traffic) so we have to obtain three different CAPEX. First for all scenarios we have to take into account the survivability coefficient 7.11.

$< kp > = \frac{2.467}{1.533} = 1.609$

Low Traffic Scenario:
In this scenario we have to take into account the traffic calculated in 4.2.1.

Using equation 7.5:

D = $\frac{1}{2}$ * (1 + 1) * ($\frac{1000}{100}$) D = 10

Replacing in equation 7.4:

$< w >$ = ($\frac{10*1.533}{8}$) * (1 + 1.609) $< w >$ = 5.218

Using equation 7.3:

N^R = ($\frac{460}{100}$-1) + ($\frac{640}{100}$-1) + ($\frac{75}{100}$-1) + ($\frac{684}{100}$ -1) + ($\frac{890}{100}$-1) + ($\frac{103}{100}$-1) + ($\frac{761}{100}$-1) + ($\frac{361}{100}$-1)

N^R = 35

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 5.218) + (35 * 4 000)

C_L = **42 124 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d >$ = $\frac{2*10}{6}$ $< d >$ = 3.333

Replacing in equation 7.12:

$< P_{exc} >$ = 3.333 * [1 + (1 + 1.609) * 1.533] $< P_{exc} >$ = 16.6637

Finally, replacing all in equation 7.7 the Node Cost is:

C_N = C_{exc} = 6 * (10 000 + (1 000 * 100 * 16.6637))

C_N = **10 058 220 €**

The CAPEX is:
$CAPEX$ = 42 124 000 + 10 058 220

$CAPEX$ = **52 182 220 €**

Medium Traffic Scenario

In this scenario we have to take into account the traffic calculated in 4.2.2.

Using equation 7.5:

$D = \frac{1}{2} * (1 + 1) * (\frac{10000}{100})$ $\qquad$ $D = 100$

Replacing in equation 7.4:

$< w > = (\frac{100*1.533}{8}) * (1 + 1.609)$ $\qquad$ $< w > = 50.22$

Using equation 7.3:

$N^R = (\frac{460}{100}-1) + (\frac{640}{100}-1) + (\frac{75}{100}-1) + (\frac{684}{100} -1) + (\frac{890}{100}-1) + (\frac{103}{100}-1) + (\frac{761}{100}-1) + (\frac{361}{100}-1)$

$N^R = 35$

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 50.22) + (35 * 4 000)

C_L = **402 140 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d > = \frac{2*100}{6}$ $\qquad$ $< d > = 33.333$

Replacing in equation 7.12:

$< P_{exc} > = 33.333 * [1 + (1 + 1.609) * 1.533]$ $\qquad$ $< P_{exc} > = 166.6516$

Finally, replacing all in equation 7.7 the Node Cost is:

$C_N = C_{exc}$ = 6 * (10 000 + (1 000 * 100 * 166.6516))

C_N = **100 050 960 €**

The CAPEX is:

$CAPEX$ = 402 140 000 + 100 050 960

$CAPEX$ = **502 190 960 €**

High Traffic Scenario
In this scenario we have to take into account the traffic calculated in 4.2.3.

Using equation 7.5:

D = $\frac{1}{2}$ * (1 + 1) * ($\frac{20000}{100}$) D = 200

Replacing in equation 7.4:

$< w >$ = ($\frac{200*1.533}{8}$) * (1 + 1.609) $< w >$ = 100.120

Using equation 7.3:

N^R = ($\frac{460}{100}$-1) + ($\frac{640}{100}$-1) + ($\frac{75}{100}$-1) + ($\frac{684}{100}$ -1) + ($\frac{890}{100}$-1) + ($\frac{103}{100}$-1) + ($\frac{761}{100}$-1) + ($\frac{361}{100}$-1)

N^R = 35

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 100.120) + (35 * 4 000)

C_L = **800 960 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d >$ = $\frac{2*200}{6}$ $< d >$ = 66.667

Replacing in equation 7.12:

$< P_{exc} >$ = 66.667 * [1 + (1 + 1.609) * 1.533] $< P_{exc} >$ = 333.3081

Finally, replacing all in equation 7.7 the Node Cost is:

C_N = C_{exc} = 6 * (10 000 + (1 000 * 100 * 333.3081))

C_N = **200 044 860 €**

The CAPEX is:
$CAPEX$ = 800 960 000 + 200 044 860

$CAPEX$ = **1 001 004 860 €**

7.1.3 Transparent without Survivability

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the analytical model for the transparent transport mode without survivability.

Model description

Before carrying out the detailed description we must take into account the following peculiarities of this mode of transport:

- $\xi = 2$
- $< k > = 0$

The first particularity exists because we are assuming that the coefficient has value 2 and finally in the last particularity we are assuming that the survivability coefficient is zero because it is without survivability.

Finally looking at the equation 7.7 we can see that we already have practically all the values with the exception of the average number of ports the electrical switch and the average number of ports the optical switch.

The average number of ports the electrical switch,$< P_{exc} >$, can be calculated as

$$< P_{exc} >= 2 < d > \tag{7.13}$$

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

$$< P_{oxc} >=< d > \times[1 + (1+ < k >) \times < h >] \tag{7.14}$$

Result description

We already have all the necessary formulas to obtain the CAPEX value for the reference network 10.1. As described in the subsection of network traffic 4.2, we have three values of network traffic (low, medium and high traffic) so we have to obtain three different CAPEX.

Low Traffic Scenario:
In this scenario we have to take into account the traffic calculated in 4.2.1.

Using equation 7.5:

$D = \frac{1}{2} * (1 + 2) * (\frac{1000}{100})$ $D = 15$

Replacing in equation 7.4:

$< w > = (\frac{15*1.533}{8}) * (1 + 0)$ $< w > = 2.875$

Using equation 7.3:

$N^R = 35$

Finally, replacing all in equation 7.2 the Link Cost is:

$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 2.875) + (35 * 4\,000)$

$C_L =$ **23 380 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d > = \frac{2*15}{6}$ $< d > = 5$

Replacing in equation 7.13 and 7.14:

$< P_{exc} > = 2 * 5 = 10$

$< P_{oxc} > = 5 * [1 + (1 + 0) * 1.533]$ $< P_{oxc} > = 12.665$

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

$C_N = C_{exc} + C_{oxc} = (6 * (10000 + (1000 * 100 * 10))) + (6 * (20000 + (2500 * 12.665)))$

$C_N = 6\,060\,000 + 309\,975 =$ **6 369 975 €**

The CAPEX is:
$CAPEX = 23\,380\,000 + 6\,369\,975$

$CAPEX =$ **29 749 975 €**

Medium Traffic Scenario:
In this scenario we have to take into account the traffic calculated in 4.2.2.

Using equation 7.5:

D = $\frac{1}{2}$ * (1 + 2) * ($\frac{10000}{100}$) D = 150

Replacing in equation 7.4:

$< w >$ = ($\frac{150*1.533}{8}$) * (1 + 0) $< w >$ = 28.75

Using equation 7.3:

N^R = 35

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 28.75) + (35 * 4 000)

C_L = **230 380 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d >$ = $\frac{2*150}{6}$ $< d >$ = 50

Replacing in equation 7.13 and 7.14:

$< P_{exc} >$ = 2 * 50 = 100

$< P_{oxc} >$ = 50 * [1 + (1 + 0) * 1.533] $< P_{oxc} >$ = 126.65

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

C_N = C_{exc} + C_{oxc} = $(6 * (10000 + (1000 * 100 * 100)))$ + $(6 * (20000 + (2500 * 126.65)))$

C_N = 60 060 000 + 2 019 750 = **62 079 750 €**

The CAPEX is:
$CAPEX$ = 230 380 000 + 62 079 750

$CAPEX$ = **292 459 750 €**

High Traffic Scenario:
In this scenario we have to take into account the traffic calculated in 4.2.3.

Using equation 7.5:

$D = \frac{1}{2} * (1 + 2) * (\frac{20000}{100})$ $D = 300$

Replacing in equation 7.4:

$< w > = (\frac{300*1.533}{8}) * (1 + 0)$ $< w > = 57.5$

Using equation 7.3:

$N^R = 35$

Finally, replacing all in equation 7.2 the Link Cost is:

$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 57.5) + (35 * 4\,000)$

C_L = **460 380 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d > = \frac{2*300}{6}$ $< d > = 100$

Replacing in equation 7.13 and 7.14:

$< P_{exc} > = 2 * 100 = 200$

$< P_{oxc} > = 100 * [1 + (1 + 0) * 1.533]$ $< P_{oxc} > = 253.3$

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

$C_N = C_{exc} + C_{oxc} = (6 * (10000 + (1000 * 100 * 200))) + (6 * (20000 + (2500 * 253.3)))$

C_N = 120 060 000 + 3 919 500 = **123 979 500 €**

The CAPEX is:
$CAPEX$ = 460 380 000 + 123 979 500

$CAPEX$ = **584 359 500 €**

7.1.4 Transparent with 1+1 Protection

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the analytical model for the transparent transport mode with 1 plus 1 protection.

Model description

Before carrying out the detailed description we must take into account the following peculiarities of this mode of transport:

- $\xi = 2$
- $< k > = < kp >$

The first particularity exists because we are assuming that the coefficient has value 2 and finally in the last particularity we are assuming that the survivability coefficient is $< kp >$ because it is with protection 1+1 where this variable are represented in equation 7.11.

Finally looking at the equation 7.7 we can see that we already have practically all the values with the exception of the average number of ports the electrical switch and the average number of ports the optical switch.

The average number of ports the electrical switch,$< P_{exc} >$, can be calculated as

$$< P_{exc} >= 2 < d > \tag{7.15}$$

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

$$< P_{oxc} >=< d > \times[1 + (1+ < k >) \times < h >] \tag{7.16}$$

Result description

We already have all the necessary formulas to obtain the CAPEX value for the reference network 10.1. As described in the subsection of network traffic 4.2, we have three values of network traffic (low, medium and high traffic) so we have to obtain three different CAPEX.

First for all scenarios we have to take into account the survivability coefficient 7.11.

$< kp >$ = $\frac{2.467}{1.533}$ = 1.609

Low Traffic Scenario:
In this scenario we have to take into account the traffic calculated in 4.2.1.

Using equation 7.5:

D = $\frac{1}{2}$ * (1 + 2) * ($\frac{1000}{100}$) D = 15

Replacing in equation 7.4:

$< w >$ = ($\frac{15*1.533}{8}$) * (1 + 1.609) $< w >$ = 7.501

Using equation 7.3:

N^R = 35

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 7.501) + (35 * 4 000)

C_L = **60 388 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d >$ = $\frac{2*15}{6}$ $< d >$ = 5

Replacing in equation 7.13 and 7.14:

$< P_{exc} >$ = 2 * 5 = 10

$< P_{oxc} >$ = 5 * [1 + (1 + 1.609) * 1.533] $< P_{oxc} >$ = 24.998

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

C_N = C_{exc} + C_{oxc} = $(6 * (10000 + (1000 * 100 * 10)))$ + $(6 * (20000 + (2500 * 24.998)))$

C_N = 6 060 000 + 494 970 = **6 554 970 €**

The CAPEX is:
$CAPEX$ = 60 388 000 + 6 554 970

$CAPEX$ = **66 942 970 €**

Medium Traffic Scenario:
In this scenario we have to take into account the traffic calculated in 4.2.2.

Using equation 7.5:

$D = \frac{1}{2} * (1 + 2) * (\frac{10000}{100})$ $D = 150$

Replacing in equation 7.4:

$< w >$ = ($\frac{150*1.533}{8}$) * (1 + 1.609) $< w >$ = 75.009

Using equation 7.3:

N^R = 35

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 75.009) + (35 * 4 000)

C_L = **600 452 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d > = \frac{2*150}{6}$ $< d >$ = 50

Replacing in equation 7.13 and 7.14:

$< P_{exc} >$ = 2 * 50 = 100

$< P_{oxc} >$ = 50 * [1 + (1 + 1.609) * 1.533] $< P_{oxc} >$ = 249.980

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

$C_N = C_{exc} + C_{oxc} = (6 * (10000 + (1000 * 100 * 100))) + (6 * (20000 + (2500 * 249.980)))$

C_N = 60 060 000 + 3 869 700 = **63 929 700 €**

The CAPEX is:
$CAPEX$ = 600 452 000 + 63 929 700

$CAPEX$ = **664 381 700 €**

High Traffic Scenario:
In this scenario we have to take into account the traffic calculated in 4.2.3.

Using equation 7.5:

D = $\frac{1}{2}$ * (1 + 2) * ($\frac{20000}{100}$) D = 300

Replacing in equation 7.4:

$< w >$ = ($\frac{300*1.533}{8}$) * (1 + 1.609) $< w >$ = 150.018

Using equation 7.3:

N^R = 35

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 150.018) + (35 * 4 000)

C_L = **1 200 524 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d >$ = $\frac{2*300}{6}$ $< d >$ = 100

Replacing in equation 7.13 and 7.14:

$< P_{exc} >$ = 2 * 100 = 200

$< P_{oxc} >$ = 100 * [1 + (1 + 1.609) * 1.533] $< P_{oxc} >$ = 499.9597

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

C_N = C_{exc} + C_{oxc} = $(6 * (10000 + (1000 * 100 * 200))) + (6 * (20000 + (2500 * 499.9597)))$

C_N = 120 060 000 + 7 619 396 = **127 679 396 €**

The CAPEX is:
$CAPEX$ = 1 200 524 000 + 127 679 396

$CAPEX$ = **1 328 203 396 €**

7.1.5 Translucent without Survivability

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the analytical model for the translucent transport mode without survivability.

7.1.6 Translucent with 1+1 Protection

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Implement the analytical model for the translucent transport mode with 1 plus 1 protection.

Capítulo 8

Comparative Analysis

8.1 Opaque without Survivability

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Comparative analysis of the results of the models used for the opaque transport mode without survivability.

In this section we will compare the CAPEX values obtained for the three scenarios in the three types of dimensioning. For a better analysis of the results will be created the table 8.1 (scenario 1), the table 8.2 (scenario 2) and the table 8.3 (scenario 3) with the different values obtained.

Low traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	16 380 000 €	9 404 000 €	12 020 000 €
Node Cost	5 125 500 €	1 862 590 €	2 362 590 €
CAPEX	**21 505 500 €**	**11 266 590 €**	**14 382 590 €**

Tabela 8.1: Table with different value of CAPEX

Medium traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	154 380 000 €	75 520 000 €	77 020 000 €
Node Cost	50 719 500 €	15 085 900 €	15 385 900 €
CAPEX	**205 099 500 €**	**90 605 900 €**	**92 405 900 €**

Tabela 8.2: Table with different value of CAPEX

High traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	307 380 000 €	148 520 000 €	149 020 000 €
Node Cost	101 380 500 €	29 711 800 €	29 814 200 €
CAPEX	**408 760 500 €**	**178 231 800 €**	**178 834 200 €**

Tabela 8.3: Table with different value of CAPEX

8.2 Opaque with 1+1 Protection

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Comparative analysis of the results of the models used for the opaque transport mode with 1 plus 1 protection.

In this section we will compare the CAPEX values obtained for the three scenarios in the three types of dimensioning. For a better analysis of the results will be created the table 8.4 (scenario 1), the table 8.5 (scenario 2) and the table 8.6 (scenario 3) with the different values obtained.

Low traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	42 124 000 €	22 520 000 €	23 520 000 €
Node Cost	10 058 220 €	4 462 590 €	4 662 590 €
CAPEX	**52 182 220 €**	**26 982 590 €**	**28 182 590 €**

Tabela 8.4: Table with different value of CAPEX

Medium traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	402 140 000 €	199 520 000 €	199 520 000 €
Node Cost	100 050 960 €	39 885 900 €	39 885 900 €
CAPEX	**502 190 960 €**	**239 405 900 €**	**239 405 590 €**

Tabela 8.5: Table with different value of CAPEX

High traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	800 960 000 €	397 520 000 €	397 520 000 €
Node Cost	200 044 860 €	79 511 800 €	79 514 200 €
CAPEX	**1 001 004 860 €**	**477 031 800 €**	**477 034 200 €**

Tabela 8.6: Table with different value of CAPEX

8.3 Transparent without Survivability

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Comparative analysis of the results of the models used for the transparent transport mode without survivability.

In this section we will compare the CAPEX values obtained for the three scenarios in the three types of dimensioning. For a better analysis of the results will be created the table 8.7 (scenario 1), the table 8.8 (scenario 2) and the table 8.9 (scenario 3) with the different values obtained.

Low traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	23 380 000 €	26 520 000 €	26 520 000 €
Node Cost	6 369 975 €	5 727 590 €	3 797 590 €
CAPEX	**29 749 975 €**	**32 247 590 €**	**30 317 590 €**

Tabela 8.7: Table with different value of CAPEX

Medium traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	230 380 000 €	84 520 000 €	84 520 000 €
Node Cost	62 079 750 €	16 885 900 €	15 180 900 €
CAPEX	**292 459 750 €**	**102 650 900 €**	**99 700 900 €**

Tabela 8.8: Table with different value of CAPEX

High traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	460 380 000 €	157 520 000 €	157 520 000 €
Node Cost	123 979 500 €	31 511 800 €	28 486 800 €
CAPEX	**584 359 500 €**	**191 256 800 €**	**186 006 800 €**

Tabela 8.9: Table with different value of CAPEX

8.4 Transparent with 1+1 Protection

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Comparative analysis of the results of the models used for the transparent transport mode with 1 plus 1 protection.

In this section we will compare the CAPEX values obtained for the three scenarios in the three types of dimensioning. For a better analysis of the results will be created the table 8.10 (scenario 1), the table 8.11 (scenario 2) and the table 8.12 (scenario 3) with the different values obtained.

Low traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	60 380 000 €	68 520 000 €	68 520 000 €
Node Cost	6 554 970 €	14 547 590 €	4 007 590 €
CAPEX	**66 942 970 €**	**83 067 590 €**	**72 527 590 €**

Tabela 8.10: Table with different value of CAPEX

Medium traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	600 452 000 €	€	226 520 000 €
Node Cost	63 929 700 €	€	15 890 900 €
CAPEX	**664 381 700 €**	**€**	**242 410 900 €**

Tabela 8.11: Table with different value of CAPEX

High traffic scenario:

	Analytical	ILP	Heuristic
Link Cost	1 200 524 000 €	€	424 520 000 €
Node Cost	127 679 396 €	€	29 821 800 €
CAPEX	**1 328 203 396 €**	**€**	**454 341 800 €**

Tabela 8.12: Table with different value of CAPEX

8.5 Translucent without Survivability

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Comparative analysis of the results of the models used for the translucent transport mode without survivability.

8.6 Translucent with 1+1 Protection

Student Name	:	Tiago Esteves (October 03, 2017 -)
Goal	:	Comparative analysis of the results of the models used for the translucent transport mode with 1 plus 1 protection.

Capítulo 9

Case Studies

9.1 Opaque without Survivability - European Optical Network

In this case study we focus on the opaque case without survivability for the realistic network. The opaque transport mode performs OEO (optical-electric-optical) conversions on each intermediate node from the source to the destination node. One advantage of this mode of transport is that it eliminates accumulation of physical impairments, and allows optimum grooming by performing grooming at each node.

9.1.1 Physical Network Topology

Student Name	:	Tiago Esteves (October 03, 2017 -)

The real network chosen for this work is the EON (European Optical Network).

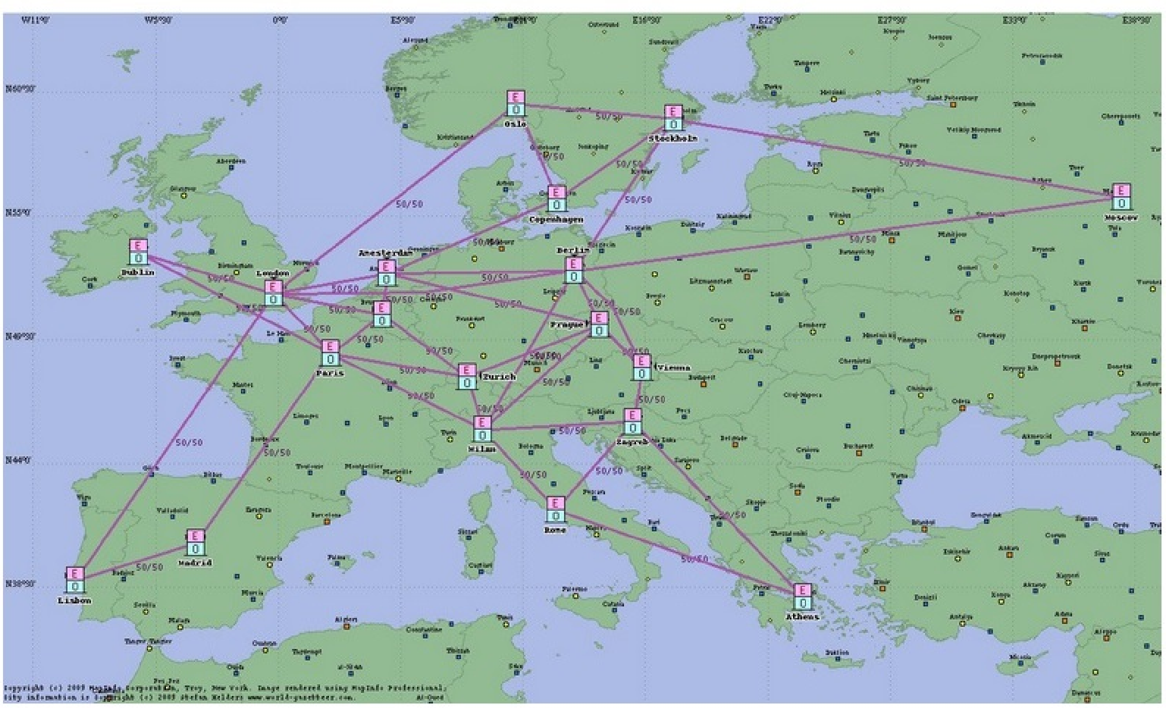


Figura 9.1: Physical topology of the realistic network.

In this real case we have take into consideration the table 9.1 because it is through it that we can see the values of the variables associated with this network.

Constant	Description	Value
N	Number of nodes	19
L	Number of bidirectional links	37
$<\delta>$	Node out-degree	3.89
<len>	Mean link length (km)	753.76
<h>	Mean number of hops for working paths	2.3
<h'>	Mean number of hops for backup paths	3.2

Tabela 9.1: Table of realistic network values

Through the previous figure we can see how nodes are organized geographically and the distance matrix created on the next page is constructed based on real distances between them. For a better understanding of the distances matrix the table 9.2 was created to assign to each city a number of a node in the network.

City	Node
Oslo	1
Stockholm	2
Moscow	3
Copenhagen	4
Berlin	5
Prague	6
Vienna	7
Zagreb	8
Athens	9
Rome	10
Milan	11
Zurich	12
Brussels	13
Amesterdan	14
London	15
Dublin	16
Paris	17
Madrid	18
Lisbon	19

Tabela 9.2: Table of city and respective node

The values indicated in the distance matrix, referred to below, are expressed in kilometers (Km). For this network we must also create matrices of ODU's to determine the total traffic used in each scenario but in this case only the matrices for low traffic are elucidated.

$$Dist = \begin{pmatrix}
0 & 417 & 0 & 484 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1155 & 0 & 0 & 0 & 0 \\
417 & 0 & 1228 & 523 & 811 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1228 & 0 & 0 & 1611 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
484 & 523 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 622 & 0 & 0 & 0 & 0 & 0 \\
0 & 811 & 1611 & 0 & 0 & 281 & 524 & 0 & 0 & 0 & 843 & 0 & 0 & 577 & 933 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 281 & 0 & 251 & 0 & 0 & 0 & 646 & 527 & 0 & 712 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 524 & 251 & 0 & 268 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 268 & 0 & 1081 & 518 & 530 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1081 & 0 & 1052 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 518 & 1052 & 0 & 477 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 843 & 646 & 0 & 530 & 0 & 477 & 0 & 219 & 0 & 0 & 0 & 0 & 640 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 646 & 0 & 0 & 0 & 0 & 219 & 0 & 493 & 0 & 0 & 0 & 488 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 493 & 0 & 173 & 321 & 0 & 264 & 0 & 0 \\
0 & 0 & 0 & 622 & 577 & 712 & 0 & 0 & 0 & 0 & 0 & 0 & 173 & 0 & 358 & 0 & 0 & 0 & 0 \\
1155 & 0 & 0 & 0 & 933 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 321 & 358 & 0 & 464 & 344 & 0 & 1587 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 464 & 0 & 782 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 640 & 488 & 264 & 0 & 344 & 782 & 0 & 1054 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1054 & 0 & 503 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1587 & 0 & 0 & 503 & 0
\end{pmatrix}$$

$$ODU0 = \begin{bmatrix}
0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

$$ODU1 = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

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

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

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

In the traffic matrices each ODU, referred previously, has its respective value being that the ODU0 corresponds to 1.25 Gbits/s, ODU1 to 2.5 Gbits/s, ODU2 to 10 Gbits/s, ODU3 to 40 Gbits/s and finally the ODU4 corresponds to 100 Gbits/s. As we can see these matrices are bidirectional because they are symmetric matrices and as such the traffic sent in one direction must be the same traffic sent in the opposite direction.

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

T_1^0 = 240x1.25 = 300 Gbits/s $\quad$ T_1^1 = 200x2.5 = 500 Gbits/s $\quad$ T_1^2 = 64x10 = 640 Gbits/s

T_1^3 = 24x40 = 960 Gbits/s $\quad$ T_1^4 = 16x100 = 1600 Gbits/s

T_1 = 300 + 500 + 640 + 960 + 1600 = 4000 Gbits/s $\quad$ T = 4000/2 = 2 Tbits/s

Where the variable T_1^x represents the unidirectional traffic of the ODUx, for example, T_1^3 represents the unidirectional traffic of the ODU3 and T_1^4 represents the unidirectional traffic of the ODU4. The variable T_1 represents the total of unidirectional traffic that is injected into the network and finally the variable T represents the total of bidirectional traffic.

Again, we can thus conclude that the total traffic for the two scenarios is as follows:

- Low Traffic: **2 TBits/s**
- High Traffic: **20 TBits/s**

9.1.2 Dimensioning using Analytical Model

Student Name	:	Tiago Esteves (October 03, 2017 -)

In this section we will do the dimensioning of the network mentioned in the previous subsection to calculate the value of your CAPEX, for this we will use the analytical formulations so as to obtain the best solution but for this we will also have to take into account the cost of the equipment used that can be consulted in table **??**. The formulas and calculations needed for the CAPEX of the network are the same as in the previous case (reference network) and therefore only the results obtained will be presented.

As described in the subsection of the network topology we have two values of network traffic, low traffic and high traffic, soon we will get two different CAPEX. Finally we have to take into account that as it is the opaque transport mode, the value of ξ is 1 and because it is without survivability, the value of $< k >$ is 0. Then we can rewrite the equations.

Scenario 1: Realistic Network Low Traffic

Using equation 7.5:

$D = \frac{1}{2} * (1 + 1) * (\frac{4000}{100})$ $D = 40$

Replacing in equation 7.4:

$< w > = (\frac{40*2.3}{37}) * (1 + 0)$ $< w > = 3$

Using equation 7.3:

$N^R \backsimeq$ L * $< N^R >$

$< N^R > = \frac{<len>}{span} - 1$

$< N^R > = \frac{<753.76>}{100} - 1$

$N^R = 259$

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 37 * 15000) + (2 * 37 * 5000 * 100 * 3) + (259 * 4000)

C_L = **113 146 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d >$ = $\frac{2*40}{19}$ $< d >$ = 4.21

Replacing in equation 7.9:

P_{exc} = 4.21 * [1 + (1 + 0) * 2.3] P_{exc} = 13.893

Finally, replacing all in equation 7.7 the Node Cost is:

C_N = C_{exc} = 19 * (10000 + (1000 * 100 * 13.893))

C_N = **26 589 700 €**

The CAPEX is:
$CAPEX$ = 113 146 000 + 26 589 700

$CAPEX$ = **139 732 700 €**

Scenario 2: Reference Network High Traffic

Using equation 7.5:

D = $\frac{1}{2}$ * (1 + 1) * ($\frac{40000}{100}$) D = 400

replacing in equation 7.4:

$< w >$ = ($\frac{400*2.3}{37}$) * (1 + 0) $< w >$ = 25

Finally, replacing all in equation 7.2 the Link Cost is:

C_L = (2 * 37 * 15000) + (2 * 37 * 5000 * 100 * 25) + (259 * 4000)

C_L = **927 146 000 €**

In relation to the cost of the nodes we first use the equation 7.10:

$< d >$ = $\frac{2*400}{19}$ $< d >$ = 42.105

Replacing in equation 7.9:

P_{exc} = 42.105 * [1 + (1 + 0) * 2.3] P_{exc} = 138.9465

Finally, replacing all in equation 7.7 the Node Cost is:

C_N = C_{exc} = 19 * (10000 + (1000 * 100 * 138.9465))

C_N = **246 188 350 €**

The CAPEX is:
$CAPEX$ = 927 146 000 + 246 188 350

$CAPEX$ = **1 191 334 350 €**

9.1.3 Dimensioning using ILP

Student Name	:	Tiago Esteves (October 03, 2017 -)

In this section we will do the dimensioning of the network mentioned in the previous section to calculate the value of your CAPEX. The initial subsection is the same as the subsection of the previous case so in this case it will be omitted presenting only the subsection of the results.

Scenario 1: Realistic Network Low Traffic

This real network consists of many nodes and with many links between them as such the lpsolve takes immense time to get an optimal solution. Therefore, in this two cases, the execution time was defined as being two days (48 hours) and after that time presented the best solution. In this scenario we used the table 9.1 and in the table 9.3 we can see the values calculated through MatLab and using the values indicated in table **??** we can finally calculate the CAPEX value.

Using equation **??** :
C_L = (2 * 15 000 * 37) + (2 * 5 000 * 100 *) + (* 4 000)
C_L = **€**

Using equation **??** :
C_{exc} = (19 * 10 000) + 1 000 * (4 000 + (2 * * 100))
C_N = C_{exc} = **€**

$CAPEX$ = + = **€**

Number of optical channels	Value
in link (1,2)	
in link (1,4)	
in link (1,15)	
in link (2,3)	
in link (2,4)	
in link (2,5)	
in link (3,5)	
in link (4,14)	
in link (5,6)	
in link (5,7)	
in link (5,11)	
in link (5,14)	
in link (5,15)	
in link (6,7)	
in link (6,11)	
in link (6,12)	
in link (6,14)	
in link (7,8)	
in link (8,9)	
in link (8,10)	
in link (8,11)	
in link (9,10)	
in link (10,11)	
in link (11,12)	
in link (11,17)	
in link (12,13)	
in link (12,17)	
in link (13,14)	
in link (13,15)	
in link (13,17)	
in link (14,15)	
in link (15,16)	
in link (15,17)	
in link (15,19)	
in link (16,17)	
in link (17,18)	
in link (18,19)	

Tabela 9.3: Table with results

Scenario 2: Realistic Network High Traffic
In this scenario we used again the table 9.1 and in the table 9.4 we can see the values calculated through MatLab and using the values indicated in table **??** we can finally calculate the CAPEX value.

Using equation **??** :
C_L = (2 * 15 000 * 37) + (2 * 5 000 * 100 *) + (24 * 4 000)
C_L = €

Using equation **??** :
C_{exc} = (19 * 10 000) + 1 000 * (40 000 + (2 * 100 *))
C_N = C_{exc} = €

$CAPEX$ = + = €

9.1.4 Dimensioning using Heuristics

Heuristics Results

9.1.5 Comparative Analysis

Number of optical channels	Value
in link (1,2)	
in link (1,4)	
in link (1,15)	
in link (2,3)	
in link (2,4)	
in link (2,5)	
in link (3,5)	
in link (4,14)	
in link (5,6)	
in link (5,7)	
in link (5,11)	
in link (5,14)	
in link (5,15)	
in link (6,7)	
in link (6,11)	
in link (6,12)	
in link (6,14)	
in link (7,8)	
in link (8,9)	
in link (8,10)	
in link (8,11)	
in link (9,10)	
in link (10,11)	
in link (11,12)	
in link (11,17)	
in link (12,13)	
in link (12,17)	
in link (13,14)	
in link (13,15)	
in link (13,17)	
in link (14,15)	
in link (15,16)	
in link (15,17)	
in link (15,19)	
in link (16,17)	
in link (17,18)	
in link (18,19)	

Tabela 9.4: Table with results

9.2 Opaque with 1+1 Protection - European Optical Network

In this case study we focus on the opaque case with 1+1 protection for the realistic network.

9.2.1 Physical Network Topology

Student Name	:	Tiago Esteves (October 03, 2017 -)

The real network chosen for this work is the EON (European Optical Network).

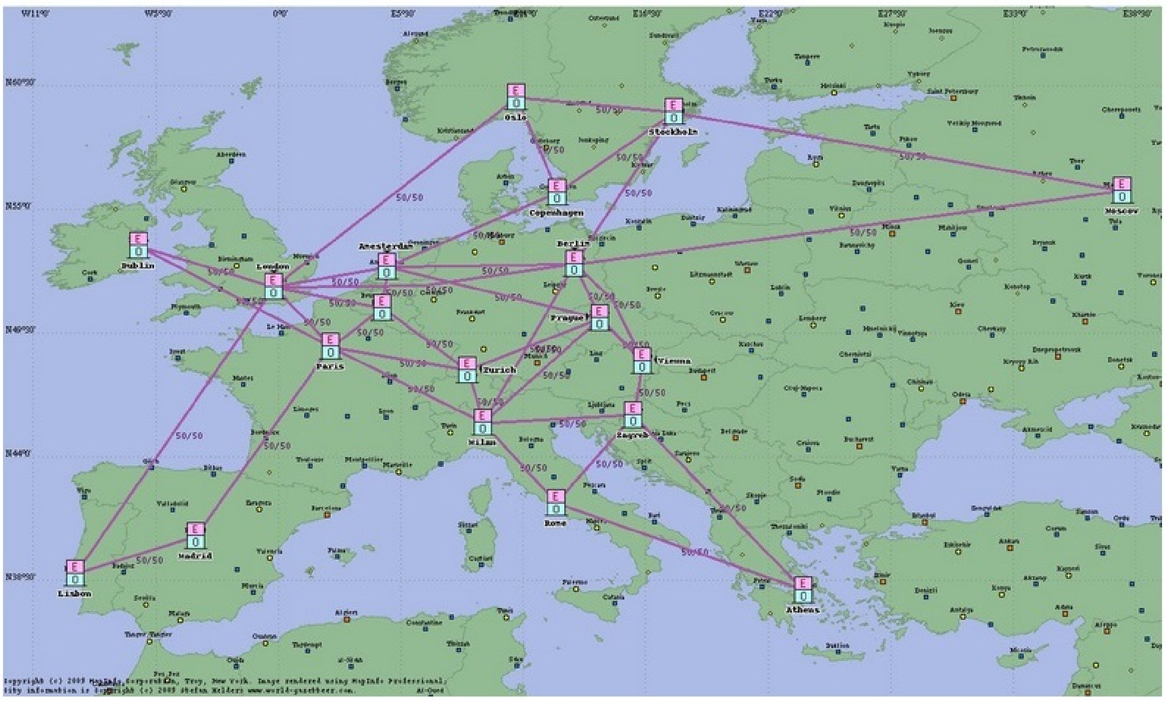


Figura 9.2: Physical topology of the realistic network.

Since the realistic network used in this case has already been mentioned previously in section 9.1 we can assume that the table 9.1 is the same and the table 9.2 where each city contains a number of a node in the network also is the same.
The distance matrix constructed based on real distances between cities and the matrices of ODU's are also the same. Finally, the total traffic for the two scenarios are:
Low Traffic: **2 TBits/s**; High Traffic: **20 TBits/s**;

9.2.2 Dimensioning using ILP

Student Name	:	Tiago Esteves (October 03, 2017 -)

The initial subsection is the same as the subsection of the previous case so in this case it will be omitted presenting only the subsection of the results. In this section we will do the dimensioning of the network mentioned in the previous section to calculate the value of your CAPEX, for this we will use the ILP model describe in section 5.1.2. This real network consists of many nodes and with many links between them as such the lpsolve takes immense time to get an optimal solution. Therefore, in this case, the execution time was defined as being two days (48 hours) and after that time presented the best solution.

Scenario 1: Realistic Network Low Traffic

In this scenario we used the table 9.1 and in the table 9.5 we can see the values calculated through MatLab and using the values indicated in table **??** we can finally calculate the CAPEX value.

Using equation **??** :
C_L = (2 * 15 000 * 37) + (2 * 5 000 * 100 * 111) + (24 * 4 000)
C_L = **112 206 000€**

Using equation **??** :
C_{exc} = (19 * 10 000) + 1 000 * (4 000 + (2 * 111 * 100))
C_N = C_{exc} = **26 390 000 €**

$CAPEX$ = 112 206 000 + 26 390 000 = **138 596 000 €**

Scenario 2: Realistic Network High Traffic

In this scenario we used again the table 9.1 and in the table 9.6 we can see the values calculated through MatLab and using the values indicated in table **??** we can finally calculate the CAPEX value.

Using equation **??** :
C_L = (2 * 15 000 * 37) + (2 * 5 000 * 100 * 1538) + (24 * 4 000)
C_L = **1 539 206 000 €**

Using equation **??** :
C_{exc} = (19 * 10 000) + 1 000 * (40 000 + (2 * 100 * 1538))
C_N = C_{exc} = **347 790 000€**

$CAPEX$ = 1 539 206 000 + 347 790 000 = **1 886 996 000€**

Number of optical channels	Value
in link (1,2)	4
in link (1,4)	4
in link (1,15)	2
in link (2,3)	3
in link (2,4)	5
in link (2,5)	5
in link (3,5)	3
in link (4,14)	2
in link (5,6)	3
in link (5,7)	6
in link (5,11)	3
in link (5,14)	1
in link (5,15)	4
in link (6,7)	3
in link (6,11)	2
in link (6,12)	1
in link (6,14)	2
in link (7,8)	4
in link (8,9)	2
in link (8,10)	2
in link (8,11)	3
in link (9,10)	2
in link (10,11)	2
in link (11,12)	1
in link (11,17)	4
in link (12,13)	2
in link (12,17)	2
in link (13,14)	1
in link (13,15)	1
in link (13,17)	2
in link (14,15)	1
in link (15,16)	2
in link (15,17)	4
in link (15,19)	7
in link (16,17)	2
in link (17,18)	7
in link (18,19)	7

Tabela 9.5: Table with results

Number of optical channels	Value
in link (1,2)	80
in link (1,4)	80
in link (1,15)	80
in link (2,3)	50
in link (2,4)	49
in link (2,5)	69
in link (3,5)	32
in link (4,14)	15
in link (5,6)	80
in link (5,7)	80
in link (5,11)	45
in link (5,14)	24
in link (5,15)	27
in link (6,7)	80
in link (6,11)	80
in link (6,12)	55
in link (6,14)	39
in link (7,8)	45
in link (8,9)	20
in link (8,10)	28
in link (8,11)	36
in link (9,10)	20
in link (10,11)	13
in link (11,12)	8
in link (11,17)	35
in link (12,13)	19
in link (12,17)	28
in link (13,14)	27
in link (13,15)	3
in link (13,17)	6
in link (14,15)	41
in link (15,16)	17
in link (15,17)	18
in link (15,19)	64
in link (16,17)	17
in link (17,18)	64
in link (18,19)	64

Tabela 9.6: Table with results

9.2.3 Dimensioning using Heuristics

Heuristics Results

9.2.4 Comparative Analysis

Capítulo 10

Appendices

10.1 Net2Plan Guide

This first section will describe how to install Net2Plan and some of the solvers.

Net2Plan Download and Installation

In the software folder (NetPlanner/software/net2plan) there is a stable version of all required installers or programs. Before downloading Net2Plan, the first step is to verify if the computer has the necessary Java Runtime Environment. The Java Runtime Environment is necessary as Net2Plan was coded in Java. Version 8 or later is recommended. In the software folder you can find an installer for the Java SE Runtime Environment 8 Update 151, file JavaSetup8u151.exe. The latest available version can be found in the Java website at https://java.com/en/download/. Having installed the Java Environment it is now possible to run the Net2Plan software program. It is possible to run Net2Plan (version 0.4.2) directly from the folder NetPlanner/software/net2plan-0.4.2. There is also available a zip file from which the program can be extracted and then executed. The program can be started just by double clicking on the "File Net2Plan.jar" or, alternatively, by right clicking the "File Net2Plan.jar → Open With → Java(TM) Platform SE binary". The latest available version can be also found in the Net2Plan website at http://net2plan.com/download.php.

Figura 10.1: Net2Plan v0.4.2. opening menu.

Net2Plan Options and Solvers Instalation

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.

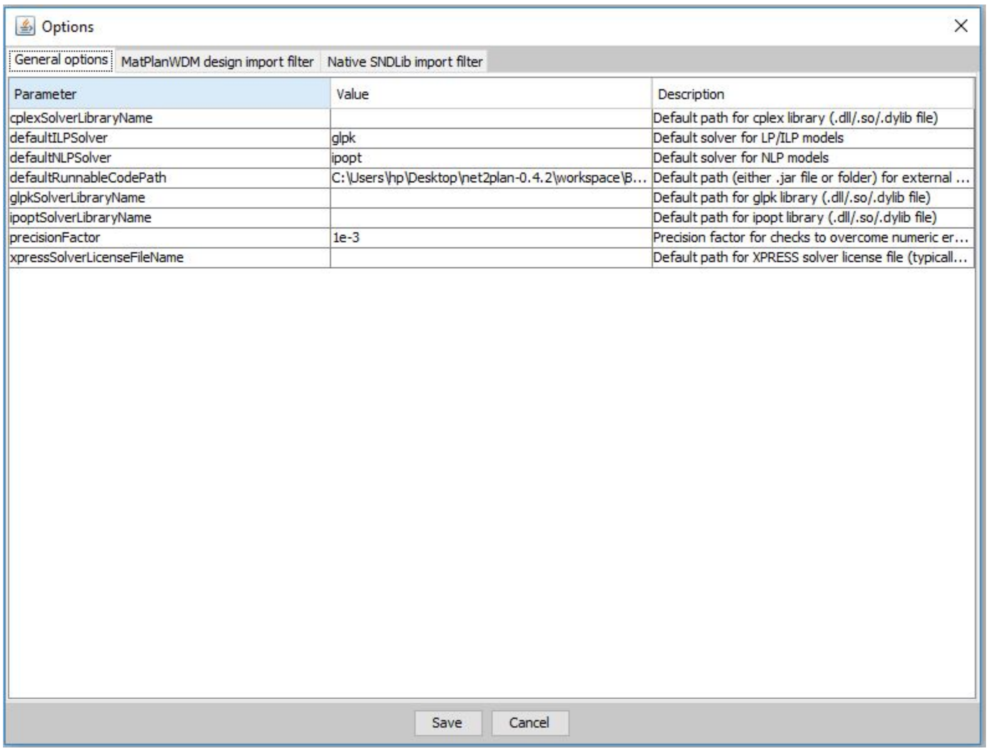


Figura 10.2: Net2Plan v0.4.2. general options.

These external solvers are not extracted along with Net2Plan and as such, they need to be downloaded if needed for the algorithms to be used.

Net2Plan Tools and Configuration

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

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 10.3.

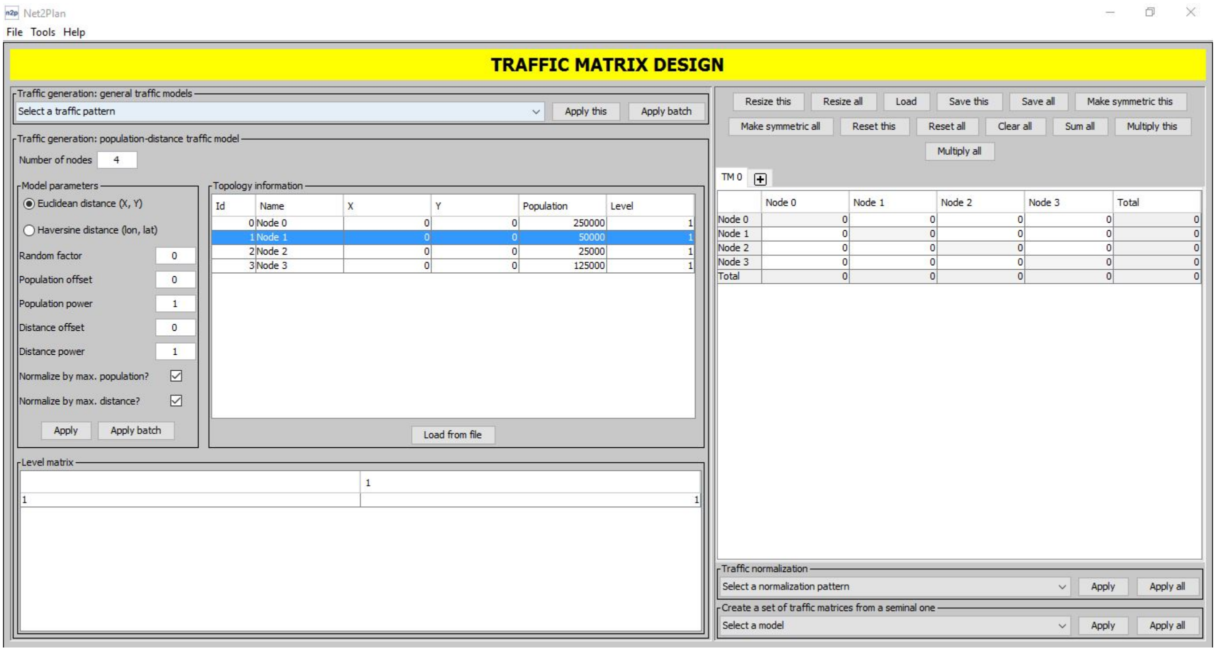


Figura 10.3: Net2Plan traffic matrix design.

On the top left side a traffic pattern can be chosen for one matrix or several matrixes 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 values by a constant number chosen. A point to note is that most options has an "all" choice as it is possible to have more than 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 10.4 shows how to create batch of matrices with constant traffic.

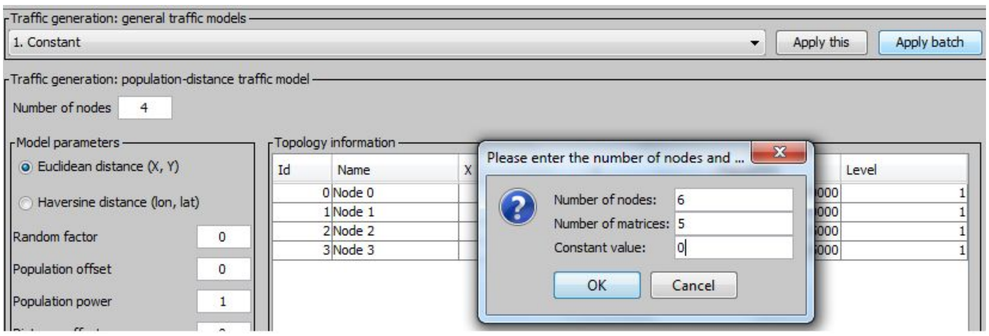
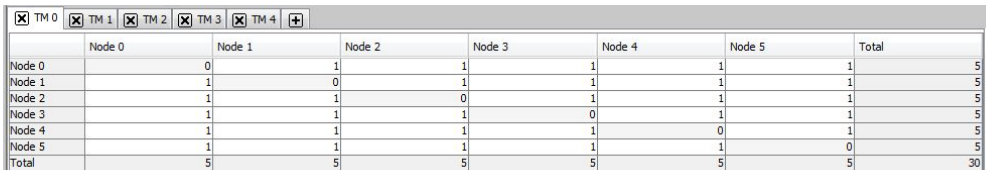


Figura 10.4: Net2Plan example on creating a batch of matrices.

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 10.5 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

Figura 10.5: 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 of them. These can then be saved individually and will further on be used as traffic matrices for ODU's 0 through 4. The traffic matrices can be saved by clicking on the "Save all" button and choose a destination path.

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 10.6.

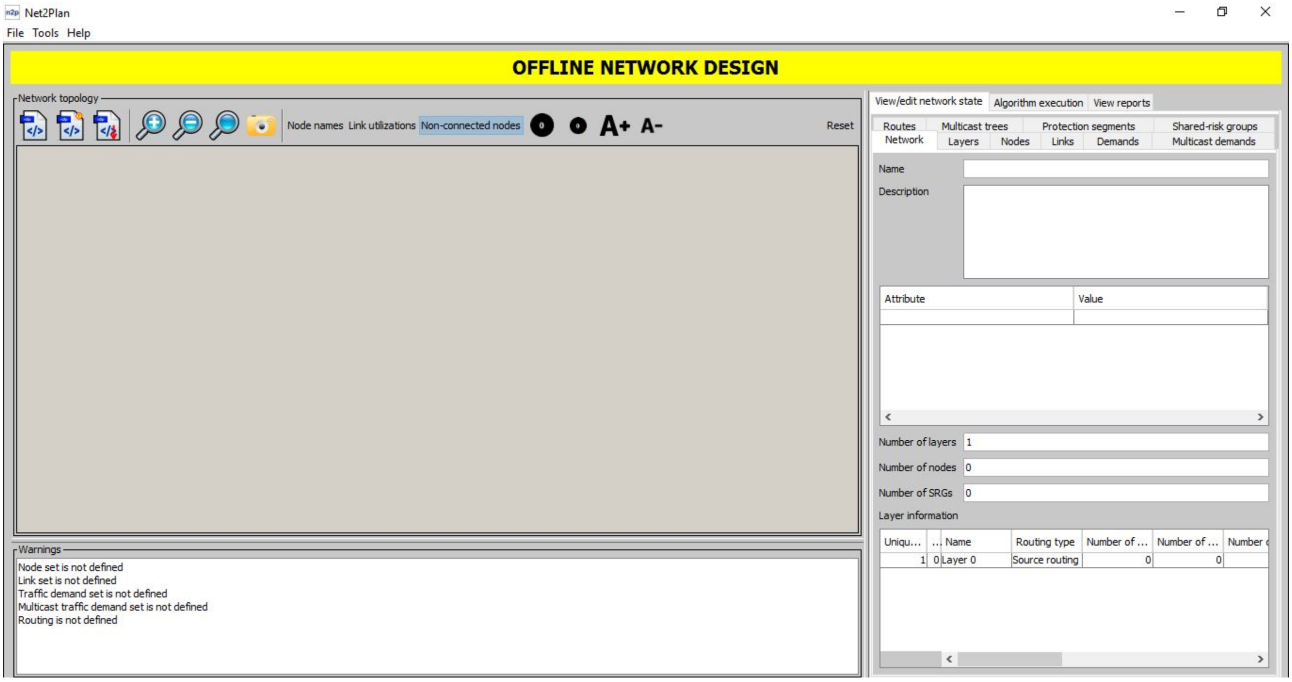


Figura 10.6: Net2Plan Offline Network Design

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 create 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 10.7 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.

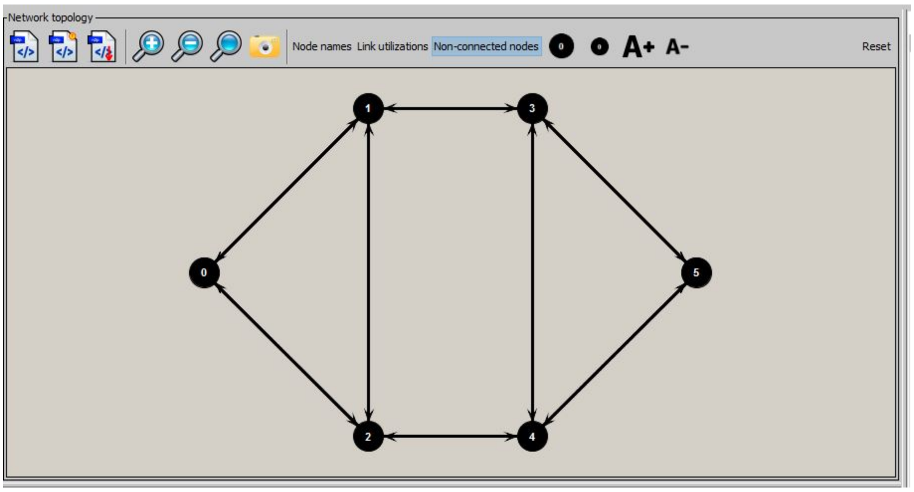


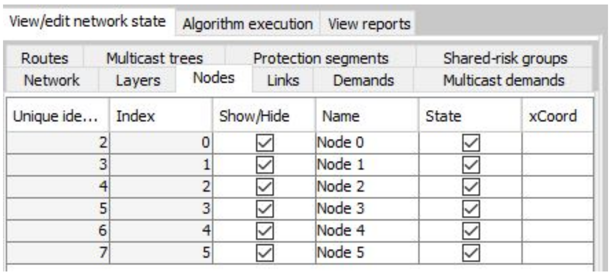
Figura 10.7: Net2Plan network example.

The links and nodes parameters created for the network can be visualized and modified as seen on figures 10.8(a) and 10.8(b) displaying the tabs for each case.

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.

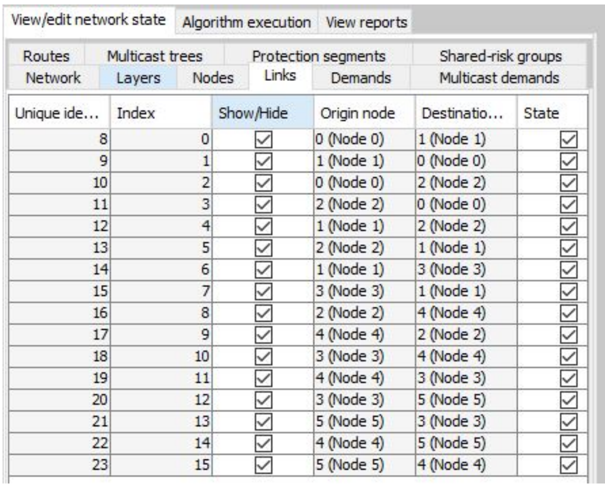
On the links tab, again most is at 0 at this moment while the parameters that can be manually set are the link capacity, at 0 until defined and the link length which was set to the same value in every link.

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 "ODUs" in order to have all the traffic in the same units. Besides converting the different ones to just one "ODUs", it also creates an attribute in



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) 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) b

Figura 10.8: Network a) Nodes tab ; b) Links tab

each demand indicating the type of the signal before converting. This attribute can be seen on the demands tab after loading the resulting demand list. Figure 10.9 shows the algorithm to be used.

As can be seen on Figure 10.9 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 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, i.e, it now needs a routing and grooming algorithm for the traffic to be carried on the network.

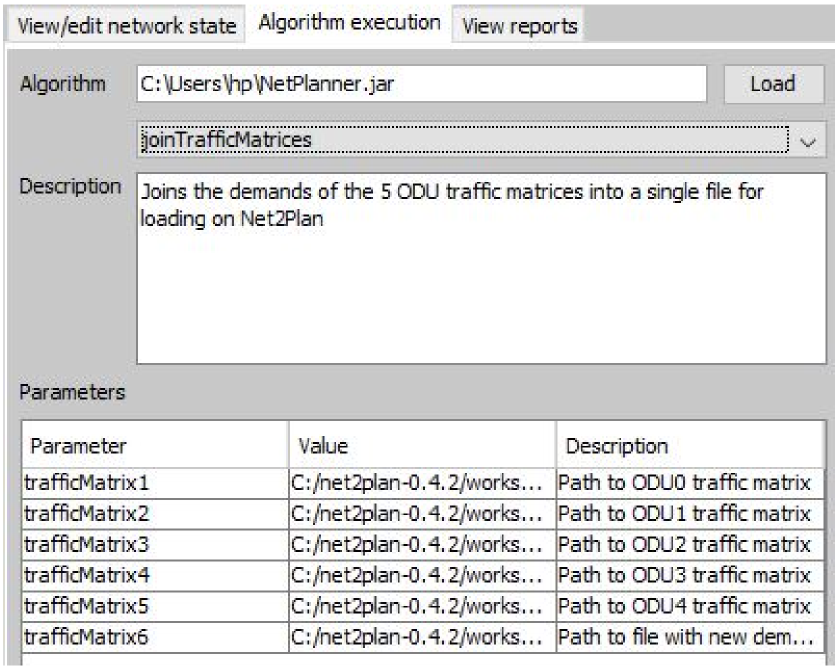


Figura 10.9: Join traffic matrices algorithm.

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 10.10.

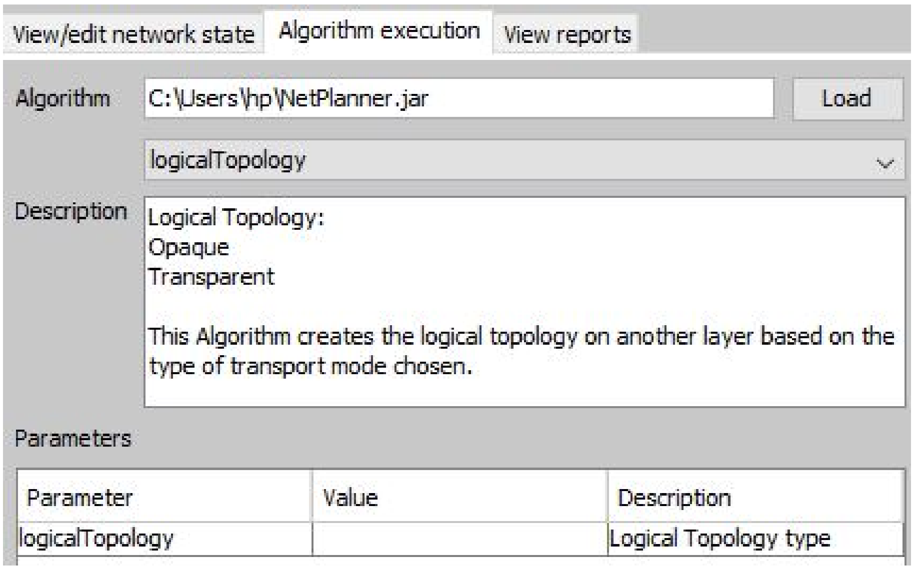
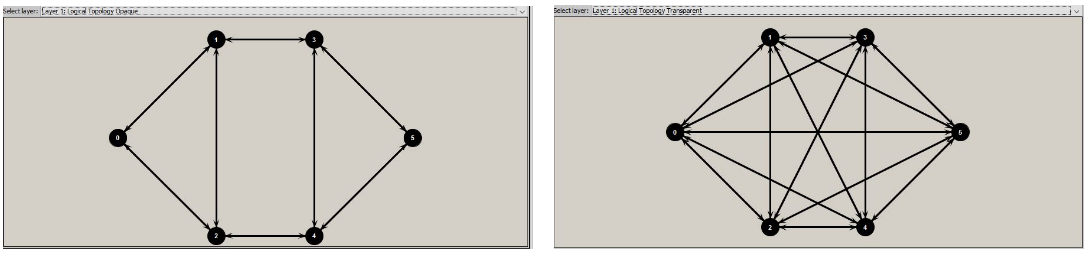


Figura 10.10: Net2Plan Logical Topology Algorithm

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 10.11(a), 10.11(b) demonstrate the resulting logical topologies for each transport mode.



(a) (b)

Figura 10.11: 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.

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 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 10.12. 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.

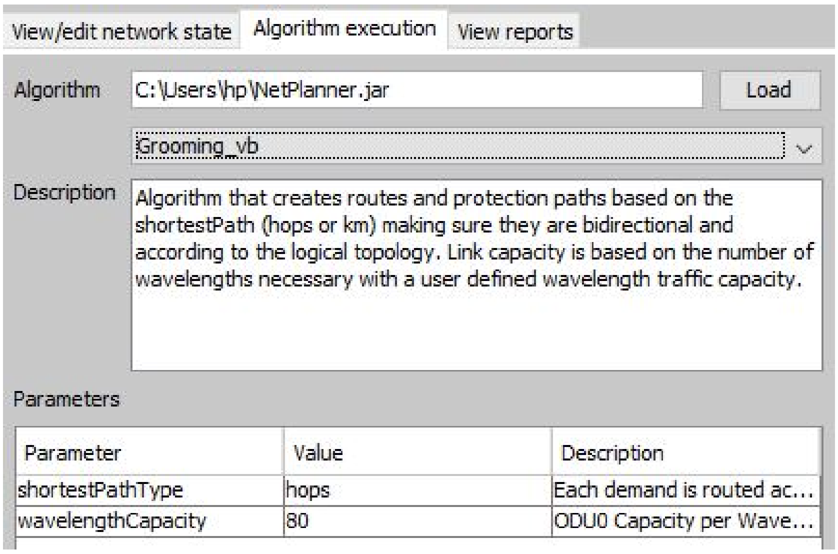


Figura 10.12: Net2Plan Grooming shortest Path Algorithm

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 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.

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 10.1.

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

Tabela 10.1: Equipment Costs

These Equipment costs are introduced into a report as user defined parameters as can be seen on Figure 10.13.

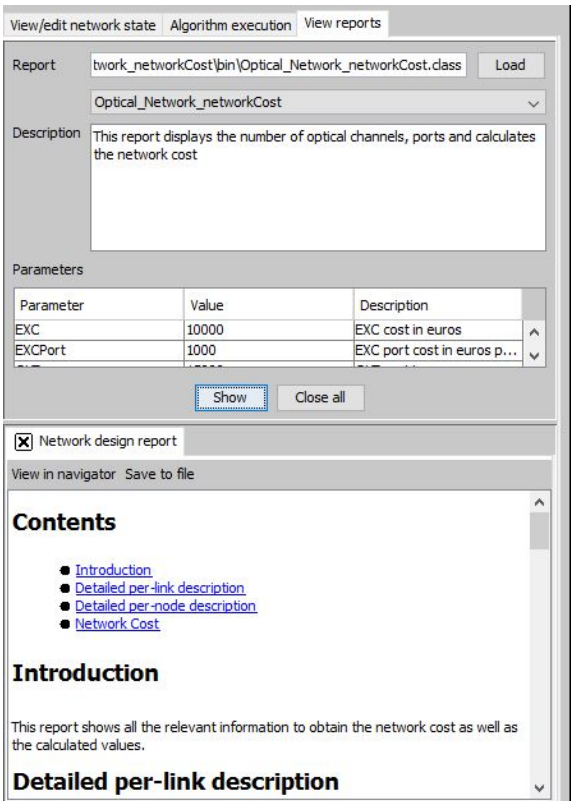


Figura 10.13: Network Cost Report

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.

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.

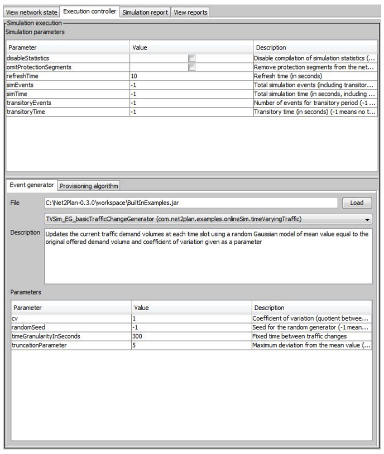
Finally the total number of ports is as expected the sum of all the tributary ports with the line ones. With this information the average and the total number of ports in the network can be obtained which will later be used in calculating the network cost.

Having the node and link information available, the network cost can then be calculated as displayed on the third category of the report and the total network CAPEX, summing the electrical and the optical costs.

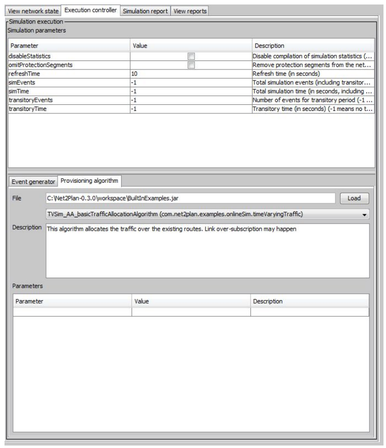
Simulations

To access the Simulations window go to "Tools → 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 10.14(a) and 10.14(b).



(a)



(b)

Figura 10.14: 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.

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 10.15 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.

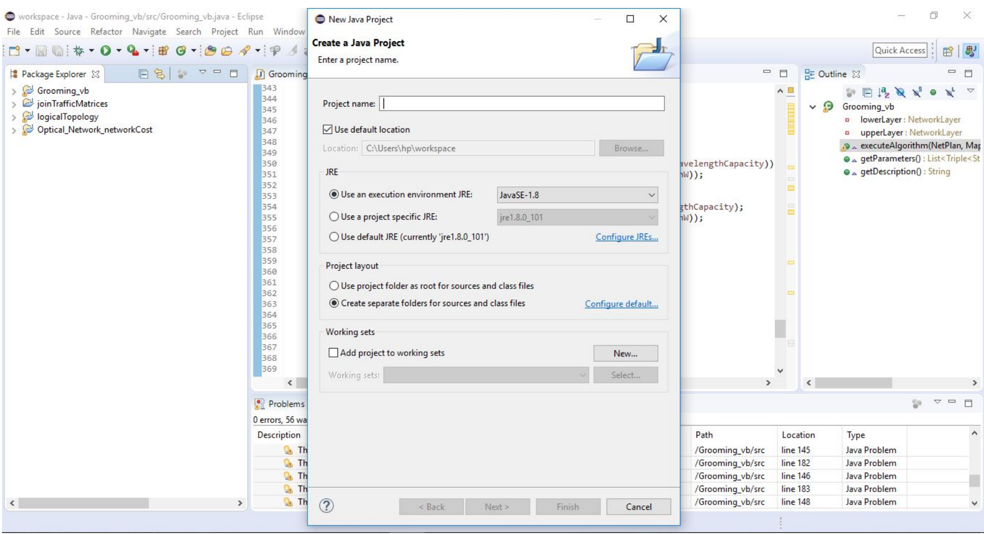


Figura 10.15: Eclipse new project

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 10.16 shows a newly created project called "logicalTopology".

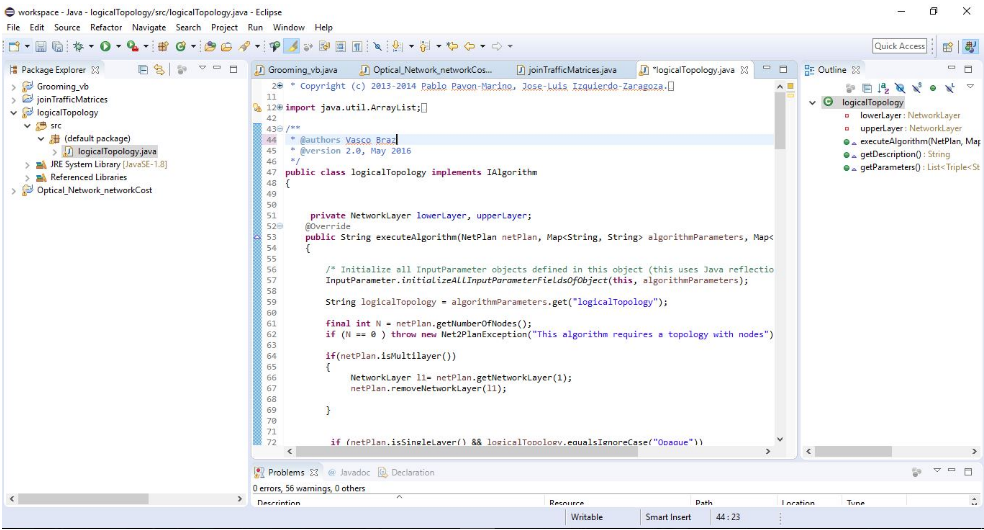


Figura 10.16: Eclipse new project with source file

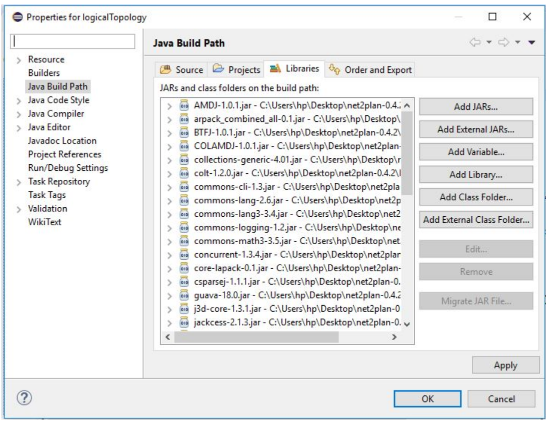
To add the library files to a project, right click on it and choose "Build Path → Configure Build Path ...". On the window that appears, press "Add External Jars..."and include all the files in the Net2Plan "lib" directory as shown on Figures 10.17(a) and 10.17(b).

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 10.15.

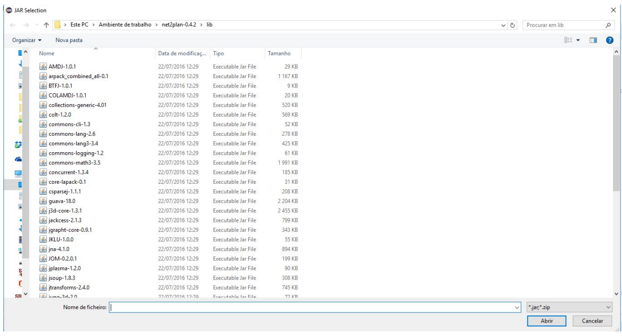
By saving this project on Eclipse a .class file is created on the bin directory of the project which can be loaded on Net2Plan. On the "Algorithm execution" tab at the "Offline network design", the "BuiltInExamples.jar" is loaded as the default location for algorithms and as it is a .jar file all the 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 10.18.

As was said before and can be seen on the "Description", this algorithm creates the network logical topology as was explained on section 10.1.

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



(a)



(b)

Figura 10.17: a) Eclipse Java Configure Build Path ; b) Net2Plan library files

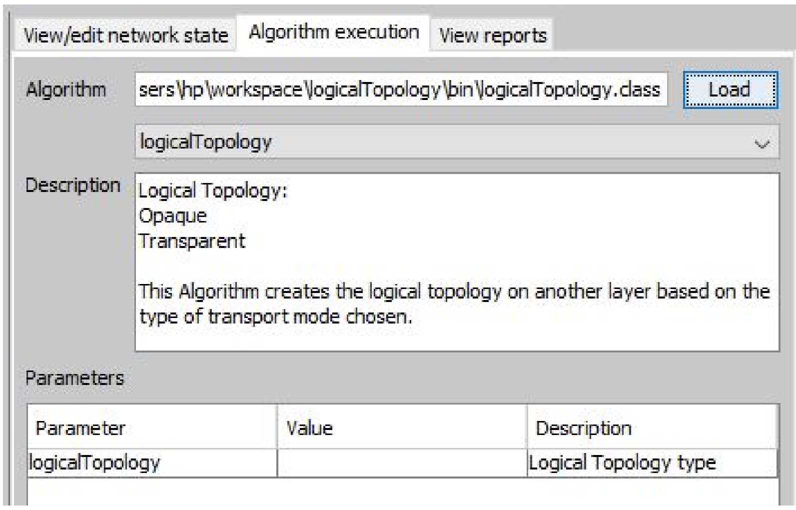
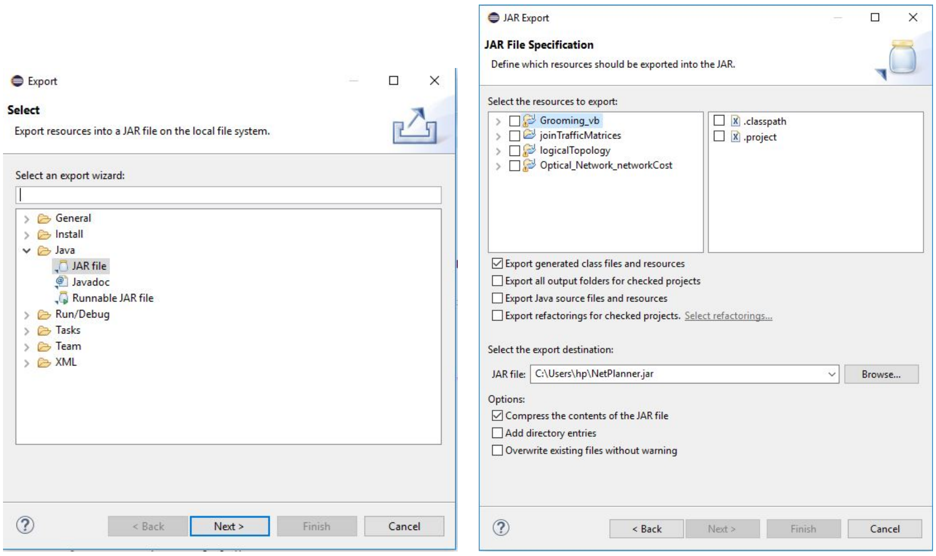


Figura 10.18: Net2Plan new algorithm

ones that came with the Net2Plan installation. The export option can be accessed by going into File $\rightarrow$ Export, and the menu are shown in Figures 10.19(a) and 10.19(b).



(a) (b)

Figura 10.19: 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.

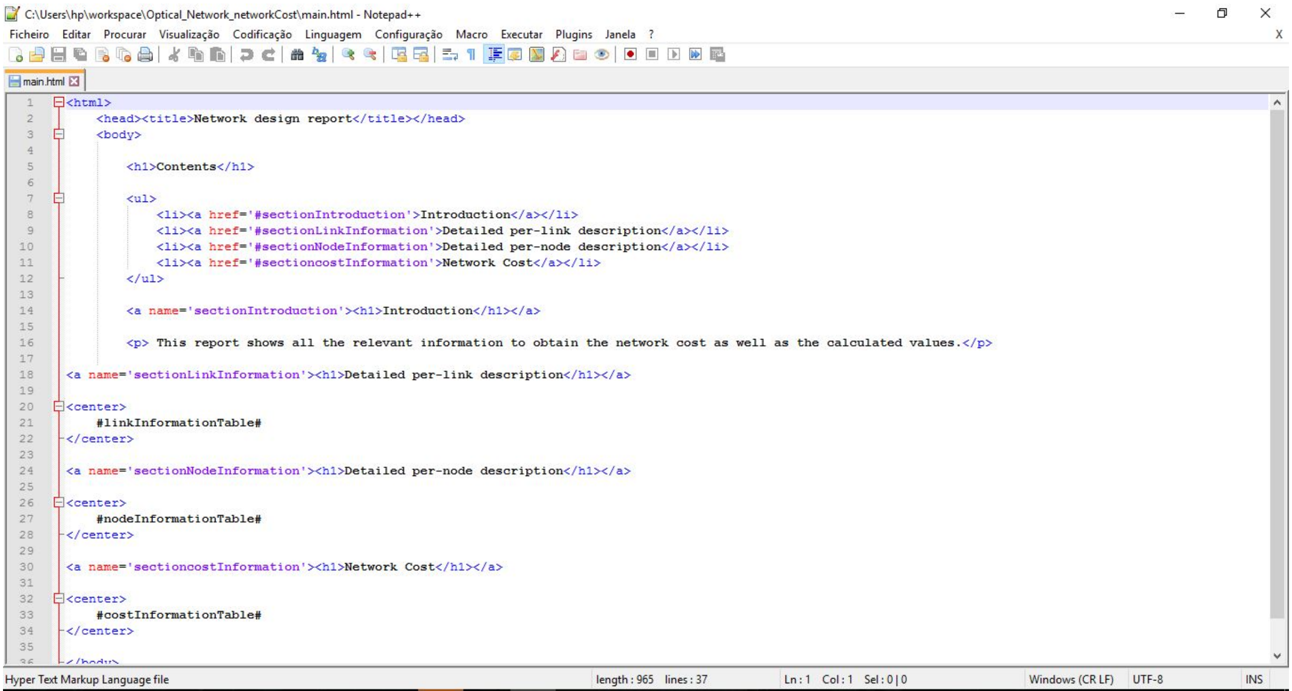
Developing new Reports

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 10.20 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>

```

Figura 10.20: 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.

Algorithms Used

Join Traffic Matrices Algorithm

The first algorithm used is the "Join Traffic Matrices" algorithm and it joins the traffic demands of the ODU traffic matrices into a file. This file will be used later for loading the traffic demands to the network topological design on Net2Plan. This algorithm aggregates the traffic matrices from ODU0 to ODU4. If it is used a network with multiple matrices and, respectively, multiple traffic demands it is possible to join each of them and save it.

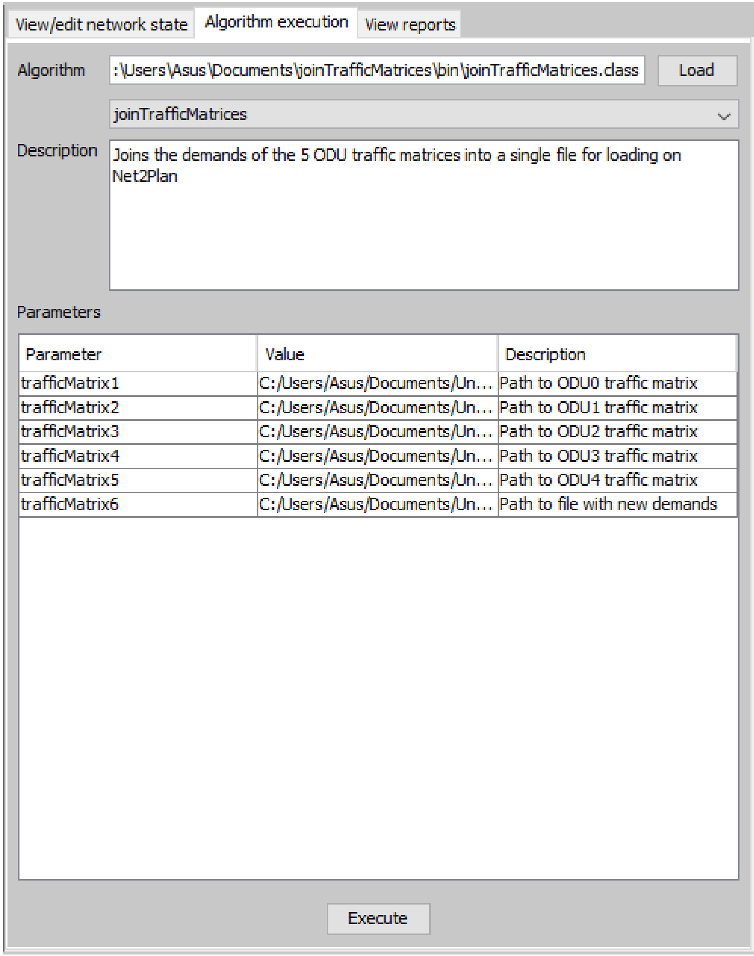


Figura 10.21: Join traffic matrices algorithm using Net2Plan.

Logical Topology Algorithm

The "Logical Topology" algorithm is the second one used and it is based on the transport mode that is used in the network and it creates the logical topology on another layer. The logical topology value is introduced by the user and it can be one of the three transport modes available. If the transport mode chosen is opaque there is no need of having a second layer because the logical layer is the same as the physical one and if the transport mode is transparent or translucent it is needed to add a new logical layer. One advantage of this algorithm is that all the traffic demands are copied to the new layer and all the arguments remains the same depending on the previous layer, not interfering with the network topology.

It is also needed to add by the user the capacity that is used in each wavelength from all origin nodes to all destination nodes and the length of the links with values of the distance matrix represented in and expressed in km.

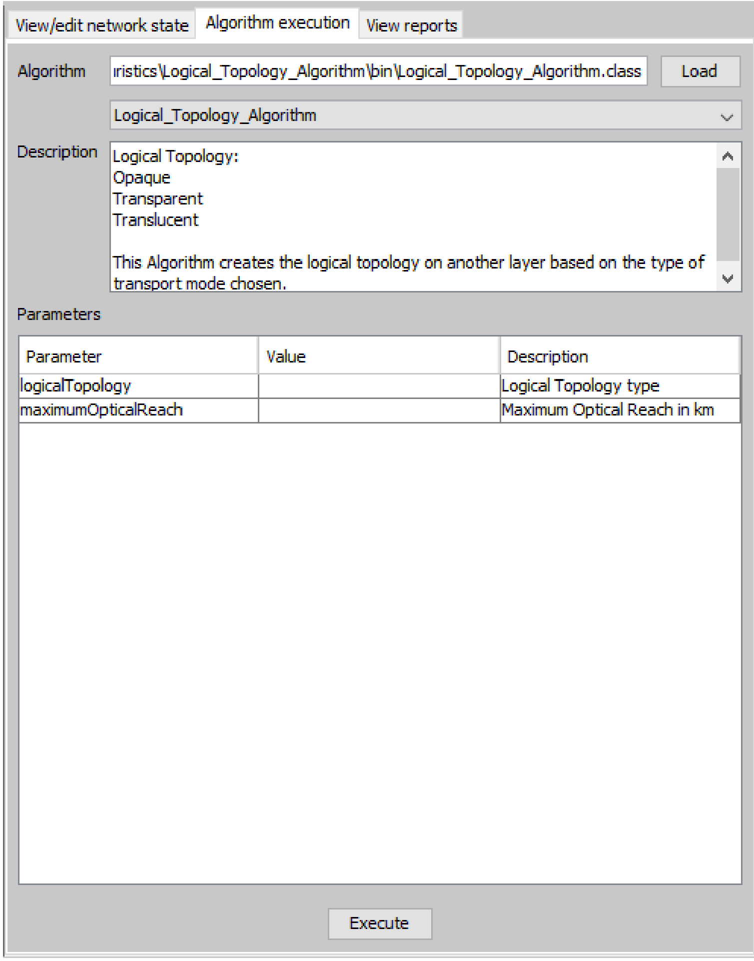


Figura 10.22: Logical topology algorithm using Net2Plan.

Grooming Algorithm

The "Grooming"algorithm is a shortest-path heuristic algorithm that creates routes and protection paths based on hops or km, accordingly to the pre-defined logical topology. The goal of this grooming algorithm is to minimize the number of links for each path between all node pairs and this will lead to the reduction of the number of wavelengths to serve a set of connections and, consequently, to a lower cost of nodes and lower CAPEX.

The approach of the routing algorithm is to route all the traffic demands using the "Dijkstra" algorithm and uses the shortest number of hops to reach the destination node. The shortest path between two nodes is the one that includes connections whose sum of weights is the least possible. Routing through the shortest path consists in routing sequentially each element of a traffic matrix to the shortest path in the network. The routing is done in the logical and physical topologies of the network. In addition, 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. It is assumed that links are bidirectional and the traffic demands are given between pairs of nodes and a network topology. In this case, each wavelength will be served by two wavelength paths. If the number of used wavelengths is minimum, the number of used fibers will be also minimum, which minimizes the CAPEX.

The 1+1 protection scheme (dedicated path protection) assumes that each link has a dedicated protection communication channel. For this scenario, it is necessary to assign different wavelengths to the primary and protection paths. It is chosen the best path based on the shortest or disjointed path, for without survivability or with 1+1 protection, respectively. The goal is to minimize the number of assigned wavelengths and network components and lower the network CAPEX.

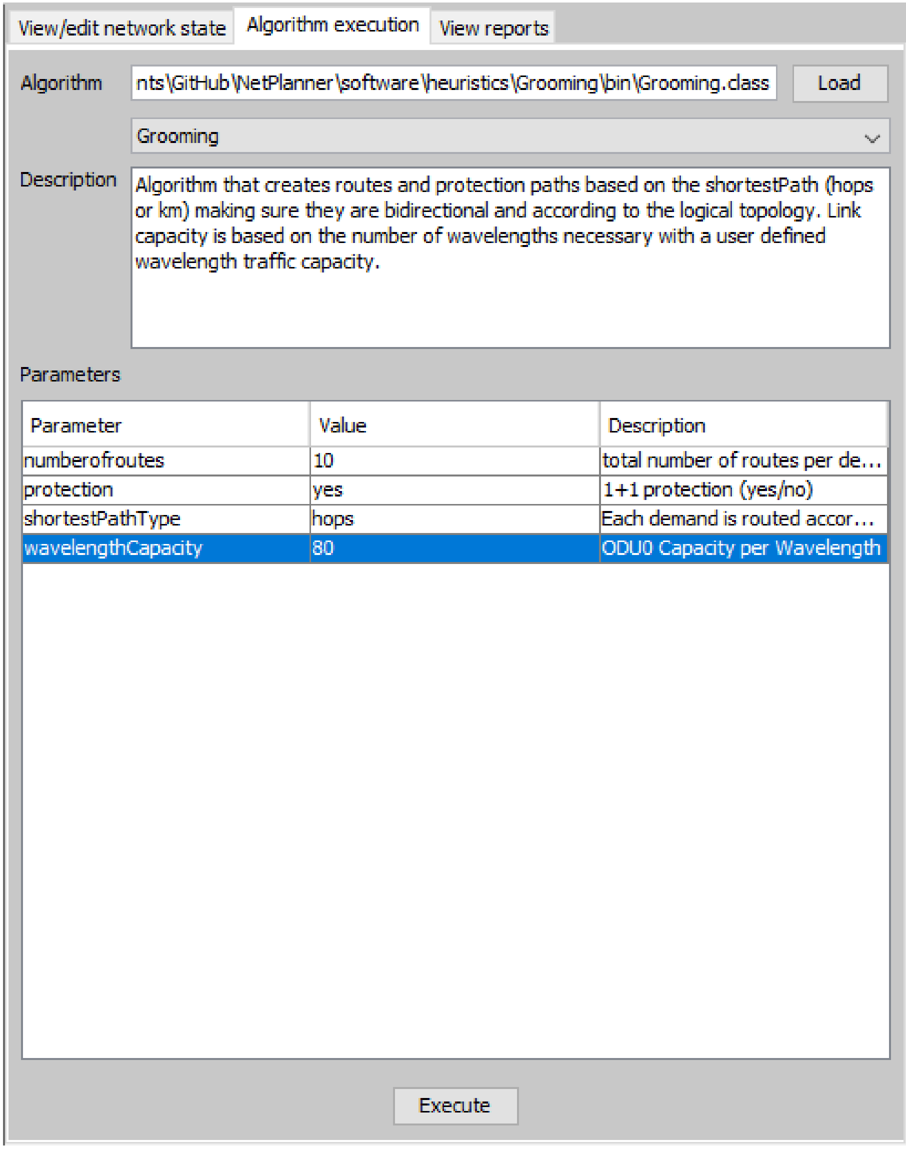


Figura 10.23: Grooming algorithm using Net2Plan.

10.2 Installing LPSOLVE for using in MatLab

Student Name	:	Tiago Esteves (November 28, 2017 - December 05, 2017)
Goal	:	Help other to install lpsolve for using in MatLab.

In this section will describe how to install lpsolve and how it can be used through matlab. For this it is necessary to follow the following steps:

1. Install lpsolve in your computer
2. Install lpsolve matlab extensions
3. Install the library

Step 1:
The first thing to do is to install lpsolve using the execute file "lp-solve-5.5.2.5-IDE-Setup"that can be found in GitHub through this link `https://github.com/netxpto/NetPlanner/tree/Develop/software/lpsolve`. The installation is quite simple and contains few steps for its execution.
In case there is any doubt or question you can always use the lpsolve reference guide in link: `http://lpsolve.sourceforge.net/5.5/`

Step 2:
In this step it is necessary to go to GitHub again and download with the name "lp-solve-5.5.2.0-MATLAB-exe-win64"in link `https://github.com/netxpto/NetPlanner/tree/Develop/software/lpsolve` and extract all the files. Then you need to put the **mxlpsolve.mexw64** and **mxlpsolve.m** files in the same folder as the .m files. In case there is any doubt or question you can always use this guide for help: `thereisanydoubtorquestionyoucanalwaysusethelpsolvereferenceguideinlink:`

Setp 3:
Finally, once again in GitHub through the link `https://github.com/netxpto/NetPlanner/tree/Develop/software/lpsolve` we can find the last folder to get the necessary library, thus downloading the folder "lp-solve-5.5.2.0-dev-win64"and then include in the Windows PATH environment.

10.3 Codify ILP in MatLab

Student Name	:	Tiago Esteves (November 28, 2017 - December 05, 2017)
Goal	:	Help other to install lpsolve for using in MatLab.

The first step to do as we can see in the image 10.24 is to define the number of nodes in our network, create the matrices ODU for our traffic and then create a vector with the number of amplifiers in our network. In relation to the latter, the number of amplifiers is calculated through the distances between the nodes. These distances can be obtained through the matrix created initially but since it is a symmetric matrix we just need to use the upper matrix to create this vector.

```
%First define the number of nodes
n=6;

%Network topology in form of adjacency matrix
G=[0,1,1,0,0,0;1,0,1,1,0,0;1,1,0,0,1,0;0,1,0,0,1,1;0,0,1,1,0,1;0,0,0,1,1,0];

%Traffic Matrices ODU0, ODU1, ODU2, ODU3, ODU4
D(:,:,1)=[0,5,1,3,1,3;5,0,0,1,5,0;1,0,0,1,4,1;3,1,1,0,1,1;1,5,4,1,0,3;3,0,1,1,3,0];
D(:,:,2)=[0,2,4,2,0,5;2,0,0,3,1,1;4,0,0,1,1,0;2,3,1,0,1,3;0,1,1,1,0,1;5,1,0,3,1,0];
D(:,:,3)=[0,1,1,1,0,0;1,0,0,0,1,0;1,0,0,1,1,0;1,0,1,0,1,0;0,1,1,1,0,1;0,0,0,0,1,0];
D(:,:,4)=[0,0,0,0,0,0;0,0,1,0,0,1;0,1,0,0,1,0;0,0,0,0,0,0;0,0,1,0,0,0;0,1,0,0,0,0];
D(:,:,5)=[0,0,0,0,0,0;0,0,0,0,0,1;0,0,0,0,0,0;0,0,0,0,0,0;0,0,0,0,0,1;0,1,0,0,1,0];

%Vector with the number of amplifier per link
%NR = Dist/100 - 1;
NR=[4,6,0,0,0,0,6,0,0,0,8,0,1,7,3];
```

Figura 10.24: Number of nodes, matrices of ODU and number of amplifiers.

Following the code we can observe several cost variables with their respective values that will be necessary for the following calculations.
The next step can be observed in the image 10.25, where in this part we have to define the number of variables used in the constraints the total of these variables and also to create the ilp with these variables. As you can see in the image, each variable is calculated differently because each variable has a different value. Ilp is created using the 'make_lp' function of mxlpsolve.

```
%Variables
number_flows = (n * (n-1))/2;              % number of possible bidirectional demands,

var_f = number_flows * (n * (n-1));        % number f^(od)_(ij) variables (unideritonal)
var_W = number_flows;                      % number W_(ij) variables (bidirectional)
var_L = number_flows;                      % number L_(ij) variables

%Total number of variables
total_var = var_f + var_W + var_L;

% this function is going to create a new ILP with total_var variables
ilp=mxlpsolve('make_lp', 0, total_var);
```

Figura 10.25: Number of variables, total number of variables and create ilp.

Through the image 10.26 we can see how the objective function defined in section 5.1.1 (Opaque without survivability) is encoded. The first thing to do for coding the objective function is to create a vector (f_row) with the total number of variables, then for each position of a given variable we have to assign its corresponding value. This value is seen through the equation 5.1. Finally, using the 'set_obj_fn' function of mxlpsolve the objective function is defined.

```
%OBJECTIVE FUNCTION
f_row = ones(1,total_var);

f_row(1,1:var_f) = 0.0000001;
f_row(1,var_f+1:var_W) = 2*cust_EXC_port*100 + 2*cust_transp*100;
f_row(1,var_f+var_W+1:total_var) = NR*cust_amplifier + 2*cust_olt;

mxlpsolve('set_obj_fn', ilp, f_row);
```

Figura 10.26: Objective function.

After defining the objective function we have to code all the necessary restrictions for the mode of transport in question. In the image 10.27 we can see the first restriction referred to in section 5.1.1. The use of the first two cycles 'for' is related to the fact that it has to be applied to all o with o being greater than d. The other two case 'for' refers to the fact that it is for all i and for all f where i is equal to o, hence the use of an 'if' in between these two 'for'. Thus, it is only necessary to have an if loop for the case of f to be different from o because this f is different from the origin. As this constraint refers to variable f_{ij}^{od} f_index is used where this variable is equal to the value calculated by the function index_calculation2. Finally, the 'add constraint' function of mxlpsolve is used to add this constraint indicating that position (f_row) must be equal (3) to 1.

```
%CONSTRAINTS
%FLOW CONSERVATION CONSTRAINTS
for o=1:n
    for d=o+1:n
        for i=1:n
            %ORIGIN NODES
            if(i==o)
                %sum over all i
                index_sum = [];
                f_row = zeros(1,total_var);
                for j=1:n
                  if(j~=o && G(i,j)==1)
                    f_index = index_calculation2(i,j,o,d,n);
                    index_sum = [index_sum, f_index];
                  end
                end
                f_row(index_sum)=1;
                mxlpsolve('add_constraint', ilp, f_row, 3, 1);
```

Figura 10.27: First constraint of this model.

After all the restrictions on the mode of transport in question have been codified, it is necessary to define the variables. As we can see in the image 10.28 for the case of section 5.1.1 (Opaque without survivability) the variables 'var_f' and 'var_L' are binary and the variable 'var_w' is integer. Finally we use the 'write_lp' function of mxlpsolve to write ilp to a file and the 'solve' function of mxlpsolve to solve this ilp.

Finally, only code is made to display the results in detail using 'fprintf' and creating variables to store the calculated values.

```
%BINARY VARIABLES DEFINITION
for i=1:var_f
    mxlpsolve('set_binary', ilp, i, 1);
end

for i=1:var_L
    mxlpsolve('set_binary', ilp, var_f+var_W+i, 1);
end

%INTEGER VARIABLES DEFINITION
for i=1:var_W
    mxlpsolve('set_int', ilp, var_f+i, 1);
end

mxlpsolve('write_lp', ilp, 'opaque_ref_LT.lp');
mxlpsolve('solve', ilp);
obj = mxlpsolve('get_objective', ilp);
var = mxlpsolve('get_variables', ilp);
```

Figura 10.28: Definition of variables, write and solve the ilp.

Capítulo 11

Master Dissertations

- Vasco Braz, Dimensioning and Optimization of Node Architecture in Optical Transport Networks, University of Aveiro, 2016

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

Vasco Rafael Brites dos Santos Braz

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

Dimensioning and Optimization of Node Architecture in Optical Transport Networks

Universidade de Aveiro
2016

Departamento de
Electrónica, Telecomunicações e Informática,

Vasco Rafael Brites dos Santos Braz

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

Dimensioning and Optimization of Node Architecture in Optical Transport Networks

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

— Albert Einstein

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

Vasco Rafael Brites dos Santos Braz

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

Dimensioning and Optimization of Node Architecture in Optical Transport 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.

o júri / the jury

presidente / president

Mário José Neves de Lima
Professor Auxiliar da Universidade de Aveiro

vogais / examiners committee

Maria do Carmo Raposo de Medeiros
Professora Associada da Universidade de Coimbra

Armando Humberto Moreira Nolasco Pinto
Professor Associado da Universidade de Aveiro

agradecimentos / acknowledgements

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Resumo

Nesta dissertação 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 baseada nos seus elementos físicos principais. Ao nível dos nós foram tidos 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 é agregado e o encaminhamento do mesmo na rede, exigem a elaboração de uma arquitetura que minimize os recursos necessários. A necessidade de otimizar este processo de dimensionamento da rede levou à construção e validação de métodos de agregação de tráfego e encaminhamento baseados 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 à topologia pretendida. A apresentação detalhada dos resultados considerando o CAPEX, bem como a sua análise são considerados na dissertação. Por fim, são apresentadas conclusões e sugerido o trabalho científico que ainda pode ser realizado neste âmbito.

Abstract

In this dissertation an introduction is presented to the multilayer optical transport networks. The two main elements of the network were characterized: nodes and links. Regarding the connections it was made a shallower approach based on its key physical elements. In terms of nodes client traffic (low bandwith) and the line traffic (high bandwith) were considered as well as the components necessary to carry them. The way the client traffic is aggregated and its forwarding in the same network requires an architecture which makes use of the minimum resources. The need of optimizing 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 routing and grooming algorithms applied to a open source 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 are also taken into account. Finally, conclusions are presented and the scientific work that can still be done in this area is suggested.

Contents

List of Figures

List of Tables

List of Acronyms

API	aplication user interface
EDFA	erbium doped fiber amplifier
EXC	electrical cross connect
CAPEX	capital expenditures
IDE	integrated development interface
ILP	integer linear programming
ITU-T	international telecommunication union - telecommunication standardization
IP	Internet protocol
MPLS-TP	multi protocol label switching - transport profile
M2M	machine-to-machine
OTN	optical transport network
OEO	optica-electrical-optical
OPEX	operational expenditures
OXC	optical cross connect
OTN	optical transport network
TCO	total cost of ownership
SDH	synchronous digital hierarchy
WAM	wide area network
WDM	wavelength division multiplexing

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 overhead on existing networks caused by a huge number of users [4][5][6]. 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.[7]

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, 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 compromising the quality of service. At the same time, there are entities concerned about the ecological footprint because of the uncontrolled increase in energy reserved for telecommunications. Therefore, it 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).[8]

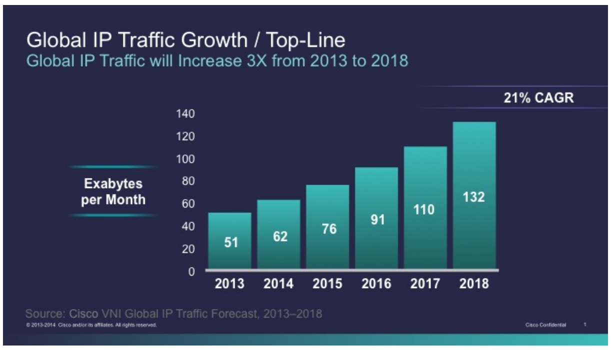

Figure 1.1: Cisco forecast for ip traffic growth [1]

1.1 Motivation

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 [9].

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 [2]. 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. 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.

1.2 Objectives

This dissertation emerges from the collaboration between University of Aveiro, Instituto de Telecomunicações 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. To achieve the main objectives of this dissertation, the following steps should be fulfilled:

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.

1.3 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 reference network dimensioning problem analysis and 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 and the consequent results. 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 on the platform used (Net2Plan). The pseudo code behind the routing and grooming is also contained in this 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 results of this two approaches are in Chapter 5. In this chapter and after validating the heuristics, they are applied to a real network and the results will be analyzed. The last step is the conclusions 6 and suggestions for future research directions.

Chapter 2

Network Design and Dimensioning

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 must be able to deal, efficiently, with time-varying traffic [10]. Thus, it is mandatory to perform 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 2.1.3, 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 2.1.4. 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) [11].

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 causes 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 contain 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.

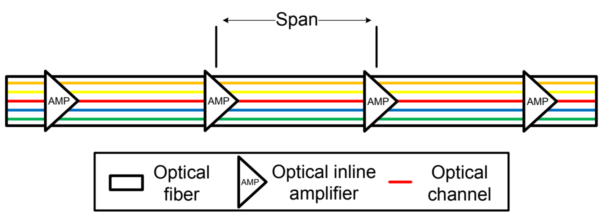

Figure 2.1: Bidirectional transmission system architecture: optical fiber and inline optical amplifiers [2]

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 [12].

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 these shelves are contained within a larger structure, capable of providing 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 [13].

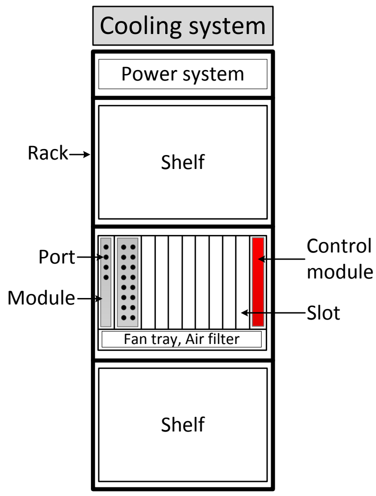

Figure 2.2: Node schematic: port, module, slot, shelf and rack [2]

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 focused 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 [14, 2].

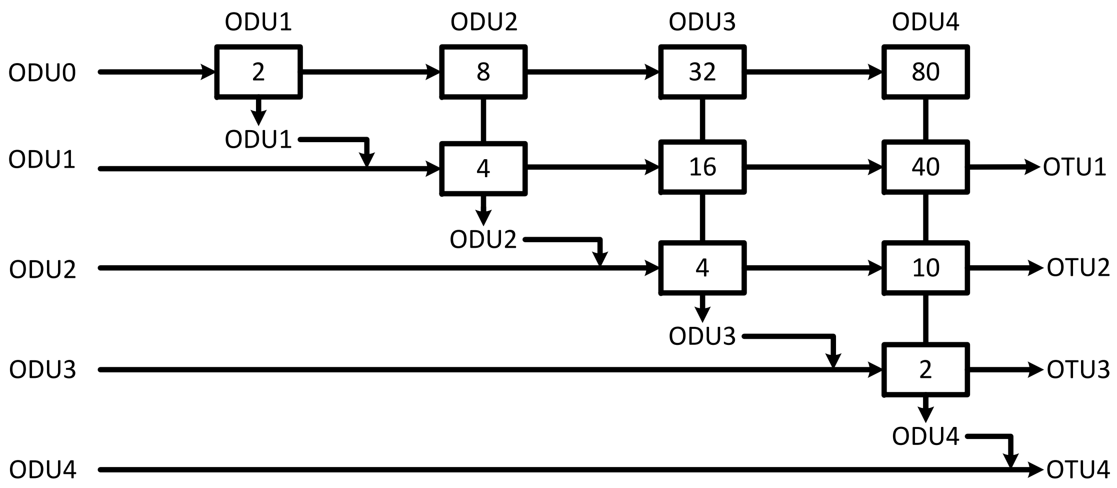

Figure 2.3: Grooming of OTN Signals [2]

As depicted in figure 2.3, the grooming of eight ODU0 client signals result in an OTU2 line signal. However, two ODU0 client signals mixed with three ODU1 is another possibility to 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 switching 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 [15].

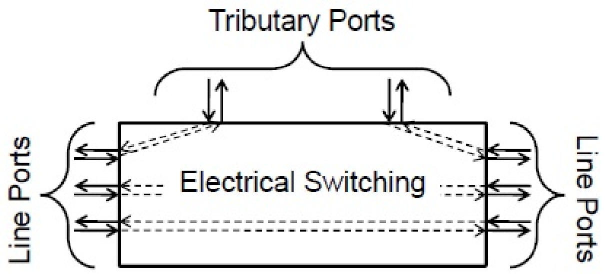

Figure 2.4: Scheme of a node for opaque transport mode network

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 a 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 [16].

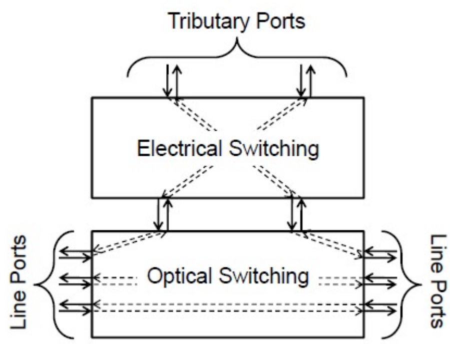

Figure 2.5: Scheme of a node using electrical an optical switching

2.1.3 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:

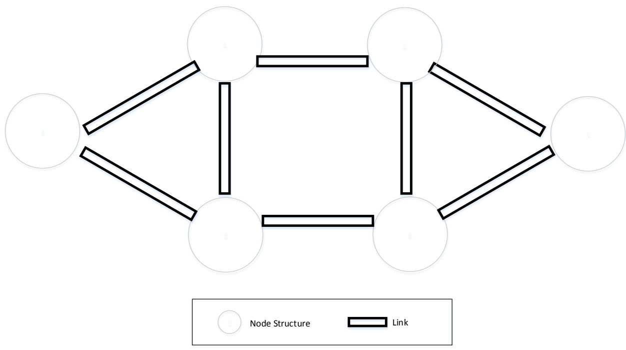

Figure 2.6: Nodes position and connection established by links located according to the real optical network

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.

2.1.4 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 on opaque and transparent models.

2.2 Transport modes

Although the logical topologies of optical networks share the same physical links, the traffic is carried differently. Depending on the number of conversions from an optical signal to the electric domain different transport modes will appear.

2.2.1 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 [17].

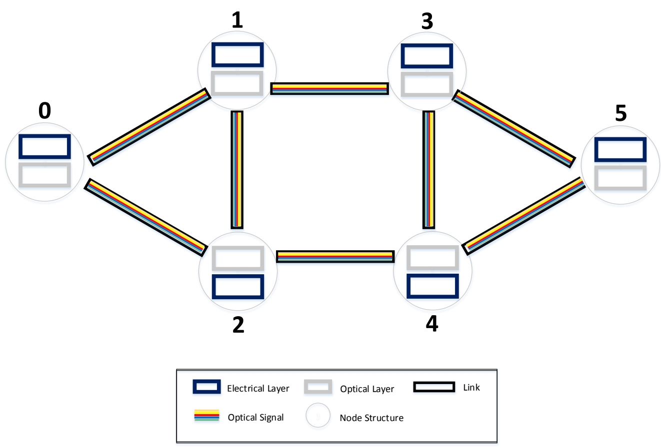

Figure 2.7: Opaque transport mode with a link-by-link grooming scheme

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.

2.2.2 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. 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 [18].

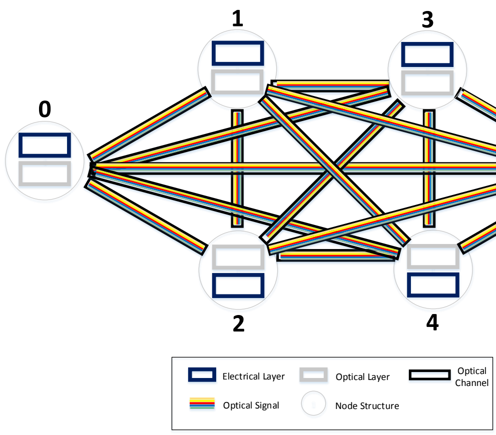

Figure 2.8: Logical topology for previous physical topology with each node connected to each other (Transparent Transport Mode)

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.

2.2.3 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.

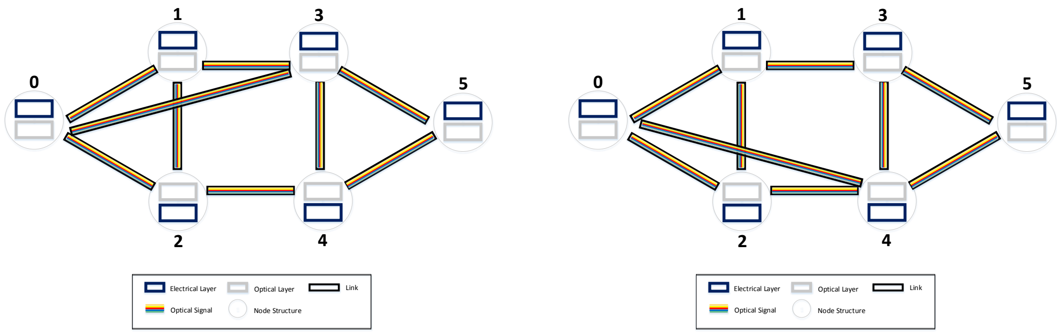

Figure 2.9: Translucent logical topologies

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.

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 [19, 20].

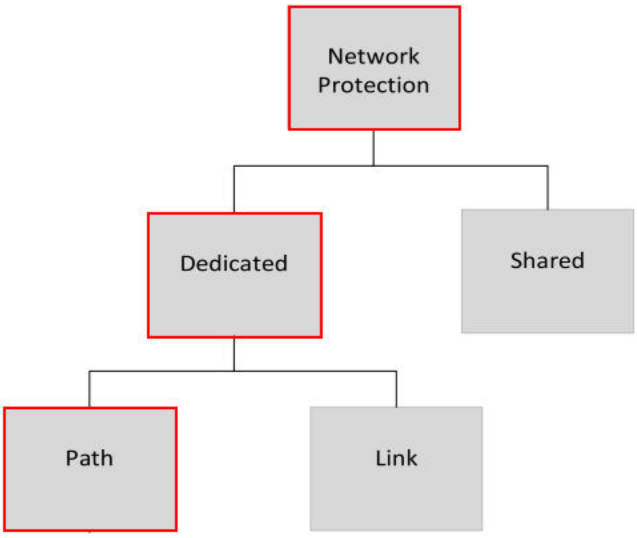

Figure 2.10: Network protection scheme

2.4 Chapter summary

In terms of optical networking design, there are two basic concepts, physical and logical topologies. The physical topology is the physical component of the network and how they are arranged, while 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.

Logical topologies are related to how the optical signal is propagated. The signal can cross the nodes without being converted to the electrical domain (transparent), thus saving on the electrical components, and still be converted to the electrical domain and aggregate with other signals that cross the same next link, optimizing the bandwidth of the optical channels and saving on the optical components. It can even be a mixture of the other two topologies combining the advantages of both. In network planning it is extremely important to consider protecting traffic from failures. The protection can be shared, thus saving on the resources assigned for protection, or can be dedicated by assigning the resources before the failure occurs, preventing any failure in nodes or links of the working path. Then, 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 function subject to a set of constraints is called optimization. Optimization models have a specific number of variables and constraints dependent on the problem to be solved. In telecommunications, ILP models are used to design networks describing real components and their capacities through a set of linear equations and inequalities. Despite the quality of the solutions obtained through the ILP models, depending on the number of variables and computational resources, the results of the ILP models can take days, months or even years [21]. The focus of the current chapter is to propose and describe two optimization models, based on opaque and transparent transport mode with protection. In section 3.1, is described a reference network protection topological design problem, including the definition of variables and inputs of the model and problem description. In section 3.2.1, it is proposed in detail the constraints of the opaque model with dedicated path protection as well as the objective function of the dimensioning problem. In accordance, the next section 3.2.2 is where the model of opaque transport mode will take place. In section 3.3, it is a brief approach to how an ILP model can be implemented through the LPsolve package. In section 3.4, will be the results of the models considering homogeneous and heterogeneous traffic while varying the number of demands. Then, the last section 3.5 contains a succinct summary of the chapter with the most important concepts.

3.1 Network protection topological design problem

The development of an ILP model requires first the definition of the inputs, outputs and variables of the problem in a mathematical representation. Then, let's consider a network consisting of a set of nodes, $V = \{1,\dots\ ,n\}$, and a set of bidirectional links connecting nodes, $L = \{\{i,j\} : i, j \in V, i < j\}$. Network node connections are in the form of an adjacency matrix called $G_{i,j}$. The client traffic demands from each origin node to the destination are also in matrix form: $D_{od} = \{[o, d] : o, d \in V, o < d\}$. For each type of client traffic, it must be created a bidirectional demand matrix D_{od}. 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.

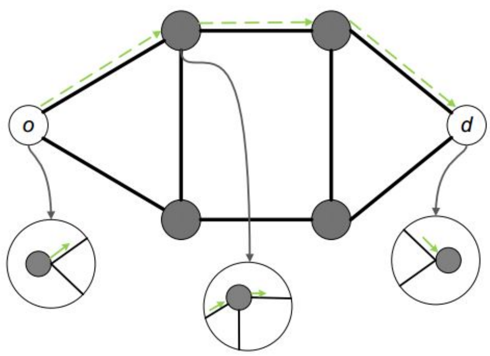

Figure 3.1: Traffic demand path from node "o" to node "d"

The traffic demands go through one or more links to reach their destination and it is assumed that the path between node o and d is the same as the path between 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 reverse direction 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. It is important to highlight that to reduce the computing time will be used bidirectional traffic matrices, i.e, $D_{cod} = D_{cod}^T$.

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

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

3.2 ILP models

Integer linear program approaches proposed below, follow the standard form. All decision variable values that satisfy the set of constraints are called admissible solutions, in the cases that the solutions set is finite and the decision variables are restricted to integer values, it is called Integer Linear Programming. The optimal solution to the problem will be the values of an admissible solution(s) that obtain 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 inequalities are satisfied and the value of the objective function is maximized or minimized. The objective function is introduced by the keyword *"minimize"* or *"maximize"*, and the set of the constraints are introduced by the expression *"subject to"*. Therefore, in order to solve the optimization models, it is required a software as MATLAB to effect a solution. There are also optimization software packages such as IBM ILOG CPLEX Optimization Studio, GLPK or Gurobi Optimizer to simplify the optimization problem description. In this dissertation, LPsolve was the package used to solve optimization problems. Then, ILP models proposed along this dissertation will be described using this structure [22].

3.2.1 Opaque with 1+1 Protection

The objective function of following ILP is a minimization of the sum of two variables: total number of flows crossing link (i, j) for all demand pairs (o, d) and total number of optical channels in each link (i, j).

$$minimize \quad \sum_{(i,j)} \sum_{(o,d)} f_{ij}^{od} + \sum_{(i,j)} W_{ij} \tag{3.1}$$

subject to

$$\sum_{j \backslash \{o\}} f_{ij}^{od} = 2 \qquad \forall (o,d) : o < d \;, \forall i : i = o \tag{3.2}$$

$$\sum_{j \backslash \{o\}} f_{ij}^{od} = \sum_{j \backslash \{d\}} f_{ji}^{od} \qquad \forall (o,d) : o < d \;, \forall i : i \neq o, d \tag{3.3}$$

$$\sum_{j \backslash \{d\}} f_{ji}^{od} = 2 \qquad \forall (o,d) : o < d \;, \forall i : i = d \tag{3.4}$$

$$\sum_{(o,d):o<d} (f_{ij}^{od} + f_{ji}^{od}) + \sum_{c \in C} (B(c) D_{cod} \leq 100 W_{ij} G_{ij} \qquad \forall (i,j) : i < j \tag{3.5}$$

$$W_{ij} \leq 80 \qquad \forall (i,j) : i < j \tag{3.6}$$

$$f_{ij}^{od}, f_{ji}^{od} \in \{0, 2\} \qquad \forall (i,j) : i < j, \forall (o,d) : o < d \tag{3.7}$$

$$W_{ij} \in \mathbb{N} \qquad \forall (i,j) : i < j \tag{3.8}$$

The objective function, to be minimized, is the expression(3.1). The flow conservation constraints are (3.2), (3.3) and (3.4). First constraint ensures that, for all demand pairs (o,d), it routes two flows of traffic for all bidirectional links (i,j) when "j" is not equal to the origin of the demand. Equation (3.4) is based on the same idea of (3.1), however applied in reverse direction. Assuming bidirectional traffic, so the number of flows in both directions of the link is the same (3.3). The inequality (3.5) is considered grooming constraint, so it means the total client traffic flows can not be greater than the capacity of optical channels on all links. Another important constraint (3.6) is the capacity of the optical channels which must be less or equal to 100 Gb/s or 80 ODU0. The number of flows per demand can be zero if there are no traffic demands or two if considering working and protection traffic (3.7). The last constraint is just needed to ensure the number optical of channels is a positive integer values greater than zero.

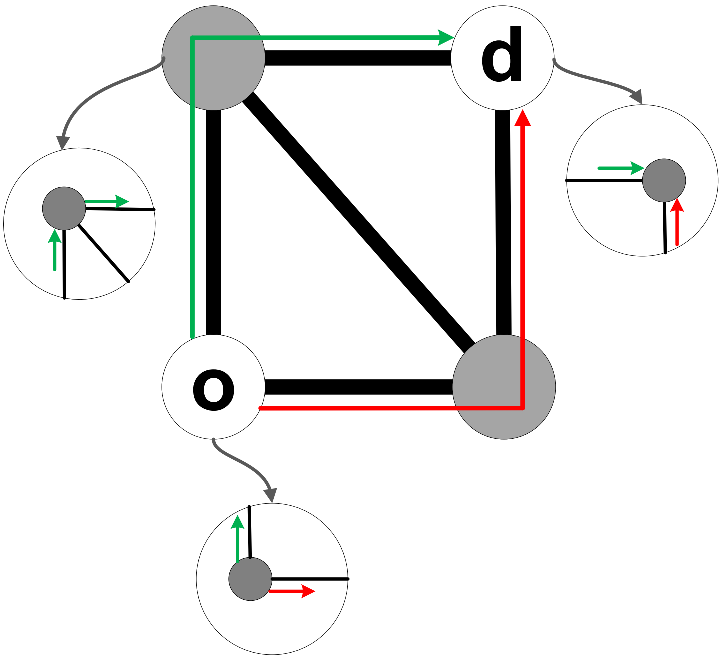

Figure 3.2: Example of two nodes in a network sending traffic through disjoint links

Constraints (3.2) and (3.4), was proposed to ensure that the flow used for protection should be different from working path. Figure 3.2 shows a signal being sent by disjoint paths as supposed in dedicated path protection. From client point of view, there is just a single flow from the origin to the destination, but as shown in the detailed view of the figure above, it's possible to verify that there is a flow arriving and another starting at each intermediate node.

3.2.2 Transparent with 1+1 Protection

The optimization model suggested for transparent transport mode with dedicated path protection intends to minimize the total number of flows crossing link (i, j) for all demand pairs (o, d). The mathematical model described below also minimizes the total number of optical channels between each demand end nodes W_{od}, instead of minimizing the number of optical link-by-link channels as in the previous model.

$$
\begin{aligned}
&\textit{minimize} \quad \sum_{(i,j)}\sum_{(o,d)} f_{ij}^{od} + \sum_{(o,d)} W_{od} && && (3.9)\\
&\textit{subject to} && && \\
&\quad \sum_{j\backslash\{o\}} f_{ij}^{od} = 2 && \forall(o,d) : o < d, \forall i : i = o && (3.10)\\
&\quad \sum_{j\backslash\{o\}} f_{ij}^{od} = \sum_{j\backslash\{d\}} f_{ji}^{od} && \forall(o,d) : o < d\ , \forall i : i \neq o, d && (3.11)\\
&\quad \sum_{j\backslash\{d\}} f_{ji}^{od} = 2 && \forall(o,d) : o < d, \forall i : i = d && (3.12)\\
&\quad \sum_{(o,d):o<d} (f_{ij}^{od} + f_{ji}^{od}) x W_{od} \leq 80 G_{ij} && \forall(i,j) : i < j && (3.13)\\
&\quad f_{ij}^{od}, f_{ji}^{od} \in \{0, 2\} && \forall(i,j) : i < j, \forall(o,d) : o < d && (3.14)\\
&\quad W_{od} \in \mathbb{N} && \forall(o,d) : o < d && (3.15)
\end{aligned}
$$

The objective function, to be minimized, is the expression(3.9). The flow conservation is performed by equations (3.10), (3.11) and (3.12) and share the same mathematical description of opaque model. The inequality (3.13) answers capacity constraint problem. Then, total flows times the traffic of the demands must be less or equal to the capacity of network links. The grooming of this model can be done before routing since the traffic is aggregated just for demands between the same nodes, thus not depending on the routes. Last two constraints define the total number of flows must be zero if there is no demand, or two for a demand with traffic protection, and the number of optical channels must be a counting number.

3.3 LPSolve and Matlab implementation

Implementation of the models described in section 3.2 requires the use of mathematical software tools. Software chosen was MATLAB, since it is ideally suited to handle linear programming problems. The use of this powerful software allows declaration and definition of variables and constraints in an iterative and simplified procedure. Variables are written and stored into vector or matrices sorted by indices known by the developer and dependent on the network size. This computing resource can call LPsolve through an external interface or MEX-function. LPsolve is used to resolve linear programming problems when declared according to a specific structure, in this case, achieved through MATLAB. LPsolve is an optimization software package that reuses other free software components to make an integrated development environment (IDE). The use of this IDE allows solving ILPs in a user-friendly graphical interface, thus making it easier to debug problems. The control of LPsolve is provided by mxlpsolve driver which is allowed to operate with data sent through an application programming interface (API).

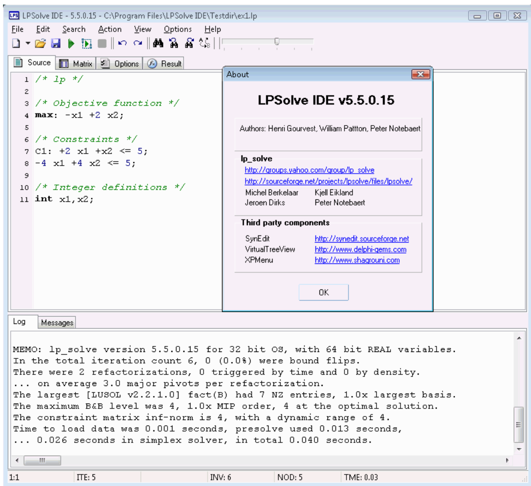

Figure 3.3: LPSolve integrated development interface

Optimization models presented in section 3.2.1 and 3.2.2 should be written on programming format imposed by mxlpsolve driver, then the following steps have to be followed [23]:

1. Create and initialize the 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. Write ILP to an .lp file
6. Solve the model
7. Returns the value of the objective function
8. Returns the value of the variables

The first step is to declare the model and send the total number of problem variables to the solver. Thereafter, it is needed to send the objective function coefficients using the appropriate API function. Then, the driver is called iteratively sending as arguments the name of the function to add a constraint, the correct indexes of the variables vector, the corresponding equality or inequality and the independent terms. It makes it possible to define all constraints of the problem. Regarding problem description, the last step is to set variables type according to the mathematical model. Hence, in order to simplify the visualization, it is advisable to write the model to a file that can be opened in LPsolve IDE. Finally, it is necessary to instruct the solver to resolve the problem and to return the results.

3.4 ILP results

The presentation and analysis of the results of the model 3.2.1 and 3.2.2 are consummated during this section. The models will be tested with homogeneous and heterogeneous traffic, changing the number of demands or fluctuating the client traffic type (lower to higher bandwith). The results for opaque and transparent models are shown using, respectively, blue and green bars. All results were obtained considering the reference network. The model was not applied to a real network because the execution time would be protracted.

Then, starting with homogeneous client traffic from the lowest to the highest bandwidth, the following results were obtained:

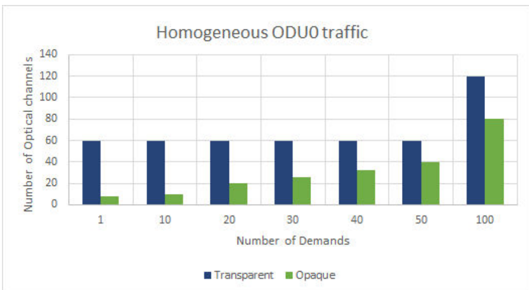

Figure 3.4: ILP solution for ODU0 client traffic

Considering a low number of demands the result of transparent model is exaggeratedly high. When there is only one traffic demand, sixty optical channels are required, since the network has six nodes and there is a demand from each node to the other five and the same number of demands for protection.

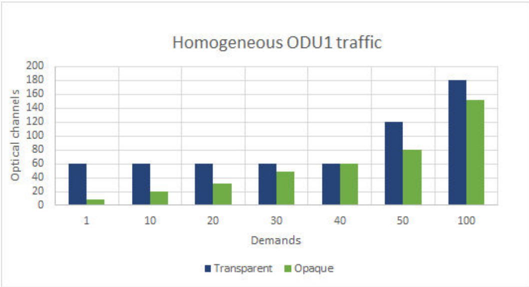

Figure 3.5: ILP solution for ODU1 client traffic

The analysis of results for ODU0 (1.25 Gb/s) client traffic is almost the same as for ODU1 traffic (2.5 Gb/s). A result to be highlighted is the number of optical channels for 40 demands of traffic. If there are 40 demands at 2.5Gb/s, then it performs 100Gb/s which is the capacity of each optical channel. So, traffic aggregation is impossible because all optical channels are completely occupied.

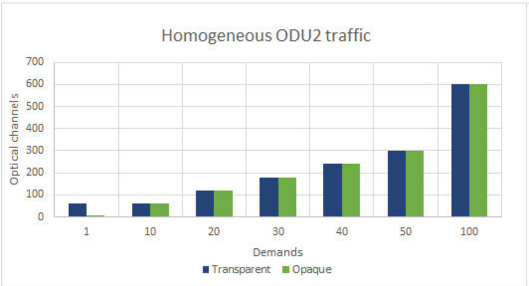

Figure 3.6: ILP solution for ODU2 client traffic

Both ILP models has approximately the same performance. As expected, the results sending one demand of traffic ODU2 (10Gb/s) are much better using opaque transport mode. When the number of demands is a multiple of 10, traffic between each node pair is a multiple of 100 (optical channel capacity), so link-by-link grooming has the same result as grooming only in end nodes.

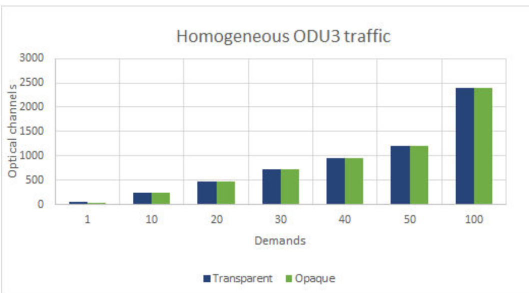

Figure 3.7: ILP solution for ODU3 client traffic

Figure 3.7 shows the behaviour of the algorithm for ODU3 (40Gb/s) traffic. The reasons why opaque and transparent models have practically the same results are mentioned above. It is important to note that 100 demands of ODU3 traffic are approximately 4Tb/s of traffic. When the number of optical channels required in a network is the same for both models, transparent is cheaper than opaque since some electrical components are not needed at intermediate nodes and the propagation of optical signals are faster. Wilfully, results for demands at 100Gb/s (ODU4) are not necessary since the demands has the same bandwidth as optical channels capacity, then there is no traffic aggregation.

After analysing and detailing the results for each client traffic and changing the number of demands, it is necessary to see the results from another point of view.

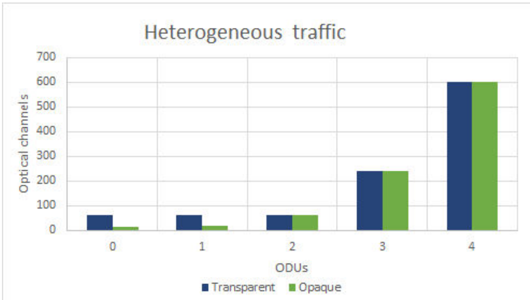

Figure 3.8: ILP solution changing client traffic type

Then, setting number of demands constant and changing the type of traffic, the number of optical channels has a big leap for client traffic based on demands of ODU3 and ODU4 traffic. Transparent model has 8 times more optical channels for signals with the lowest bandwidth.

3.5 Chapter Summary

In sum, this chapter was dedicated to the introduction of linear programming concept. In order to understand the meaning of mathematical models, all models used were described in the first section. The description of proposed integer linear problems in mathematical form as well as the use of optimization packages and their specific syntax are essential for the developer. Finally, the results prove the efficiency of opaque model for lower bandwidth traffic and a small difference when client traffic has higher bandwidth. In cases where the number of optical channels is lower, it will be beneficial to use an opaque network, however when the number of optical channels is similar to the transparent network, transparent network is cheaper and the signals take less time to reach their destinations.

Chapter 4

Heuristics

Heuristic approaches are techniques for solving a problem, faster than optimal methods and able to find an acceptable solution. Heuristics can be applied in several problems and are widely used in computer science and telecommunication networks [24, 25]. There are some commonly used heuristics such as genetic algorithm or simulated annealing. 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 a networks design software. The software was chosen for being open source and, consequently, easy to employ in academic projects. The grooming and routing algorithms presented in this chapter involve a graphical user interface developed for Net2Plan tool. Thus, section 4.1 is an overview of the routing algorithm, starting by trying to find the protection and work paths used by grooming algorithm. Aggregation algorithm is proposed in section 4.2. Routing and grooming algorithms are the core of the code behind the graphical user interface and focus in all the steps required for an offline simulation. 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 obtaining the number of necessary ports of the designed network. Concerning publication of the results, node features and most expensive components are depicted on the last subsection. In section 4.4, the algorithms proposed in previous sections are tested and compared with those of the previous chapter. Finally, 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.

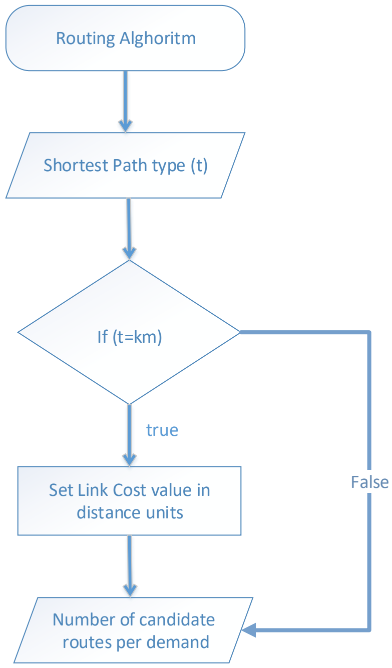

Figure 4.1: Heuristic routing algorithm code flow

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, in order 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 corresponding 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.

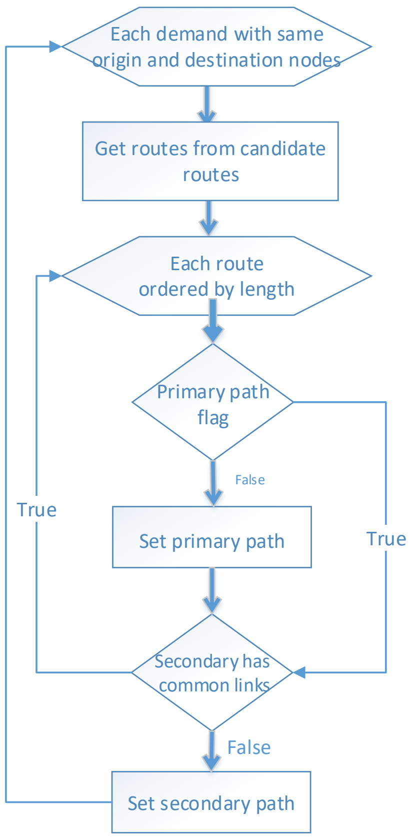

Figure 4.2: Heuristic routing algorithm code flow

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 disabled. 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 to 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".

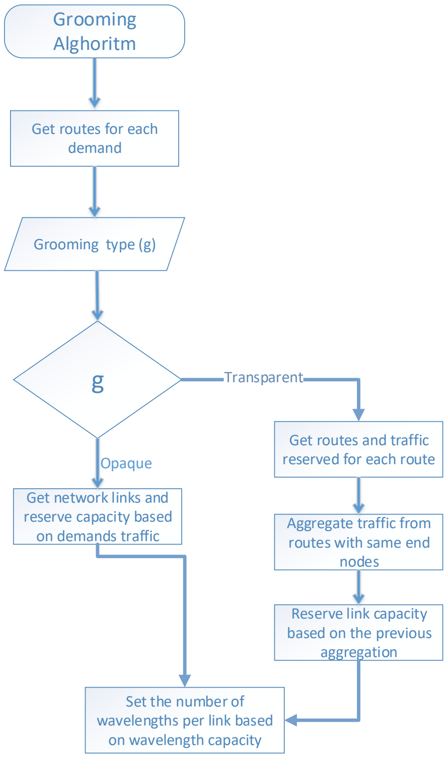

Figure 4.3: Heuristic grooming algorithm code flow

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 gives 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 ports) in each node. 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 needs to be divided by wavelength capacity as in the previous grooming type. Obviously, these 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 [2]. 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.

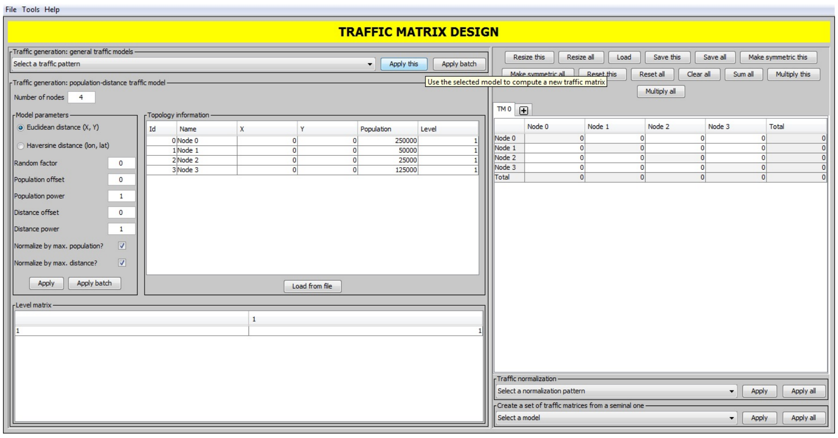

Figure 4.4: Net2Plan user interface for traffic matrices creation

The matrices created can be defined as a matrix with constant traffic, so the amount of traffic between all node pairs are the same. Another possibility is to 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 them manually as 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 type of client bit rate (ODU0, ODU1...) is needed a network topological design.

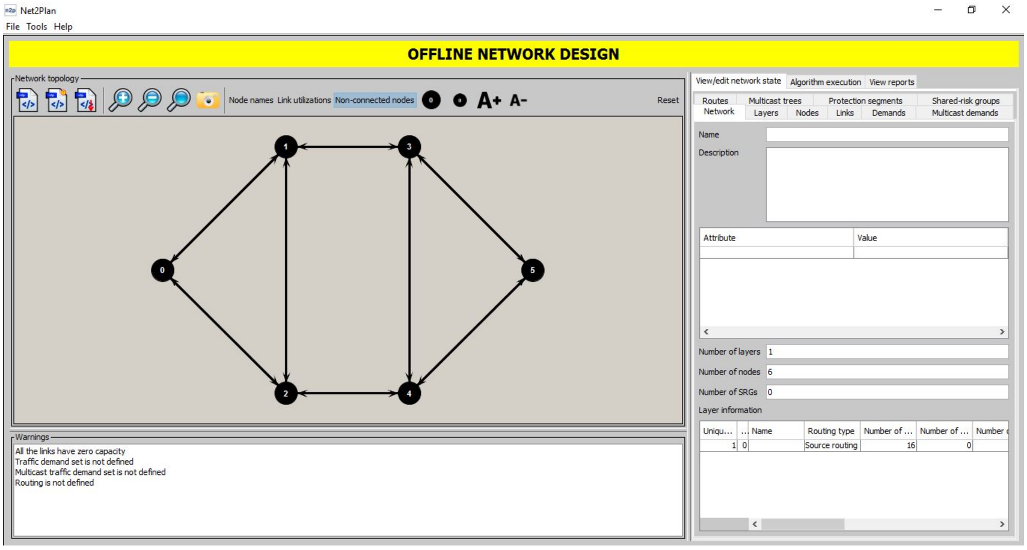

Figure 4.5: Net2Plan user interface for reference network topological design

In figure 5.2 it 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.

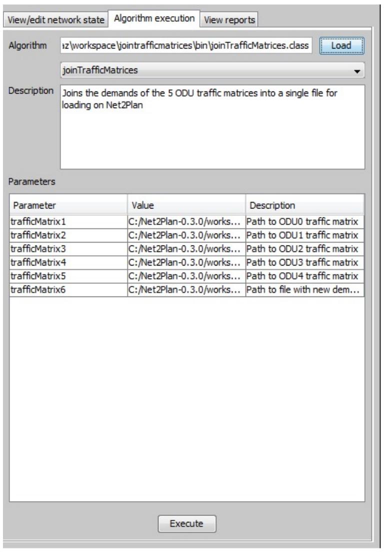

Figure 4.6: Net2Plan join traffic matrices alghoritm input parameters

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.

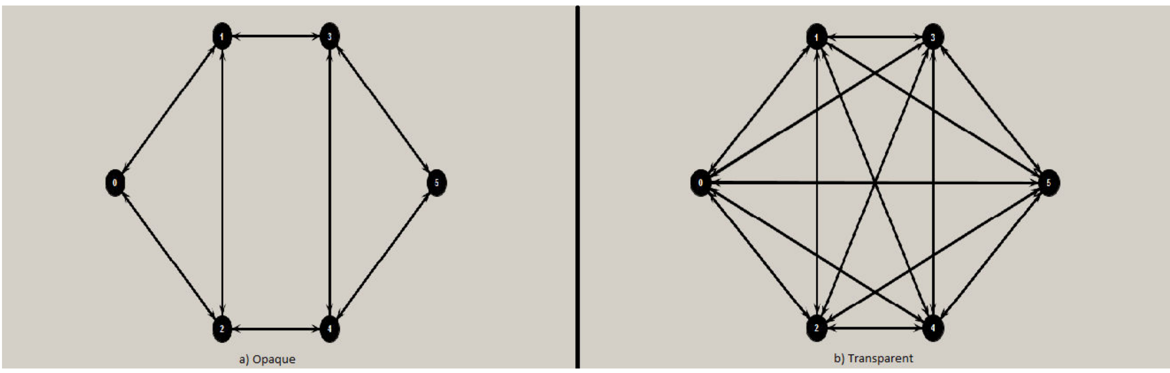

Figure 4.7: Net2Plan logical topology for reference network physical topology based on a) Opaque transport mode b)Transparent transport mode

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.

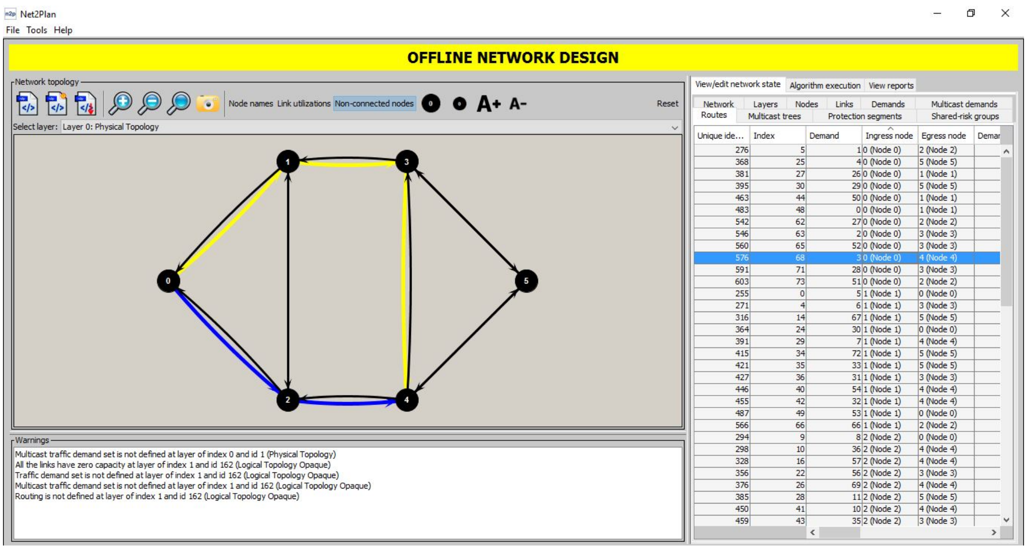

Figure 4.8: Net2Plan route using *grooming dedicated* alghoritm

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, for instance, of 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

More information can be obtained on the reporting algorithms that will be detailed in next chapter.

4.4 Heuristic results validation

Heuristics are approximate results so their results when not compared to a solution taken as correct may be misleading. Thus, the algorithms were tested using the same inputs as ILP models and the results are presented through line graphs and compared with previously obtained bar graphs. The blue line is relative to the results for transparent transport mode and the yellow line for the opaque transport mode.

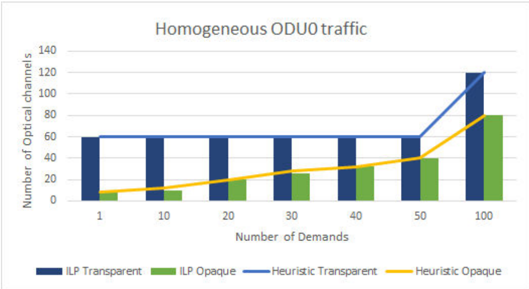

Figure 4.10: Heuristic solution for ODU0 client traffic

The figure above shows that even when grooming is done for small amounts of low-bandwidth traffic, the results are close. In the results of transparent transport mode, the line has exactly the same points as the graph which means that the traffic was aggregated through the same method. On the other hand, for opaque transport mode the results are slightly different, but as the number of demands increases the relative error suffers a huge decrease.

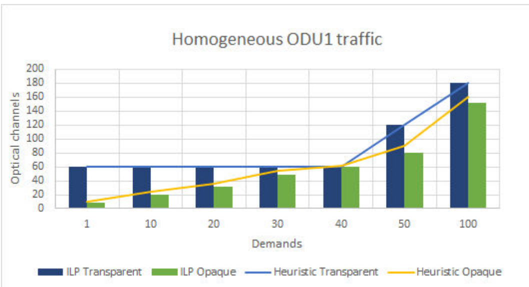

Figure 4.11: Heuristic solution for ODU1 client traffic

From the results for ODU1 traffic the same considerations are correct. Then, the comparative results are the same for transparent model and have small differences for opaque. The results for 40 demands are the same for all models and transport modes, because 40 demands requires 100Gb/s of bandwidth which is the total capacity of each optical channel, then there is no possible traffic aggregation.

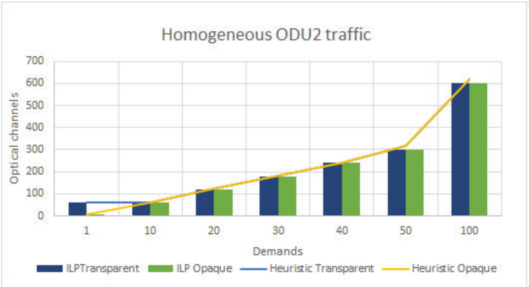

Figure 4.12: Heuristic solution for ODU2 client traffic

When demands at 10Gb/s are used the differences between ilps and heuristics are minimal and they are only visible when the number of demands is not a multiple of 10. When one demand is sent the opaque model is much more advantageous in terms of grooming for both approaches.

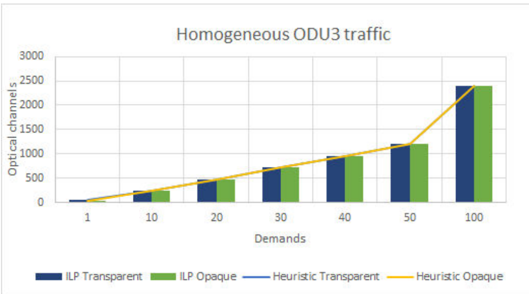

Figure 4.13: Heuristic solution for ODU3 client traffic

Traffic at 40Gb/s (ODU3) is high bandwidth traffic, therefore the aggregation in channels in 100Gb/s can not be done in different ways, so the results are approximately the same for both transport modes and methods. Sending 100 demands of traffic, it has 2500 optical channels which is a huge number and a consequence of the flow of 4Tb/s between each node pair.

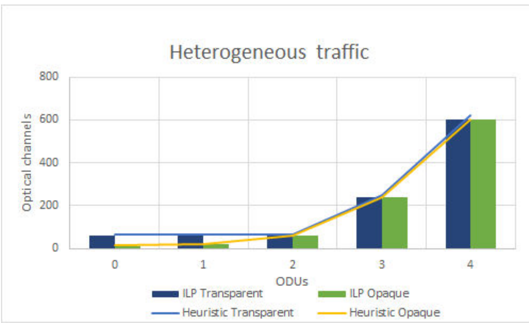

Figure 4.14: Heuristic comparative results for heterogeneous traffic

The last validation results were obtained applying heuristic methods in sex node reference network and changing client traffic type. Relative error between ILP solution and heuristic is less than 0.1. The number of optical channels for high bandwidth traffic is accordingly high.

4.5 Chapter Summary

In sum, the implementation of heuristics involves not only the creation of the algorithms but also their implementation in an open source software with graphical user interface called Net2Plan. This customized software has four algorithms developed in the context of this dissertation. The first is used for conversion of traffic matrices. The visualization of the network logical topology is performed by the second algorithm proposed. Routing and grooming algorithm is the core of the program. The code flow and graphical user interface of this algorithm can be seen in this chapter. The last customization made on net2plan concerns the presentation of results that is done in the reports section. Then, regarding the validation of the heuristic methods, in the last section is shown the comparative results between ILPs and Heuristics. The results of heuristics are in line with ILP results for homogeneous and heterogeneous traffic and using the six node reference network.

Chapter 5

Case Study

A network dimensioning software is used in the design of real networks. The cost of a network depends on the network size and capacity, but this huge investment from network stakeholders re-enforces the importance of network planning. There are networks created for research purposes and installed in the field. Then, to get results from a real network, it will be studied a network from United States known as NFSNET. The first section of this chapter is a network characterization in terms of physical network elements regarding their geographic location and the traffic matrix generated. In section 5.2 is presented an approach for network cost, considering the cost of links and the cost of nodes. This section has the equations used as the basis of network cost reports in Net2Plan. This equations perform network cost using as input the most expensive network components cost defined by the designer. In section 5.3, the results in terms of tributary and line ports and network cost of opaque transport mode are shown. The results of the transparent transport mode for the same matrix of traffic are described in the next section (5.4). The chapter ends, as in previous chapters, with a brief overview of all important information and results of the chapter.

5.1 NSFNET

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.

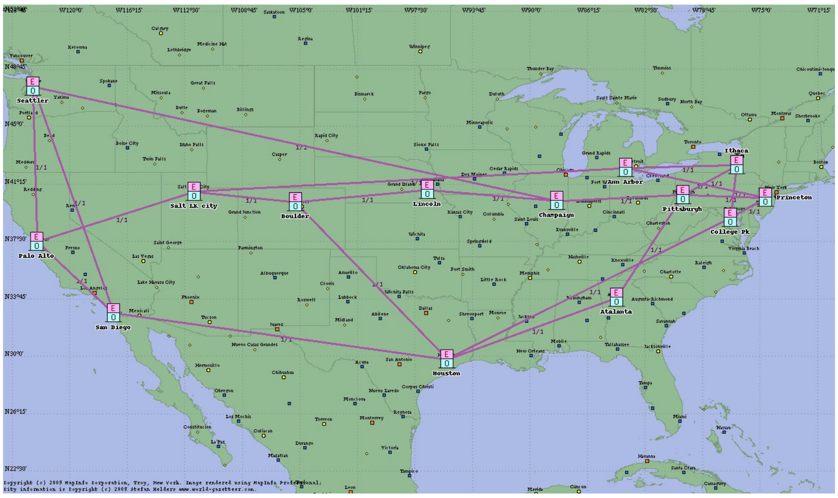

Figure 5.1: NSF Network topology [3].

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.

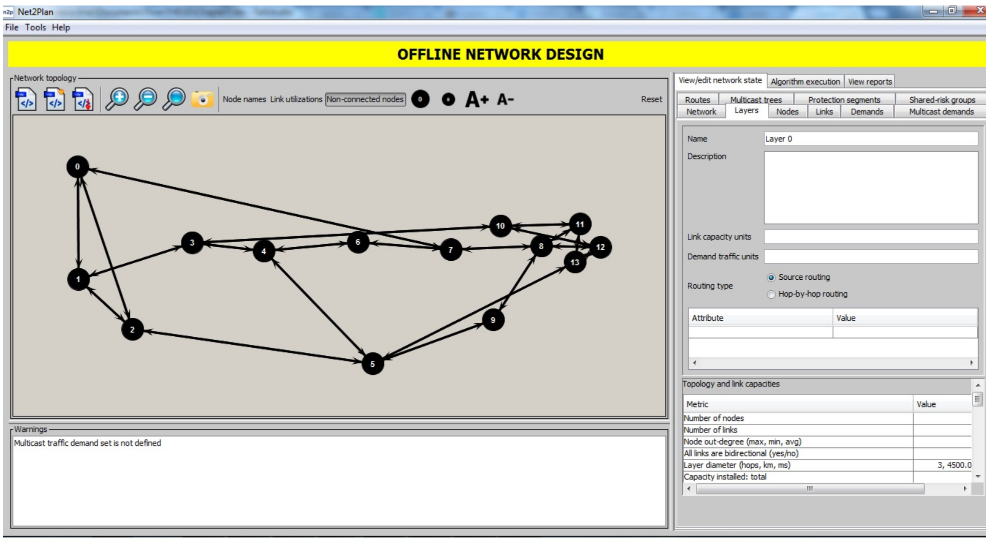

Figure 5.2: Net2Plan user interface for NSFNET topological network design

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

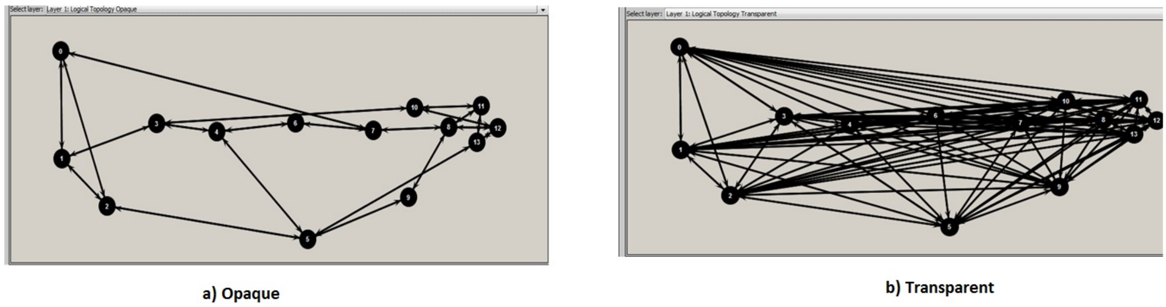

Figure 5.3: Net2Plan logical topology for NSFNET physical topology based on a) Opaque transport mode b)Transparent transport mode

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.

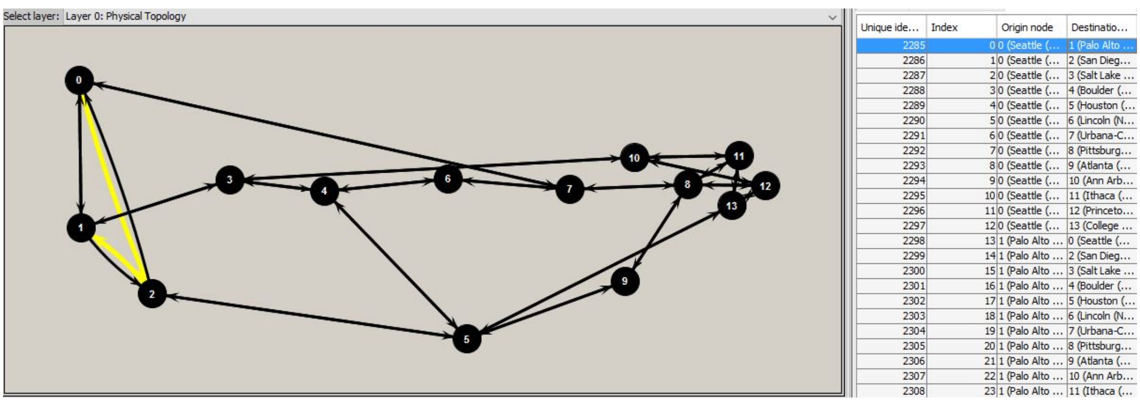

Figure 5.4: Protection traffic route between Seattle and Palo Alto

5.2 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 [26].

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

- $C_L \rightarrow$ 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

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.

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

- $C_{exc} \rightarrow$ Electrical Equipment 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 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

5.3 Opaque topology results

The consequences of the network designing can be seen in Net2Plan reports. As previous chapters the results for opaque transport mode are obtained first. So, using the traffic matrix proposed in the first section, the results in terms of tributary and line ports are:

Name	Trib ports in	Trib ports out	Line Ports in	Line Ports out	Total Ports in	Total Ports out
Seattle (WA)	5	5	21	21	26	26
Palo Alto (CA)	5	5	17	17	22	22
San Diego (CA)	5	5	19	19	24	24
Salt Lake City (UT)	4	4	22	22	26	26
Boulder (CO)	4	4	27	27	31	31
Houston (TX)	6	6	34	34	40	40
Lincoln (NE)	5	5	17	17	22	22
Urbana-Champaign (IL)	6	6	27	27	33	33
Pittsburgh (PA)	6	6	33	33	39	39
Atlanta (GA)	4	4	16	16	20	20
Ann Arbor (MI)	5	5	17	17	22	22
Ithaca (NY)	5	5	16	16	21	21
Princeton (NJ)	4	4	20	20	24	24
College Park (MD)	7	7	20	20	27	27
Total	71	71	306	306	377	377

Figure 5.6: Opaque ports per node

The number of ports per node for opaque transport mode. Tributary ports are the ports used for input traffic in a node from access networks. For instance, Seattle node requires 10 tributary ports because of bidirectional traffic. To send line signals is required line ports, two ports are required per line signal because signals considered are bidirectional also. The table above is given by reports algorithm and is the basis to calculate network cost.

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

Figure 5.7 contains the table of the network cost for NFSNET and the input traffic of 5Tb/s. The important information, besides total cost, is the cost of optical switches which is equals to zero. The switching is performed in electrical domain, so the node cost is given by the electrical switching equipments. The number of transponders is proportional to the number of optical channels and the most expensive components. The total network cost in euros is 193,118,000 for the equipments price defined in previous chapter.

5.4 Transparent topology results

The results for transparent transport mode in NFSNET are shown in the current section. The number of input and output ports for each node and the network CAPEX given by the network design software are crucial information for network planning. Then, the results for the same traffic matrix are:

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

An important information is the total number of ports. In opaque transport mode, the total number of ports were 377 and for transparent transport mode are 1242. Obviously, it will affect the cost of the network. The huge number of line ports is related with the grooming. The grooming link-by-link is more efficient than grooming in end nodes.Then, it is important to see the impact of the number of ports on the total cost of the network.

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

Unlike the previous model, this transport mode requires optical components in nodes. The total network cost in euros is 571,603,000 and comparing with opaque transport mode which is less than half of this value it shows how grooming is important. The number of transponders is almost five times more, because of the number of optical channels. The number of optical amplifiers for transparent and opaque transport modes is the same, because the physical links as the same length. Transparent transport mode requires less electrical switches than opaque transport mode, but the price to pay for less efficient grooming is great.

5.5 Chapter Summary

In summary, heuristic methods are crucial for network planning, since they can be applied in real networks. Despite there are several networks used for researching and academic studies, NFSNET was the option taken for testing in this work. This network from the United States of America has fourteen nodes and twenty one links, making it more generic and useful for testing. Applying both transport modes and the algorithms proposed on previous chapter, it is possible to obtain an estimation of the network ports per node and cost. It is also possible to conclude that, in general, opaque networks are cheaper than transparent networks, but this is not true when the number of optical channels is equal in both transport modes. The signal propagation is faster in transparent transport mode, then depending on the network requirements, the most efficient model may vary.

Chapter 6

Conclusions and future directions

6.1 Conclusions

Through this dissertation the optical network design problem was studied having dedicated path protection insight. The same physical topology may have several logical topologies, choosing for further study opaque and transparent types. For each logical topology approach an ILP model was developed. These models contain a set of constraints used to minimize or maximize an objective function, in order to find an optimal solution. Both ILP models proposed were implemented using a mathematical software and an open source solver, and both of them were tested in a reference network, with the comparison results being shown and analysed during chapter 3. Having ILP results as optimal solutions for the dimensioning problem, heuristic approaches were then developed to find similar solutions for the same problems.

The main advantage of using heuristics is the save in processing time. Then, in chapter 4, a set of algorithms capable of being implemented in an open source software with graphical user interface was proposed. The results obtained through the algorithms were compared with those obtained by ILP models to verify their quality. The relative error was not considerably high, so the algorithms could be a good solution for the real network design problem. By the end, in chapter 5, the heuristic solution was applied to a real network which is used primarily for academic and research purposes. The results of this test, in a more real environment, revealed some advantages in terms of cost for the opaque network, since grooming is more efficient. However, from the results of the previous chapters, it is known that when the number of channels is equal in both models it is advantageous to choose the transparent model, as it is cheaper to implement and is able to achieve a faster signal transmission. As it can be verified in the results section of the chapter 5, optical network has a huge CAPEX so it is important to invest in the improvement of the dimensioning tools to minimize the required resources.

6.2 Future directions

Through this dissertation it was clearly shown the importance of network planning in a world with an increasing number of digital devices requiring faster and infallible interconnections. While data is exponentially growing and its transport means everything, this dissertation gives way to a new exploration work which should be stopped here. There is always space for improvement especially when optimization is involved. Some of the most important topics are presented below:

1. Heuristics and ILP tested in this dissertation with transparent and opaque networks can be applied in the future to different transport types, making it possible to evaluate advantages and disadvantages of choosing translucent transport.

2. Regarding protection methods, there are also several options that should be taken into account affecting directly the network planning. The usage of shared protection or dedicated link protection may also be considered and tested. The combination of transport type and protection type create a whole new range of options which might come up as a better solution for some specific situation.

3. The customization and the inclusion of new features in Net2Plan would ease the testing process and retrieve results quicker.

4. A GIT repository was already created during this dissertation. There the existing code was released, as well as a document, shown in appendices, which explains in detail how to generate algorithms to be used in Net2Plan. Giving continuity to this repository also composes an important part of the future work, ensuring code organization and a well-documented investigation.

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Appendices

NetPlanner

University of Aveiro

October 26, 2016

Contents

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.

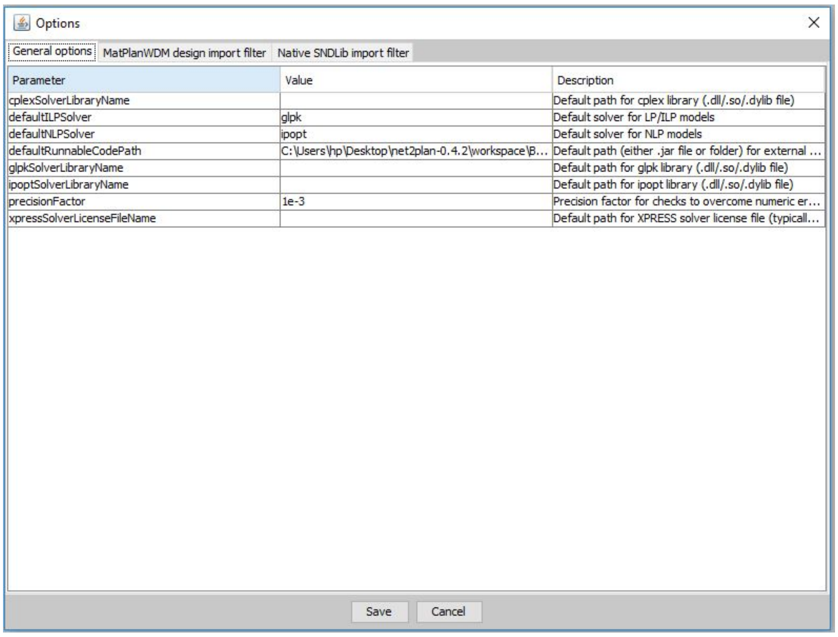


Figure 2: Net2Plan General Options

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.

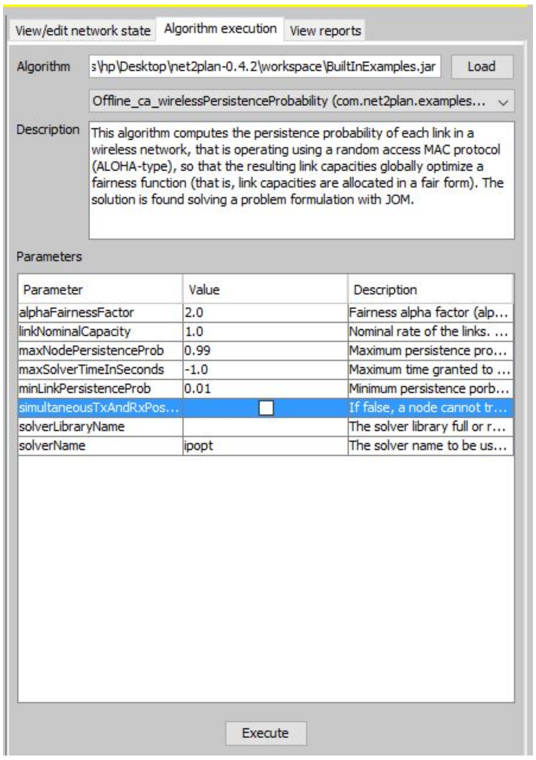


Figure 3: Net2Plan Algorithm with *ipopt* solver

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.

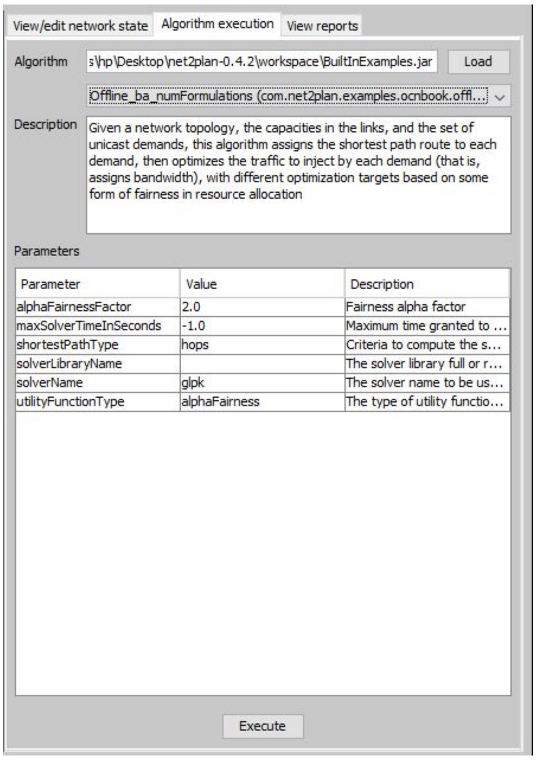


Figure 4: Net2Plan Algorithm with *glpk* solver

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.

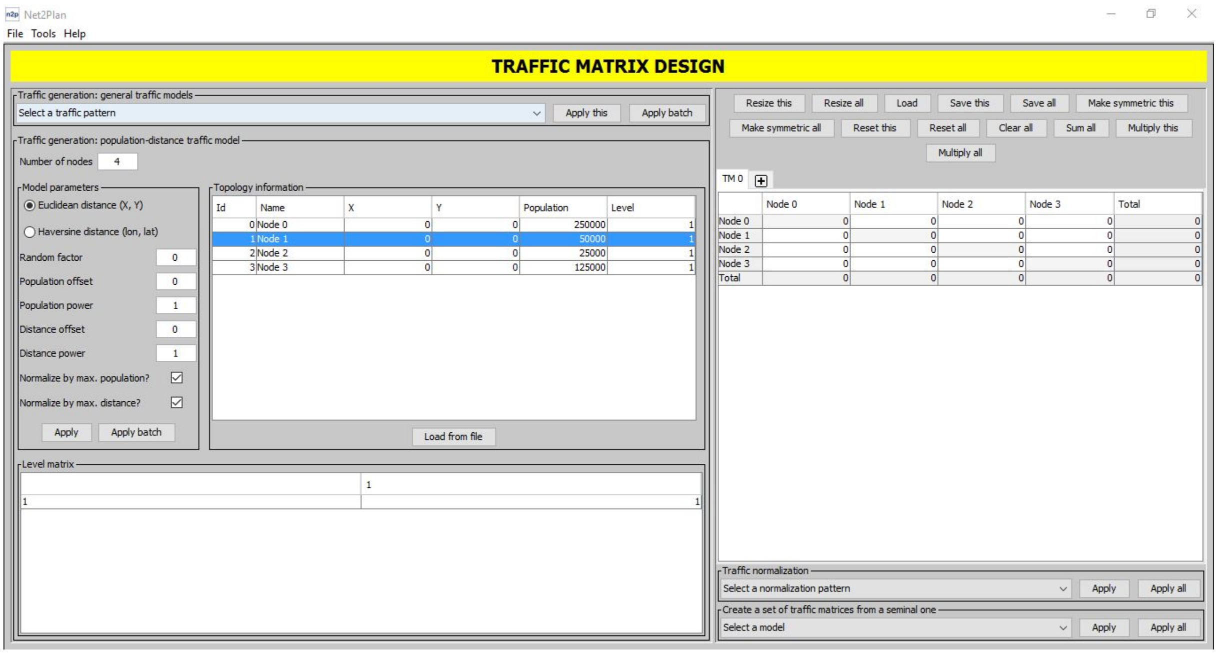


Figure 5: Net2Plan Traffic Matrix Design

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.

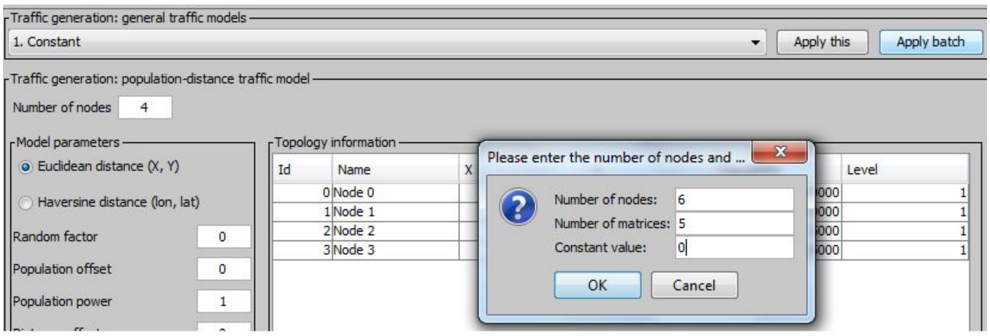
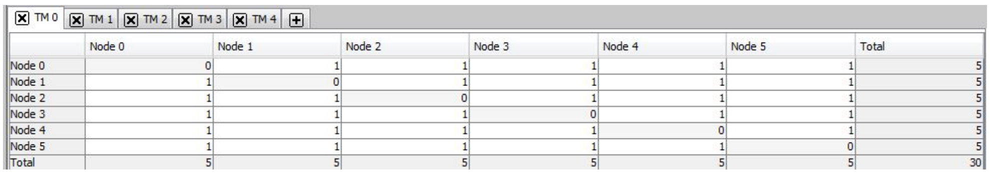


Figure 6: Net2Plan example on creating a batch of matrices

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.

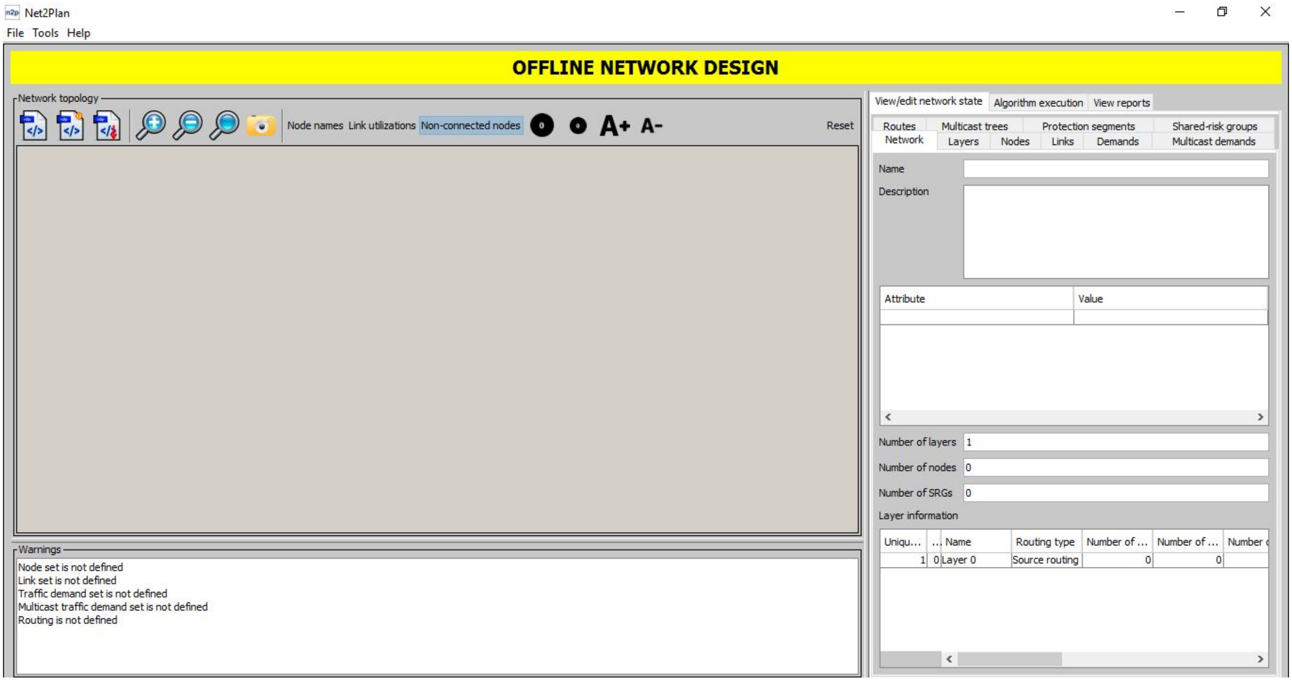


Figure 8: Net2Plan Offline Network Design

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.

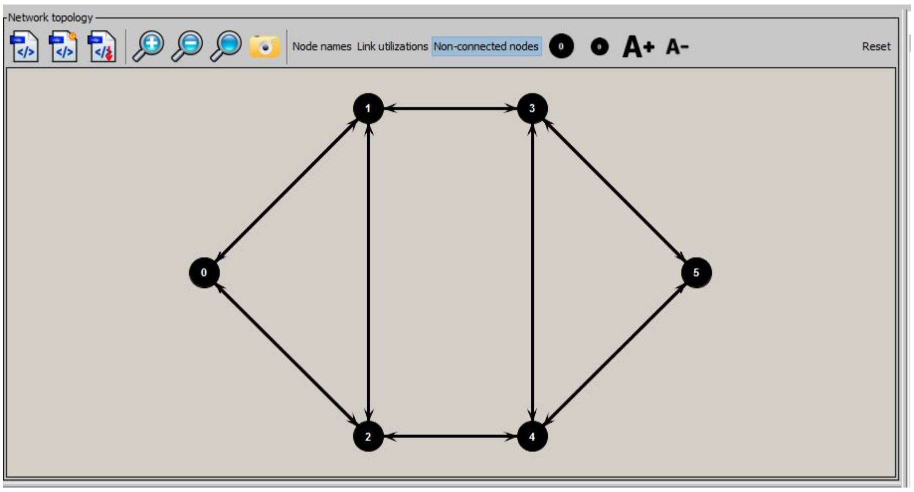


Figure 9: Net2Plan Network Example

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.

View/edit network state | Algorithm execution | View reports

Routes | Multicast trees | Protection segments | Shared-risk groups
Network | Layers | Nodes | Links | Demands | Multicast demands

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)

View/edit network state | Algorithm execution | View reports

Routes | Multicast trees | Protection segments | Shared-risk groups
Network | Layers | Nodes | Links | Demands | Multicast demands

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.

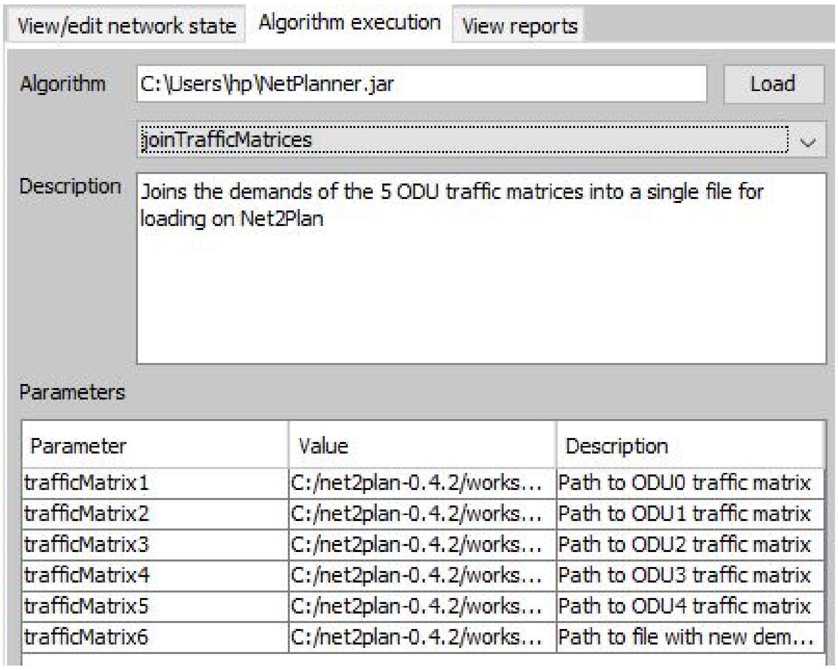


Figure 11: joinTrafficMatrices Algorithm

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.

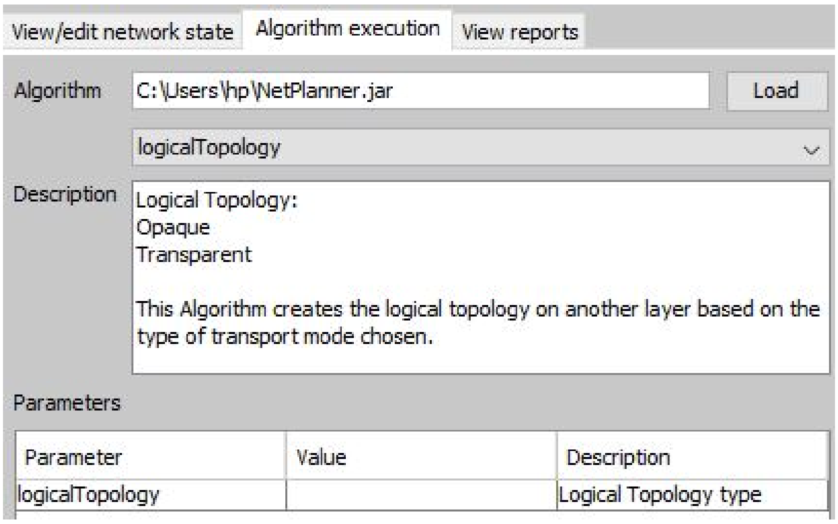
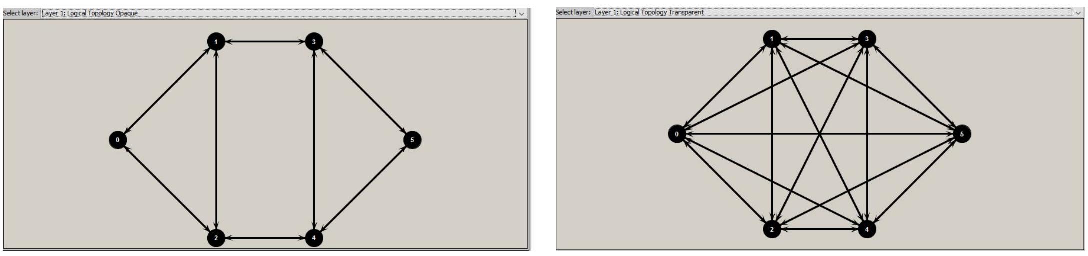


Figure 12: Net2Plan Logical Topology Algorithm

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.

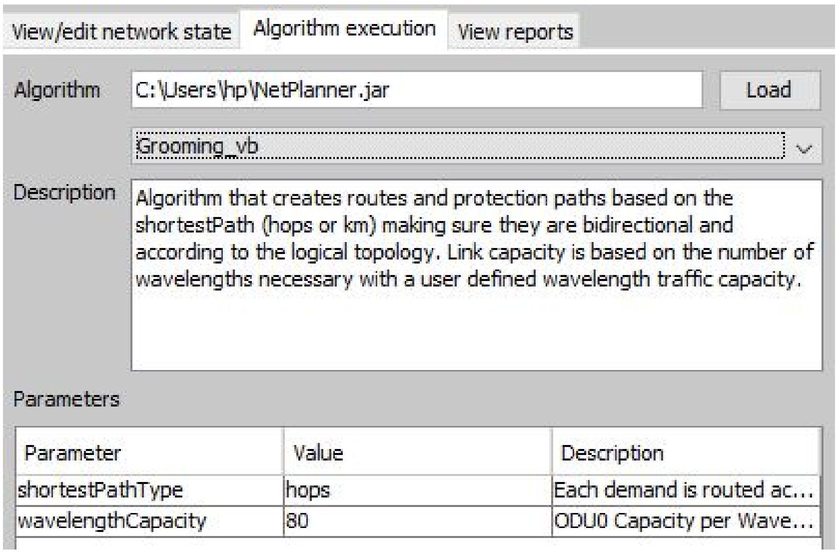


Figure 14: Net2Plan Grooming shortest Path Algorithm

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.

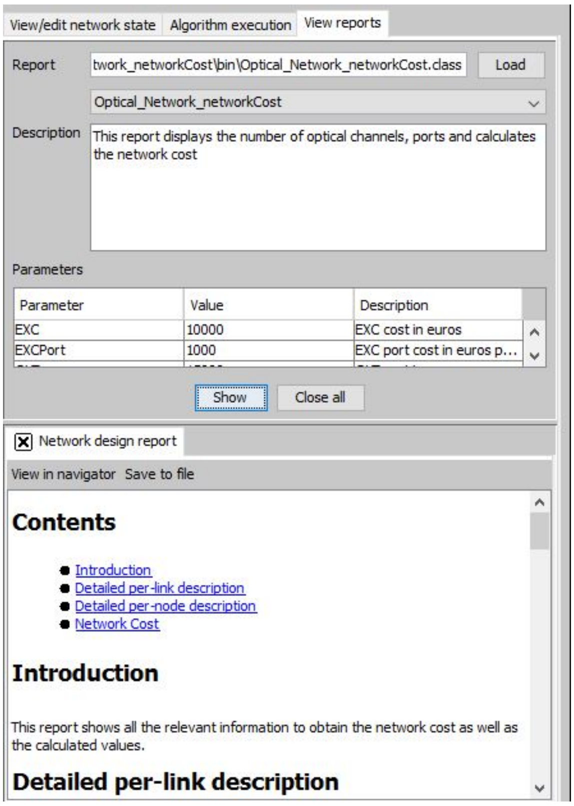


Figure 15: Network Cost Report

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

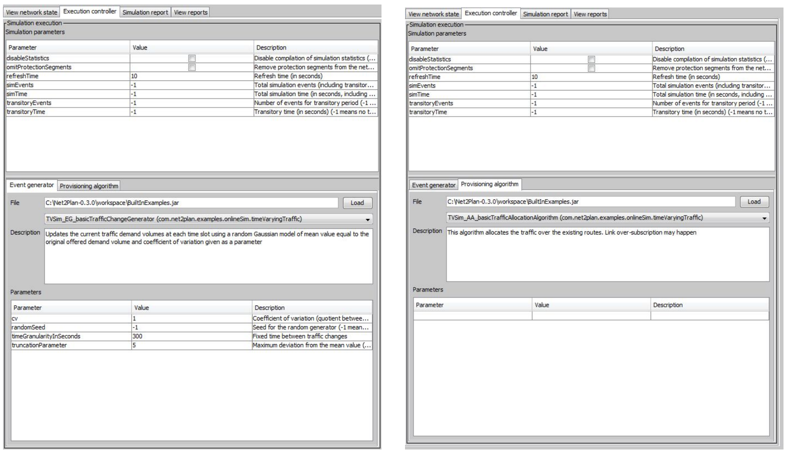
The results obtained for the network Cost confirm those obtained in the previous categories in this report. The OLT and amplifiers cost does not change as the number of links and amplifiers remains the same. Similarly, the electrical ports cost is also the same as the amount of ADD/DROP ports remains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

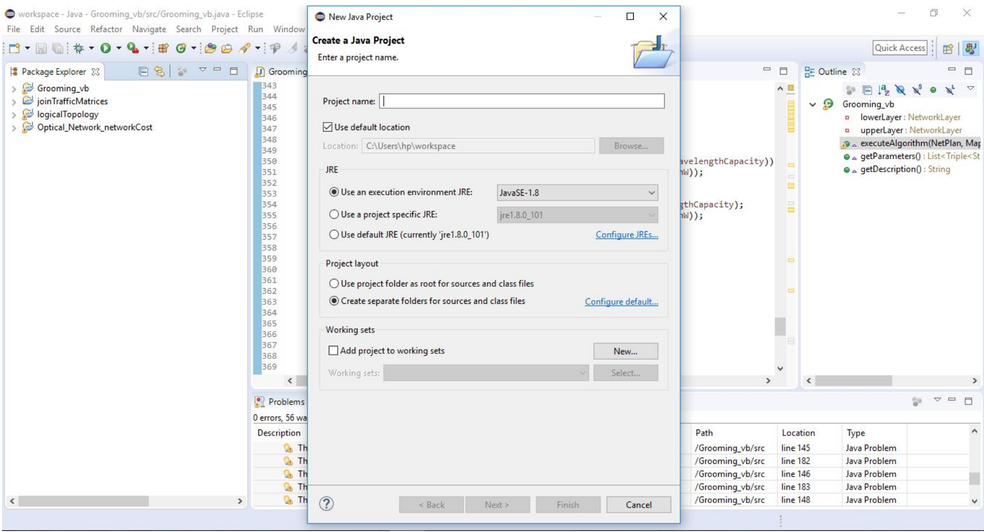


Figure 24: Eclipse new project

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”.

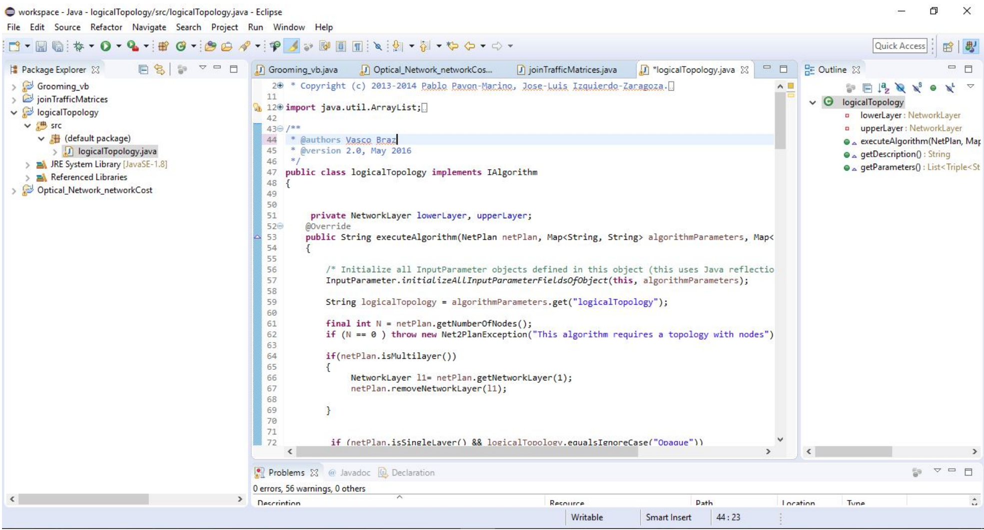
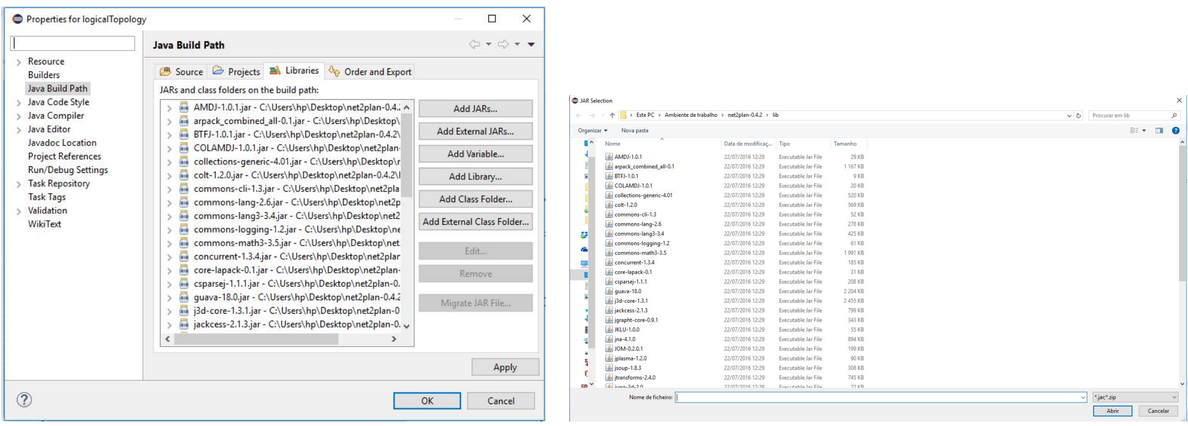


Figure 25: Eclipse new project with source file

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.

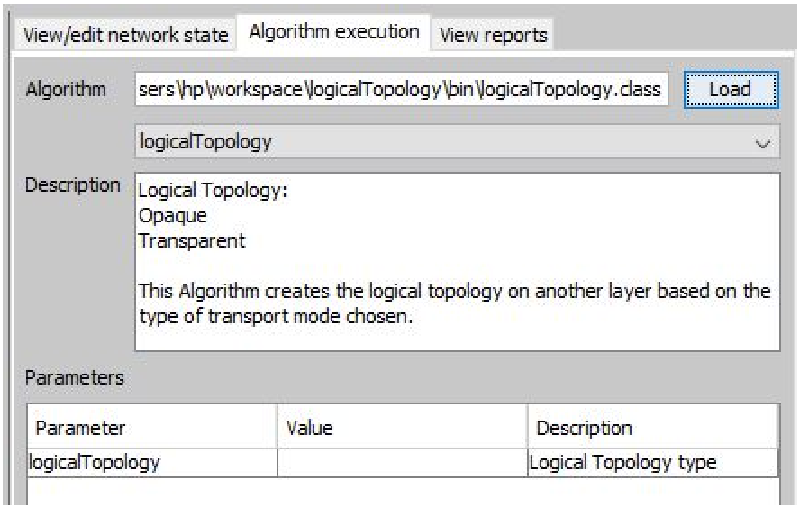
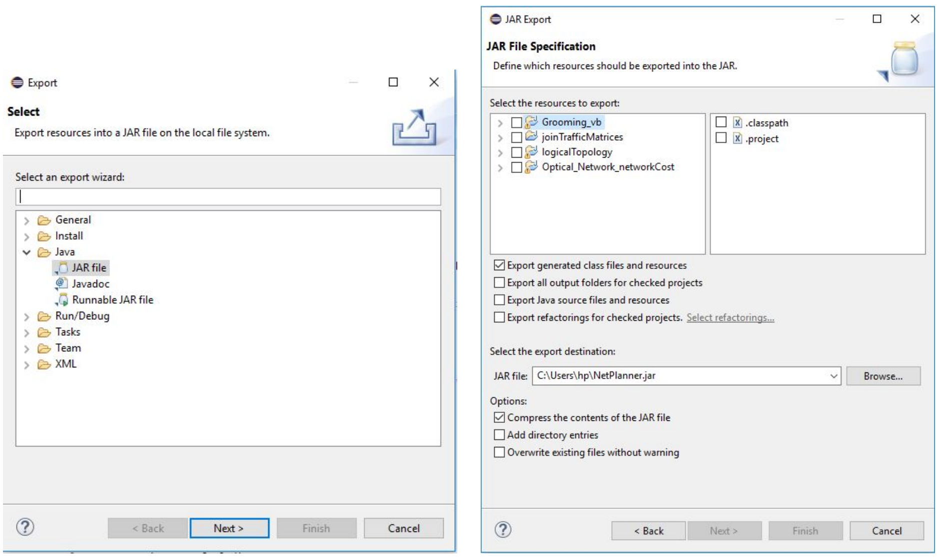


Figure 27: Net2Plan new algorithm

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.

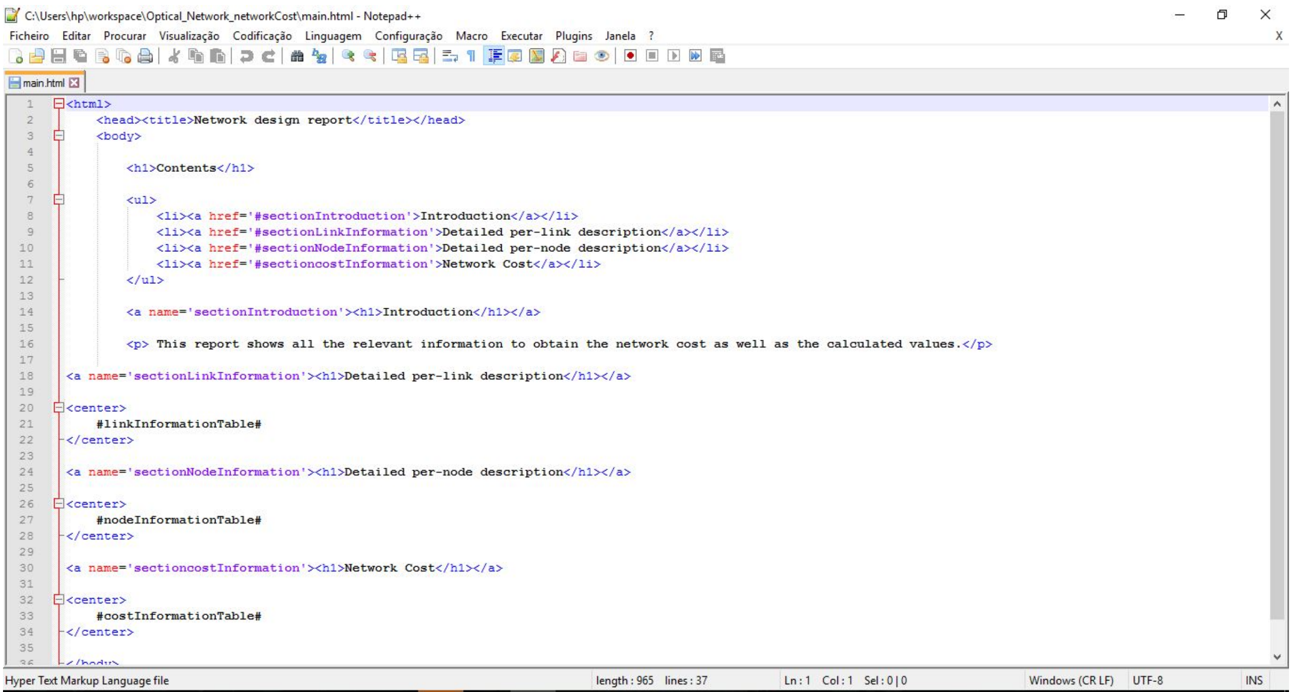
6 Developing new Reports

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>

</body>
```


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.