

NetXPTO - NetPlanner

12 de Julho de 2019

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

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

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 his own branch with his/her name.

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.

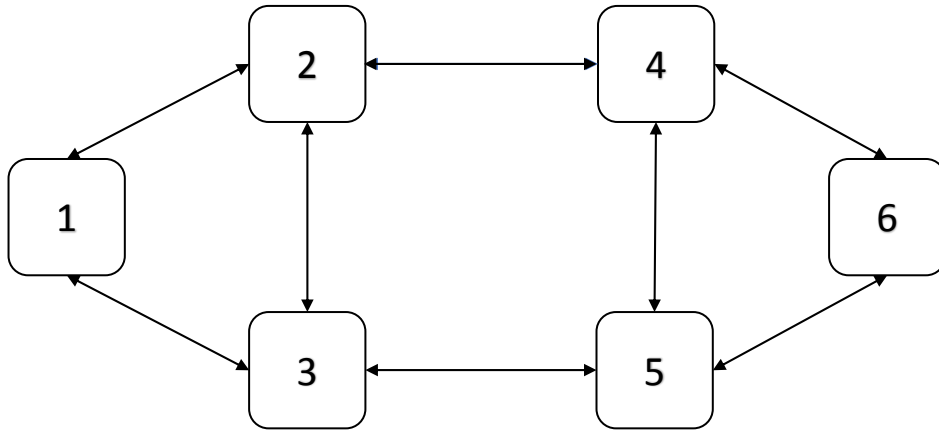


Figura 4.1: Physical topology of the reference network.

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
$\langle \delta \rangle$	Nodal degree	2.667
$\langle \text{len} \rangle$	Mean link length (km)	500
$\langle h \rangle$	Mean number of hops for working paths	1.533
$\langle h' \rangle$	Mean number of hops for backup paths	2.467

Tabela 4.1: Table of reference network values

4.2 Traffic Matrices

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

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:

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

$$\begin{aligned}
 ODU2 &= \begin{bmatrix} 0 & 1 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} & ODU3 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \\
 ODU4 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix}
 \end{aligned}$$

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

$$T_1^0 = 60 \times 1.25 = 75 \text{ Gbits/s} \quad T_1^1 = 50 \times 2.5 = 125 \text{ Gbits/s} \quad T_1^2 = 16 \times 10 = 160 \text{ Gbits/s}$$

$$T_1^3 = 6 \times 40 = 240 \text{ Gbits/s} \quad T_1^4 = 4 \times 100 = 400 \text{ Gbits/s}$$

$$T_1 = 75 + 125 + 160 + 240 + 400 = 1000 \text{ Gbits/s} \quad T = 1000/2 = \mathbf{0.5 \text{ Tbits/s}}$$

Where the variable T_1^x represents the unidirectional traffic of the ODU x , 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:

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

$$\begin{aligned}
 ODU2 &= \begin{bmatrix} 0 & 10 & 10 & 10 & 0 & 0 \\ 10 & 0 & 0 & 0 & 10 & 0 \\ 10 & 0 & 0 & 10 & 10 & 0 \\ 10 & 0 & 10 & 0 & 10 & 0 \\ 0 & 10 & 10 & 10 & 0 & 10 \\ 0 & 0 & 0 & 0 & 10 & 0 \end{bmatrix} & ODU3 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 10 \\ 0 & 10 & 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 & 0 \end{bmatrix} \\
 ODU4 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \\ 0 & 10 & 0 & 0 & 10 & 0 \end{bmatrix}
 \end{aligned}$$

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

$$T_1^0 = 600 \times 1.25 = 750 \text{ Gbits/s} \quad T_1^1 = 500 \times 2.5 = 1250 \text{ Gbits/s} \quad T_1^2 = 160 \times 10 = 1600 \text{ Gbits/s}$$

$$T_1^3 = 60 \times 40 = 2400 \text{ Gbits/s} \quad T_1^4 = 40 \times 100 = 4000 \text{ Gbits/s}$$

$$T_1 = 750 + 1250 + 1600 + 2400 + 4000 = 10000 \text{ Gbits/s} \quad T = 10000/2 = \mathbf{5 \text{ Tbits/s}}$$

4.2.3 High traffic scenario (10 Tbits/s)

The traffic matrices for this scenario are:

$$\begin{aligned}
 ODU0 &= \begin{bmatrix} 0 & 100 & 20 & 60 & 20 & 60 \\ 100 & 0 & 0 & 20 & 100 & 0 \\ 20 & 0 & 0 & 20 & 80 & 20 \\ 60 & 20 & 20 & 0 & 20 & 20 \\ 20 & 100 & 80 & 20 & 0 & 60 \\ 60 & 0 & 20 & 20 & 60 & 0 \end{bmatrix} & ODU1 &= \begin{bmatrix} 0 & 40 & 80 & 40 & 0 & 100 \\ 40 & 0 & 0 & 60 & 20 & 20 \\ 80 & 0 & 0 & 20 & 20 & 0 \\ 40 & 60 & 20 & 0 & 20 & 60 \\ 0 & 20 & 20 & 20 & 0 & 20 \\ 100 & 20 & 0 & 60 & 20 & 0 \end{bmatrix} \\
 ODU2 &= \begin{bmatrix} 0 & 20 & 20 & 20 & 0 & 0 \\ 20 & 0 & 0 & 0 & 20 & 0 \\ 20 & 0 & 0 & 20 & 20 & 0 \\ 20 & 0 & 20 & 0 & 20 & 0 \\ 0 & 20 & 20 & 20 & 0 & 20 \\ 0 & 0 & 0 & 0 & 20 & 0 \end{bmatrix} & ODU3 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 20 & 0 & 0 & 20 \\ 0 & 20 & 0 & 0 & 20 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 20 & 0 & 0 & 0 \\ 0 & 20 & 0 & 0 & 0 & 0 \end{bmatrix}
 \end{aligned}$$

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

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

$$T_1^0 = 1200 \times 1.25 = 1500 \text{ Gbits/s} \quad T_1^1 = 1000 \times 2.5 = 2500 \text{ Gbits/s}$$

$$T_1^2 = 320 \times 10 = 3200 \text{ Gbits/s} \quad T_1^3 = 120 \times 40 = 4800 \text{ Gbits/s}$$

$$T_1^4 = 80 \times 100 = 8000 \text{ Gbits/s}$$

$$T_1 = 1500 + 2500 + 3200 + 4800 + 8000 = 20000 \text{ Gbits/s}$$

$$T = 20000/2 = \mathbf{10 \text{ Tbits/s}}$$

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.

5.1 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 ??, 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, some 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 5.1

$$C_C = C_L + C_N \quad (5.1)$$

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)

On the first hand, the links' cost, C_L , in monetary units (e.g. euros, or dollars), is calculated by the equation 5.2. 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

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

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 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 5.3

$$C_N = C_{EXC} + C_{OXC} \quad (5.3)$$

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 constitution of the electrical node part can be seen in the Integer Linear Programming section ???. The electrical nodes' cost, C_{EXC} , in monetary units (e.g. euros, or dollars), is given by the equation 5.4

$$C_{EXC} = \sum_{n=1}^N N_{exc,n} \left(\gamma_{e0} + \sum_{c=-1}^B \gamma_{e1,c} P_{exc,c,n} \right) \quad (5.4)$$

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 5.1: Table with index and your corresponding bit rate

The constitution of the optical node part can be seen in the Integer Linear Programming section ?? . Finally, the optical nodes' cost, C_{OXC} , in monetary units (e.g. euros, or dollars), is given by the equation 5.5

$$C_{OXC} = \sum_{n=1}^N N_{oxc,n} (\gamma_{o0} + \gamma_{o1} P_{oxc,n}) \quad (5.5)$$

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

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 5.2 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 5.2: Table with costs

5.1.1 Opaque without Survivability

Student Name	:	Élio Coelho (01/10/2018 -)
	:	Pedro Coelho (01/03/2018 - 30/06/2018)
Goal	:	Implement the Heuristic model for the opaque transport mode without survivability.

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 cost report algorithm will be applied to visualize the network CAPEX results 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:

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

As previously mentioned, equation 5.6 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

$$P_{exc,-1,n} = \sum_{j=1}^N w_{nj} \quad (5.6)$$

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

As previously mentioned, equation 5.7 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

$$P_{exc,c,n} = \sum_{d=1}^N D_{nd,c} \quad (5.7)$$

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, $D_{nn,c} = 0$.

To implement this heuristic approach there are used algorithms made in Java in a programming software called Eclipse and they are tested in an open-source network program called Net2Plan. In the Net2Plan guide section ?? there is an explanation on how to use and test them in this network planner.

In the next pages it will be described all the steps performed to obtain the final results in the opaque transport mode without survivability. In the figure below 5.1 it is shown a fluxogram with the description of this transport mode approach.

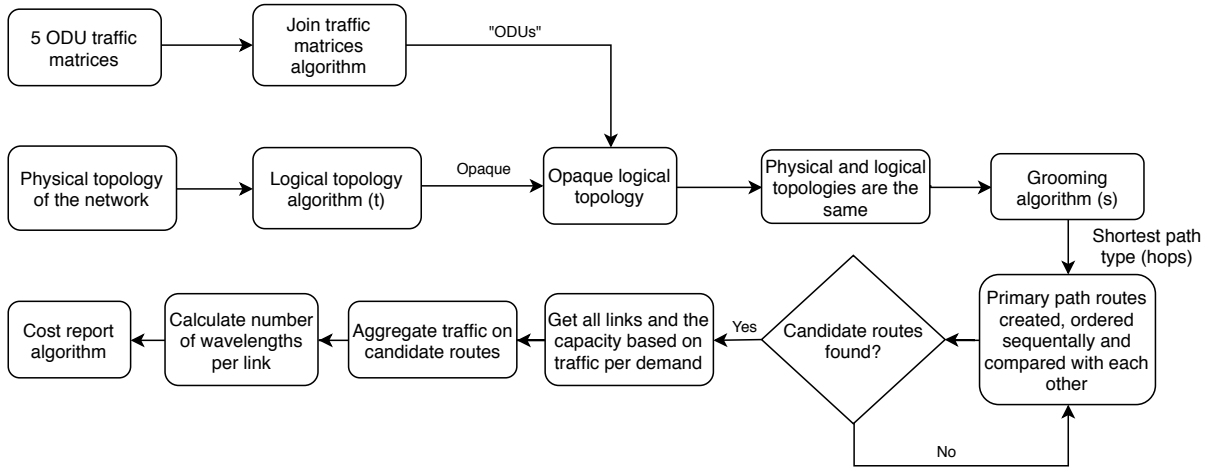


Figura 5.1: Fluxogram with the steps performed in the opaque without survivability transport mode approach.

Creation and join the traffic matrices

The first step is to create the traffic matrices based on the reference network 4.1. In order to create the 5 traffic matrices in Net2Plan it is necessary the length of all the links and the total traffic used in this network, so later it is needed to define in Net2Plan the length in all end nodes and the total traffic depends on the value of traffic used (low traffic - 0.5 Tbit/s, medium traffic - 5 Tbit/s and high traffic - 10 Tbit/s). As you can see in the figure below, it is defined the path of the 5 ODUs and they will be aggregated in just one single ODU, making it possible to join all the demands in just one file and load it later into the network. This final resulting ODU joins the multiple traffic demands from all the traffic matrices previously created and, of course, the traffic demands will depend on the values used on the creation of the matrices (low, medium and high traffic).

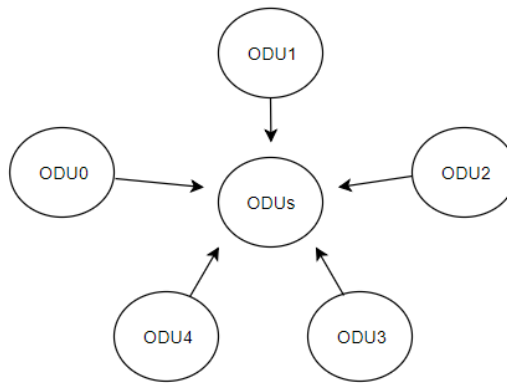


Figura 5.2: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.

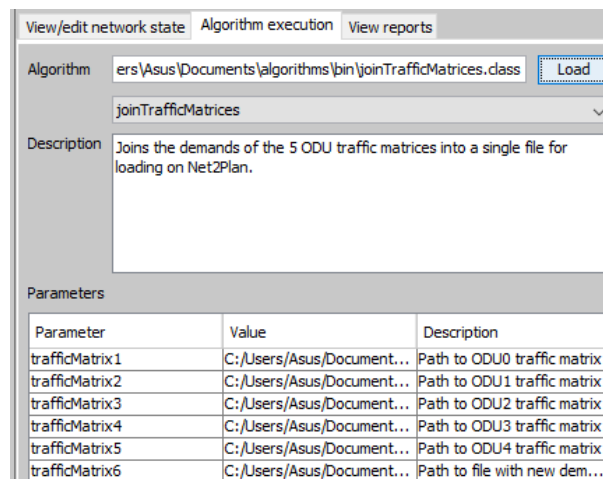


Figura 5.3: Load of the join traffic matrices algorithm for the opaque transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

The next step is to create the allowed physical topology of the network in Net2Plan. This network consists in 6 nodes and 8 bidirectional links. It is now also possible to define the length in all links. In the figure below it is shown the allowed physical topology in this transport mode.

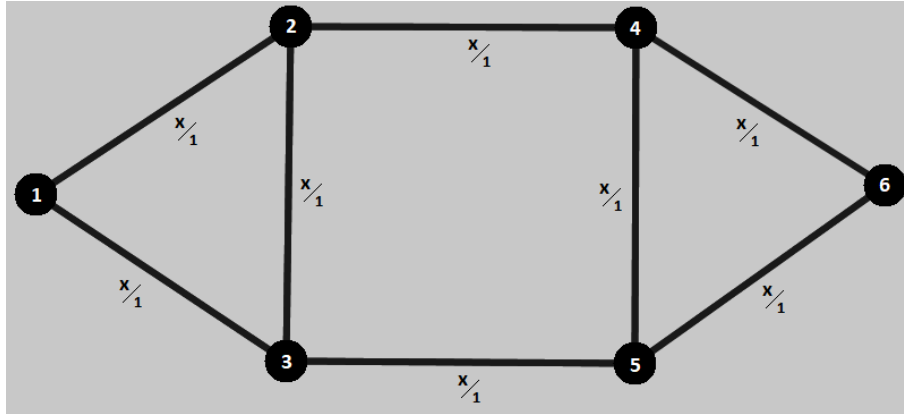


Figura 5.4: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. 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 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 physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 5.1.1 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the opaque transport mode without survivability.

```

if (netPlan.isSingleLayer() && logicalTopology.equalsIgnoreCase("Opaque"))
{
    lowerLayer = netPlan.getNetworkLayerDefault();
    upperLayer = netPlan.addLayerFrom(lowerLayer);
    netPlan.setRoutingType(RoutingType.HOP_BY_HOP_ROUTING, upperLayer);
    lowerLayer.setName("Physical Topology");
    upperLayer.setName("Logical Topology Opaque");
    upperLayer.setDescription("Opaque Logical Topology");
}

```

Figura 5.5: Java code of the logical topology approach for the opaque transport mode. The logical layer is created from the physical layer, as in this transport mode they are the same. The new layer is now the opaque logical topology of the network.

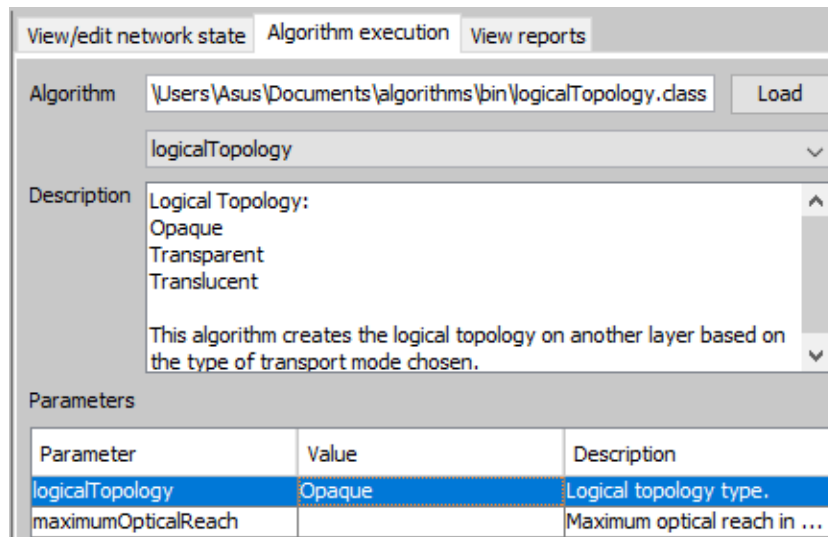


Figura 5.6: Load of the logical topology algorithm for the opaque transport mode.

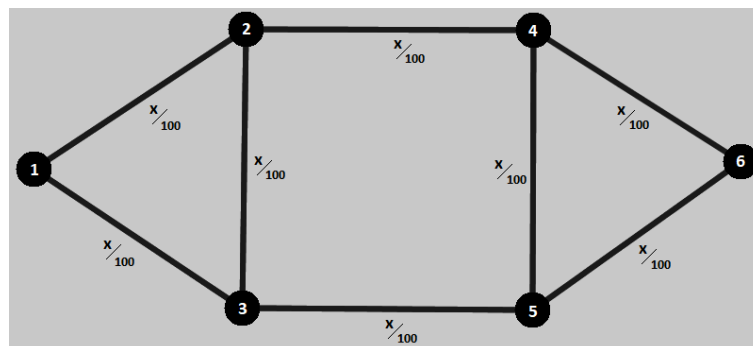


Figura 5.7: Allowed optical topology. It is assumed that each transmission system supports up to 100 optical channels.

Creation of routes and aggregation of traffic

After a network topology is created, it is now time to set the routing algorithm. In the opaque without survivability transport mode the routing algorithm starts with going through all the demands, create bidirectional routes (in this case the primary paths) based on the shortest path Dijkstra algorithm and then search the candidate routes for the respective demand. In this report it is used the shortest path type in hops. These routes are ordered sequentially and the shortest one per each demand is the primary path. The demands from the lower layer are removed and then saved in the upper layer. After this step, it is needed to set the traffic demands into the candidate routes that will integrate the network.

```
case "Logical Topology Opaque":
    for (Demand d : netPlan.getDemands(lowerLayer)) {
        boolean odd=true;
        int counter=0;

        Set<Route> droutes = d.getRoutes();
        System.out.println("droutes: " + droutes.size());

        for(Route c: droutes) {
            counter++;
            boolean jump=false;

            if(odd) {
                c.setCarriedTraffic(d.getOfferedTraffic(), d.getOfferedTraffic());
                save=c;
                odd=false;
                System.out.println("Roots");
            }
        }
    }
}
```

Figura 5.8: Creation of routes and aggregation of traffic for the opaque without survivability transport mode. The candidate routes are searched by the shortest path type method and the offered traffic demands are set into these routes.

Function	Definition
netPlan.getDemands(lowerLayer)	Returns the array of demands for the lower layer.
d.getRoutes()	Returns all the routes associated to the demand "d".
c.setCarriedTraffic()	Sets the route carried traffic and the occupied capacity in the links, setting it up to be the same in all links.
d.getOfferedTraffic()	Returns the offered traffic of the demand "d".

Tabela 5.3: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

The final step of the routing and grooming algorithms is to calculate the number of wavelengths per link for the whole network. This is the last and an important step because with the number of wavelengths per link in the network, it is possible to calculate other network components. In the opaque transport mode, as in the figure below shows, the algorithm starts with going through all the links and getting the capacity based on the traffic per demand. The total carried traffic in the link including protection and non-protection segments will be divided by the wavelength capacity and it is now possible to obtain the number of wavelengths per link.

```
Link p;
for(long e:linkIds) {
    p=netPlan.getLinkFromId(e);
    double sumTraffic = p.getCarriedTrafficNotIncludingProtectionSegments() + p.getReservedCapacityForProtection();
    int nw = (int) (Math.ceil(sumTraffic/wavelengthCapacity));
    String numberWavelengths = String.valueOf(nw);
    p.setCapacity(nw*wavelengthCapacity);
    p.setAttribute("nw", numberWavelengths);
}
break;
```

Figura 5.9: Calculation of the number of wavelengths per link for the opaque transport mode. The link capacity is based on the traffic per demand.

Parameter	Value	Description
numberofroutes	10	Total number of routes p...
protection	no	1+1 protection (yes/no).
shortestPathType	hops	Each demand is routed ac...
wavelengthCapacity	100	Capacity per wavelength.

Figura 5.10: Load of the grooming algorithm for the opaque without survivability transport mode. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 5.1.1 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details. In the opaque transport mode the optical node cost is 0 because all the network ports are electrical, so it only has to be considered the electrical nodes' costs and the electrical links' costs.

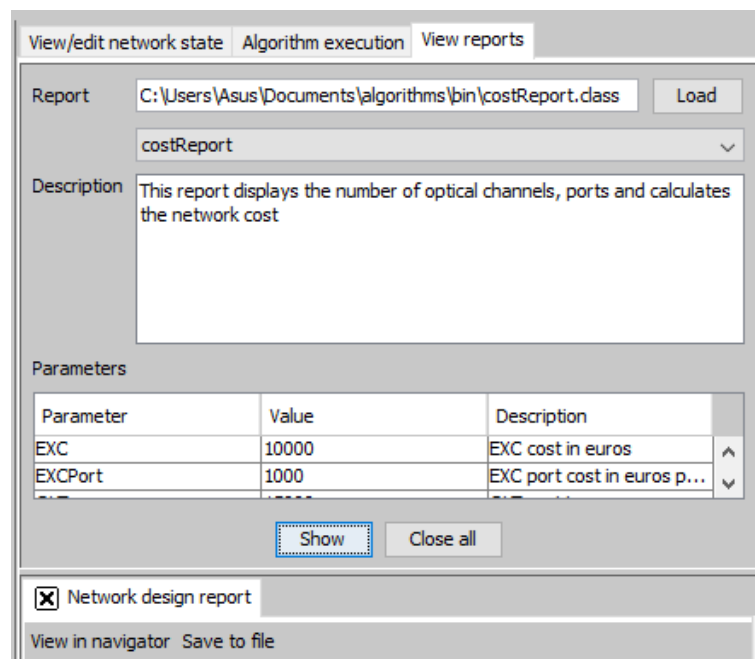


Figura 5.11: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

It is already known all the necessary formulas to obtain the CAPEX value for the reference network 4.1. 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.

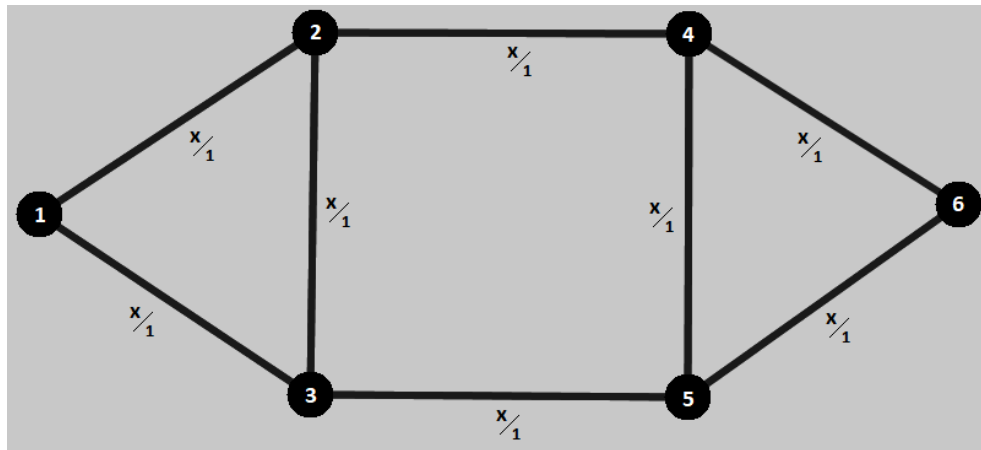


Figura 5.12: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

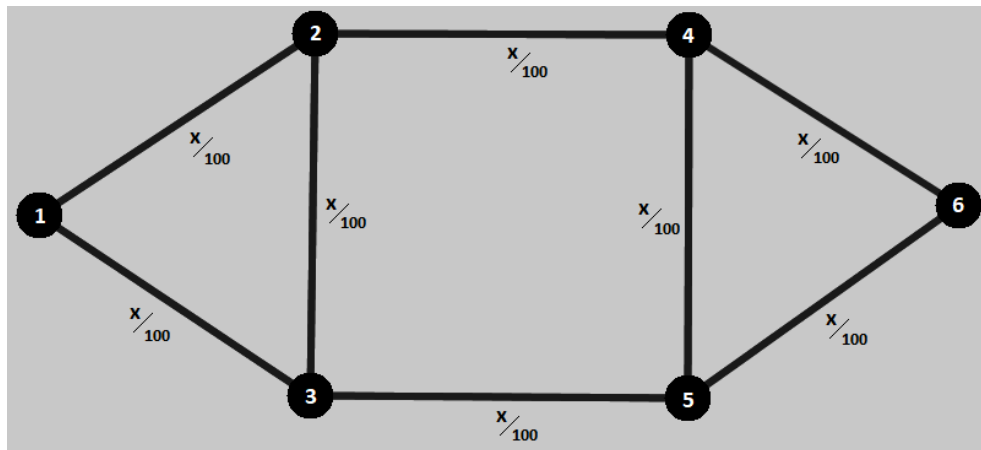


Figura 5.13: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

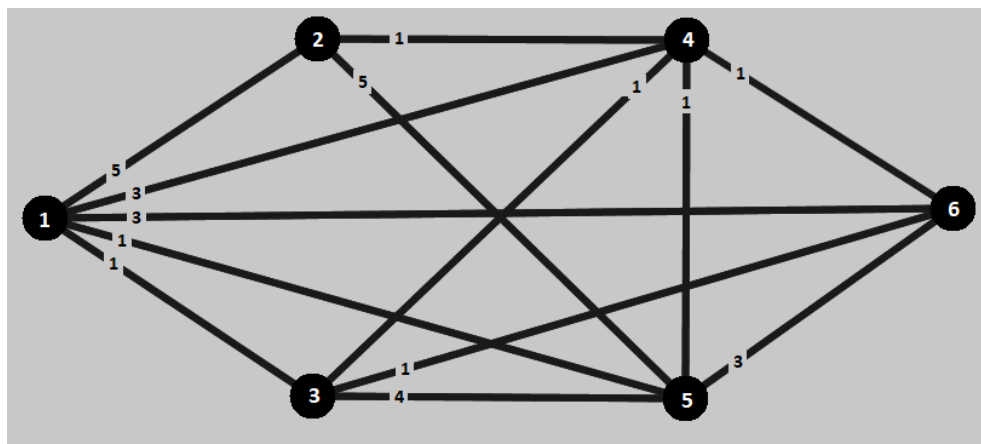


Figura 5.14: ODU0 logical topology defined by the ODU0 traffic matrix.

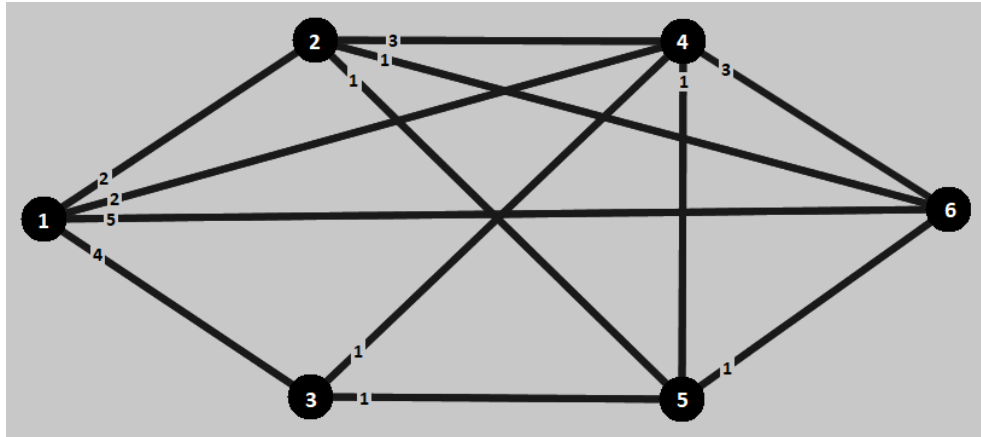


Figura 5.15: ODU1 logical topology defined by the ODU1 traffic matrix.

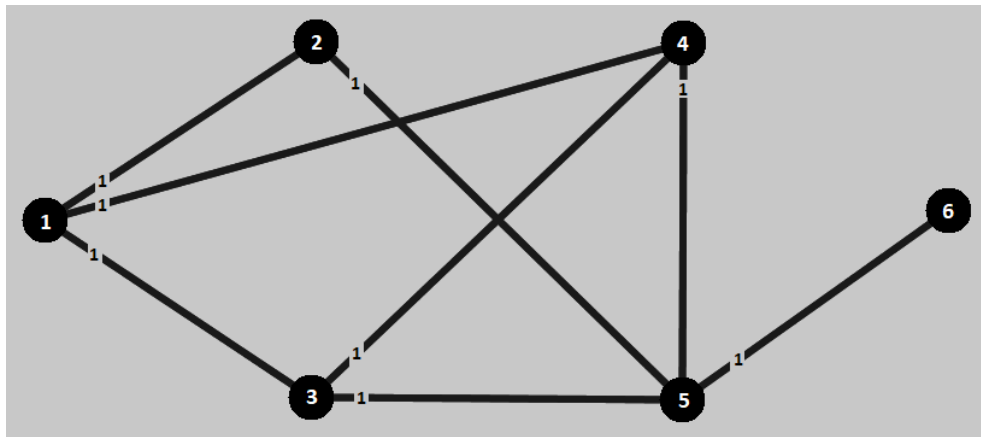


Figura 5.16: ODU2 logical topology defined by the ODU2 traffic matrix.

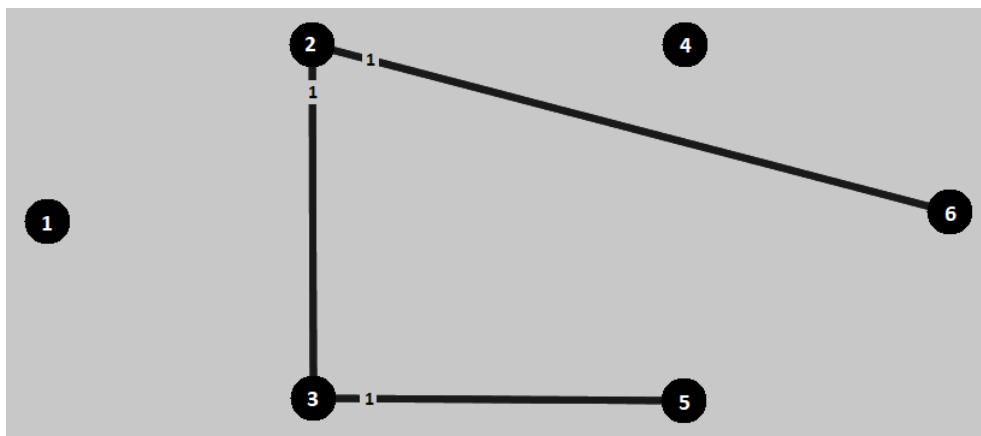


Figura 5.17: ODU3 logical topology defined by the ODU3 traffic matrix.

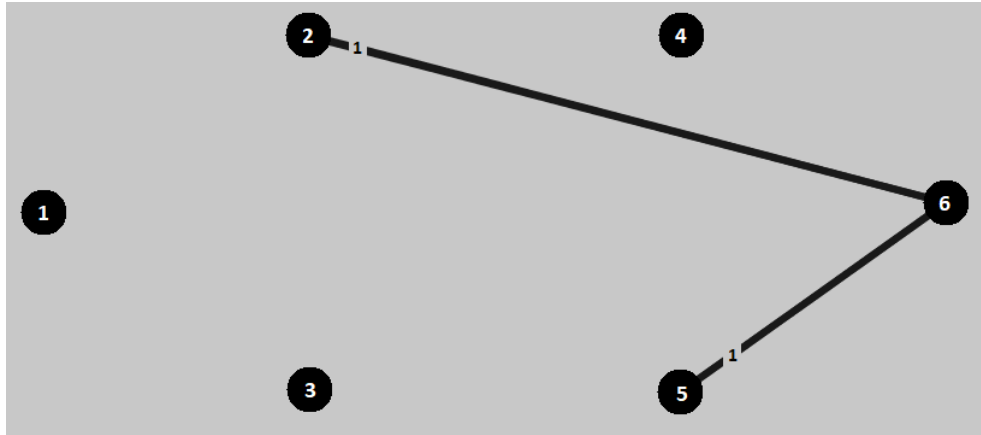


Figura 5.18: ODU4 logical topology defined by the ODU4 traffic matrix.

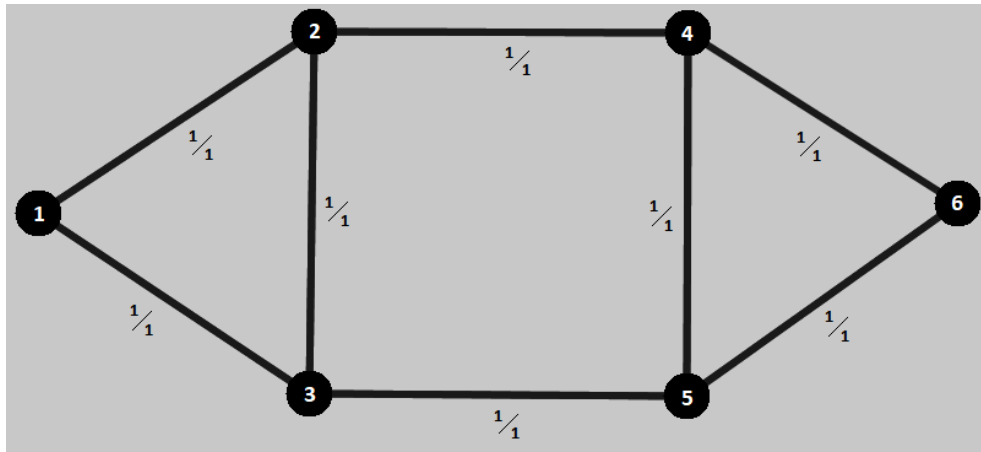


Figura 5.19: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 5.4.

All the values calculated in the previous table were obtained through the equations 5.2 and 5.3 referred to in section 5.1, but for a more detailed analysis we created table 5.5 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 5.4: 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 5.5: 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.

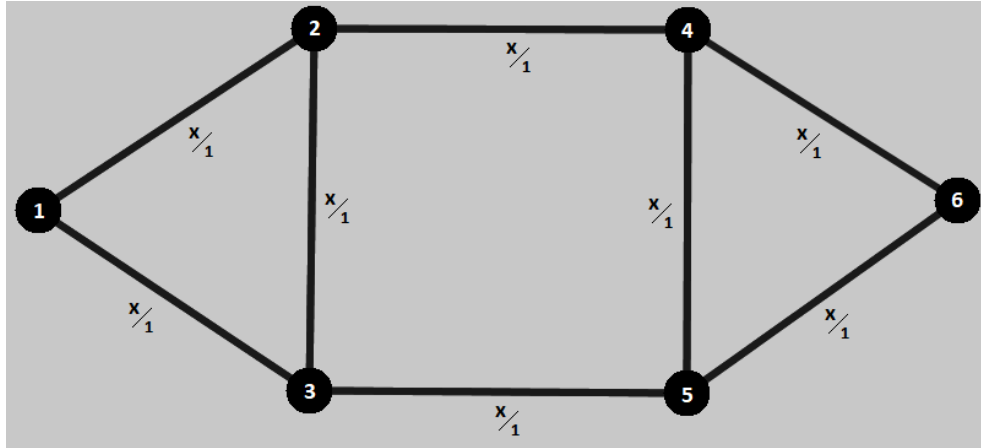


Figura 5.20: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

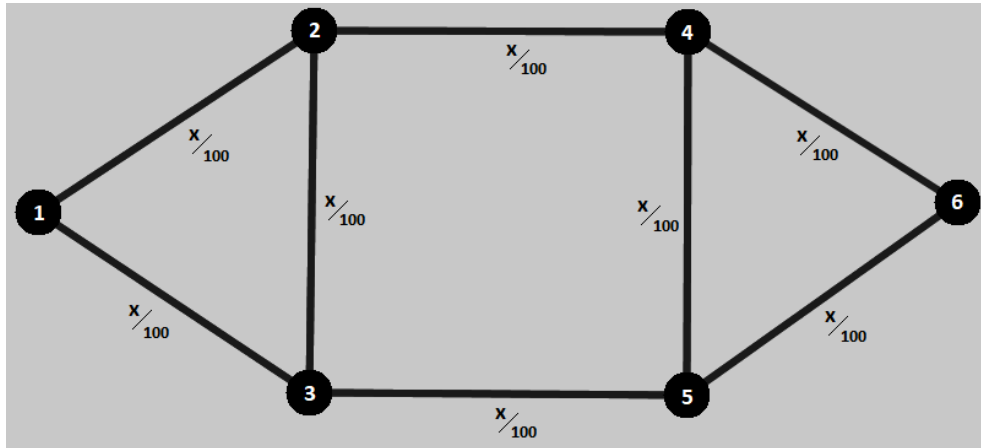


Figura 5.21: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

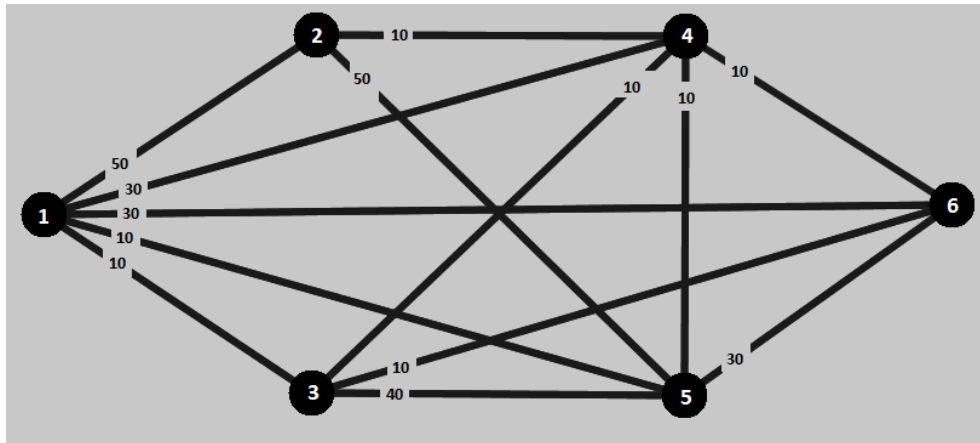


Figura 5.22: ODU0 logical topology defined by the ODU0 traffic matrix.

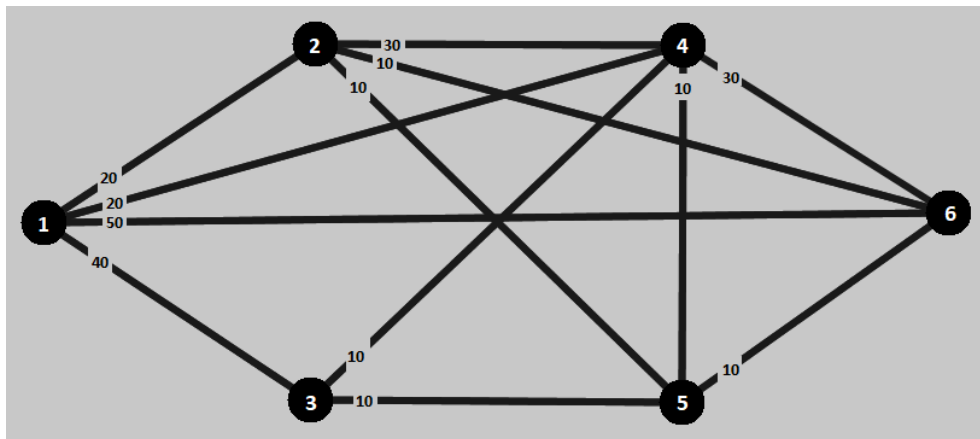


Figura 5.23: ODU1 logical topology defined by the ODU1 traffic matrix.

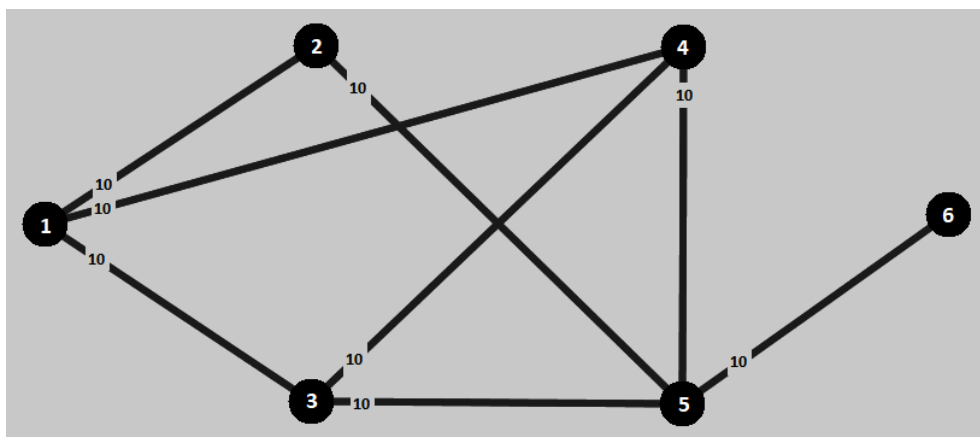


Figura 5.24: ODU2 logical topology defined by the ODU2 traffic matrix.

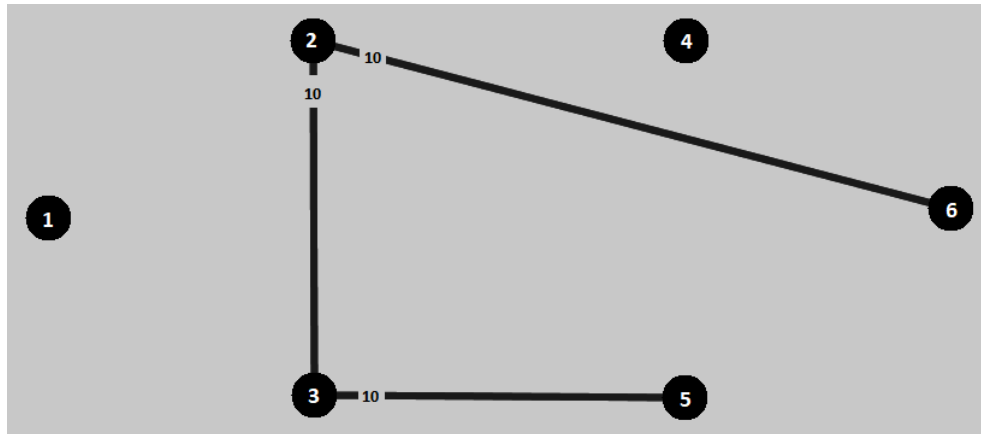


Figura 5.25: ODU3 logical topology defined by the ODU3 traffic matrix.

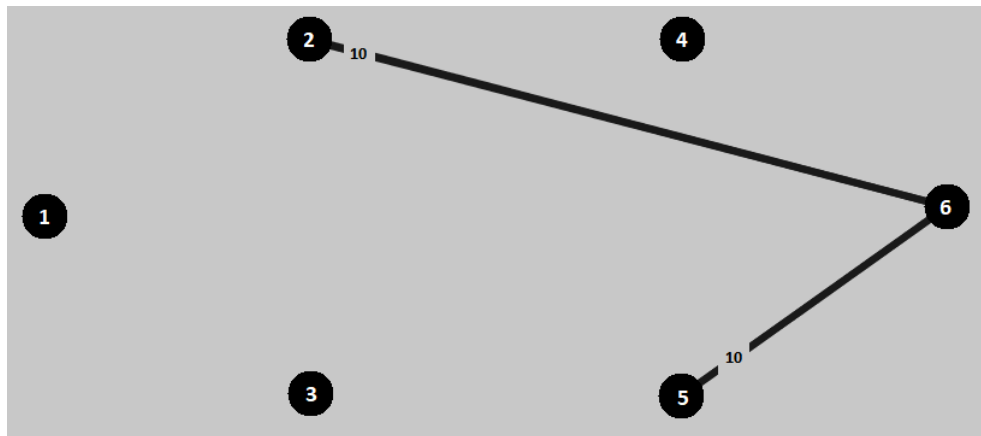


Figura 5.26: ODU4 logical topology defined by the ODU4 traffic matrix.

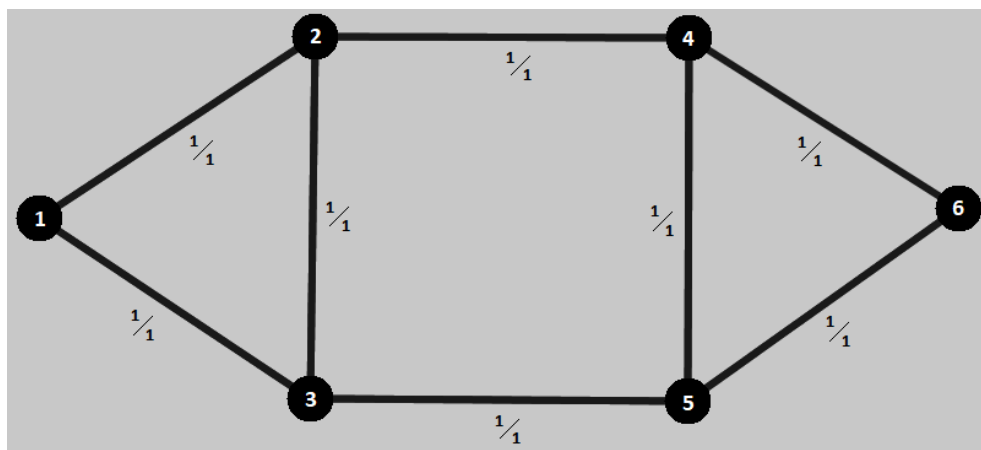


Figura 5.27: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 5.6. In table 5.5 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 5.6: 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.

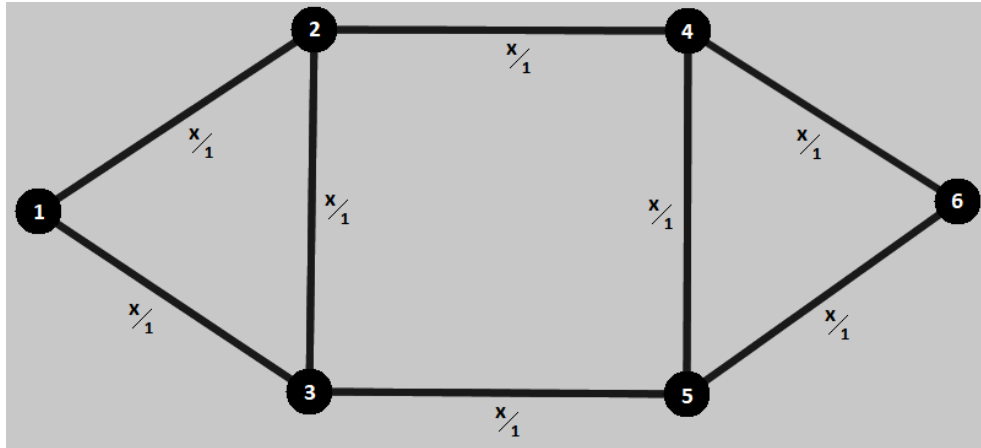


Figura 5.28: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

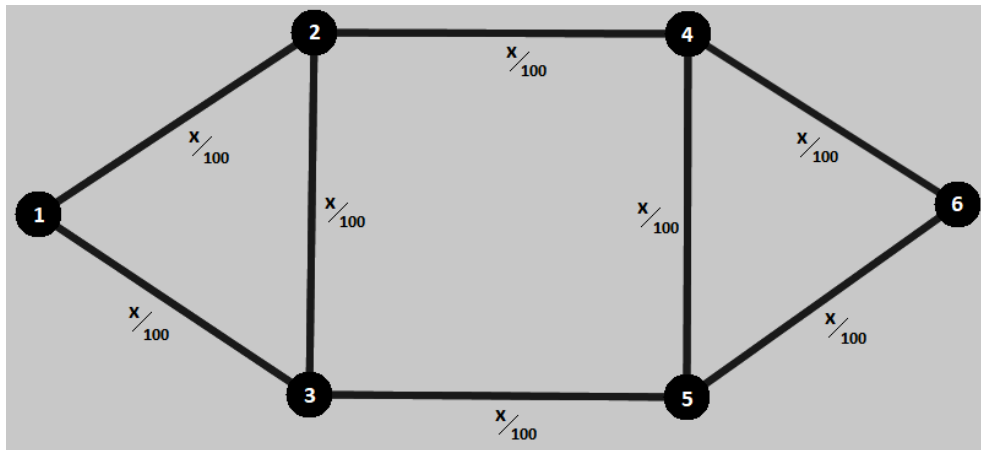


Figura 5.29: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

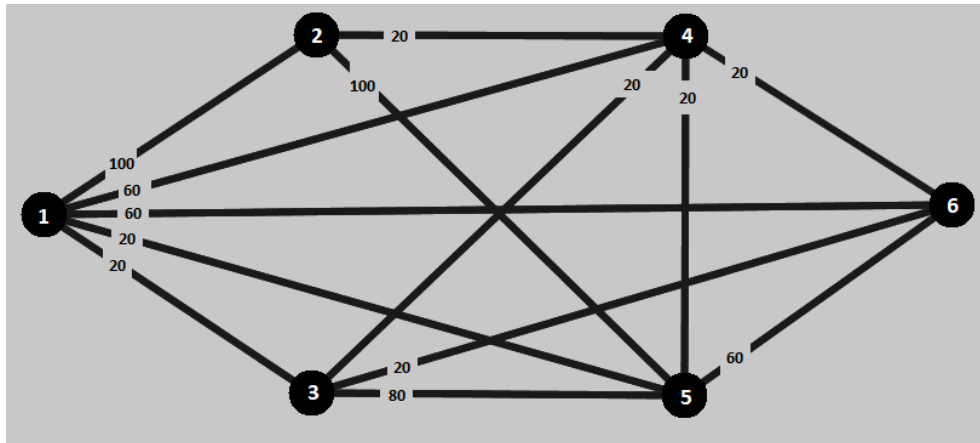


Figura 5.30: ODU0 logical topology defined by the ODU0 traffic matrix.

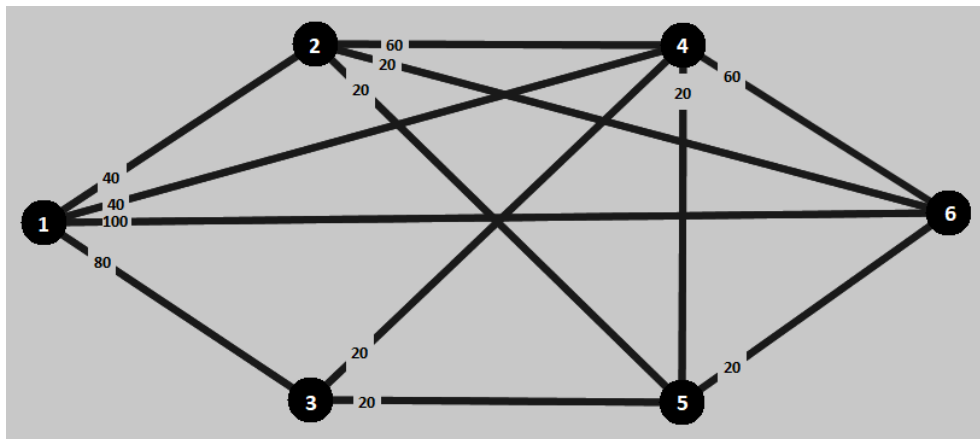


Figura 5.31: ODU1 logical topology defined by the ODU1 traffic matrix.

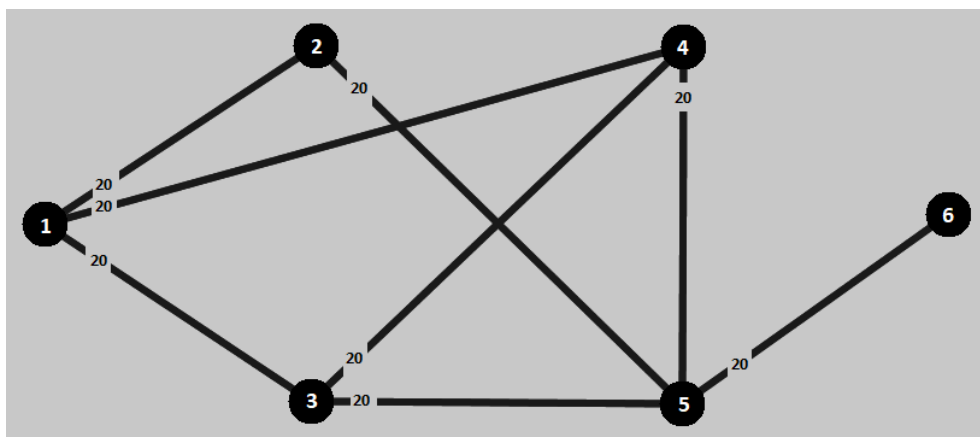


Figura 5.32: ODU2 logical topology defined by the ODU2 traffic matrix.

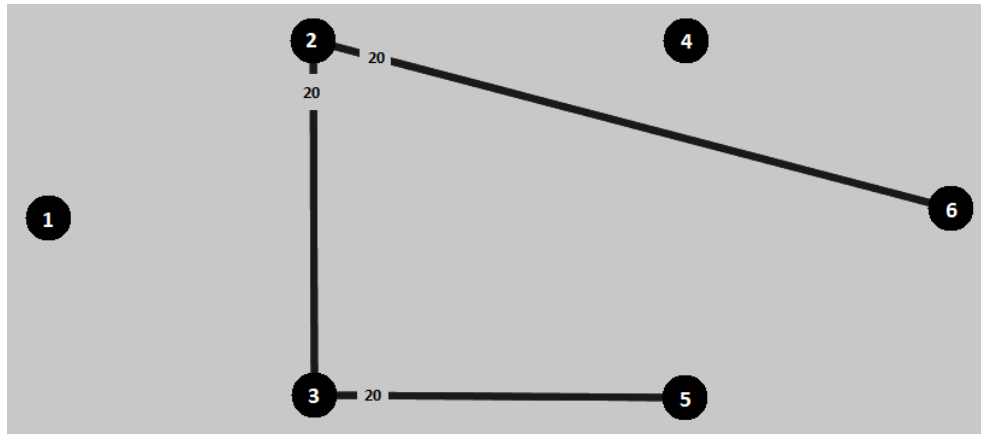


Figura 5.33: ODU3 logical topology defined by the ODU3 traffic matrix.

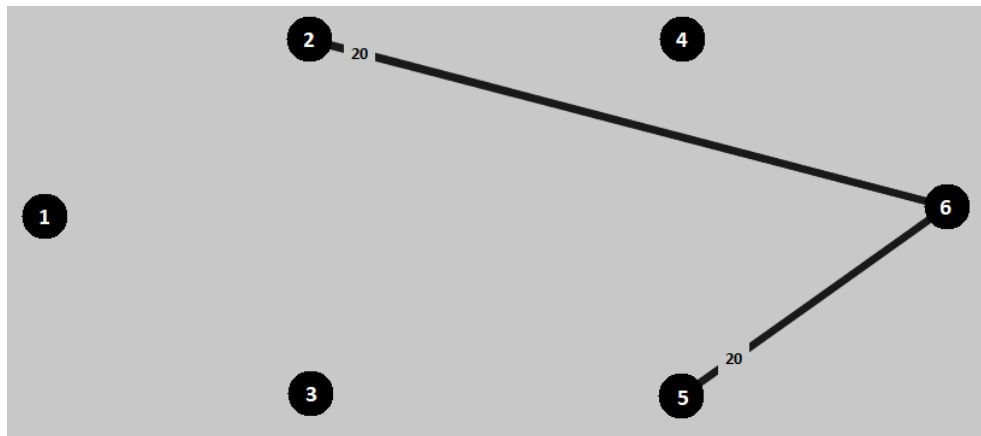


Figura 5.34: ODU4 logical topology defined by the ODU4 traffic matrix.

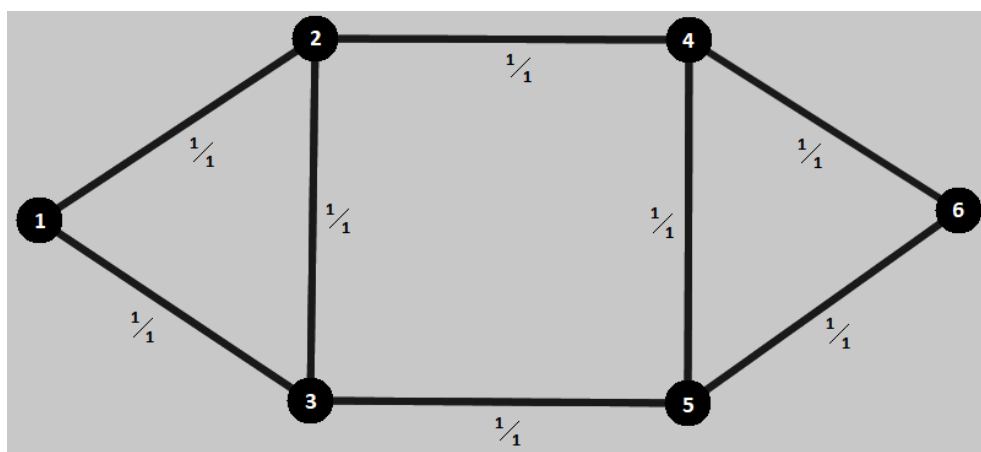


Figura 5.35: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 5.7. In table 5.5 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 €	149 020 000 €
	100 Gbits/s Transceivers		297	5 000 €/Gbit/s	148 500 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	29 811 800 €
		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 €	
	Optical	Line Ports	297	100 000 €/port	29 700 000 €	
		OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						178 831 800 €

Tabela 5.7: 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 5.8 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 €	29 811 800 €
CAPEX	14 382 590 €	92 405 900 €	178 831 800 €
CAPEX/Gbit/s	28 765 €/Gbit/s	18 481 €/Gbit/s	17 883 €/Gbit/s

Tabela 5.8: 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.

Allow Blocking

Student Name : Élio Coelho (08/10/2018 -)

Goal : Allows blocking, i.e., some demands are not routed.

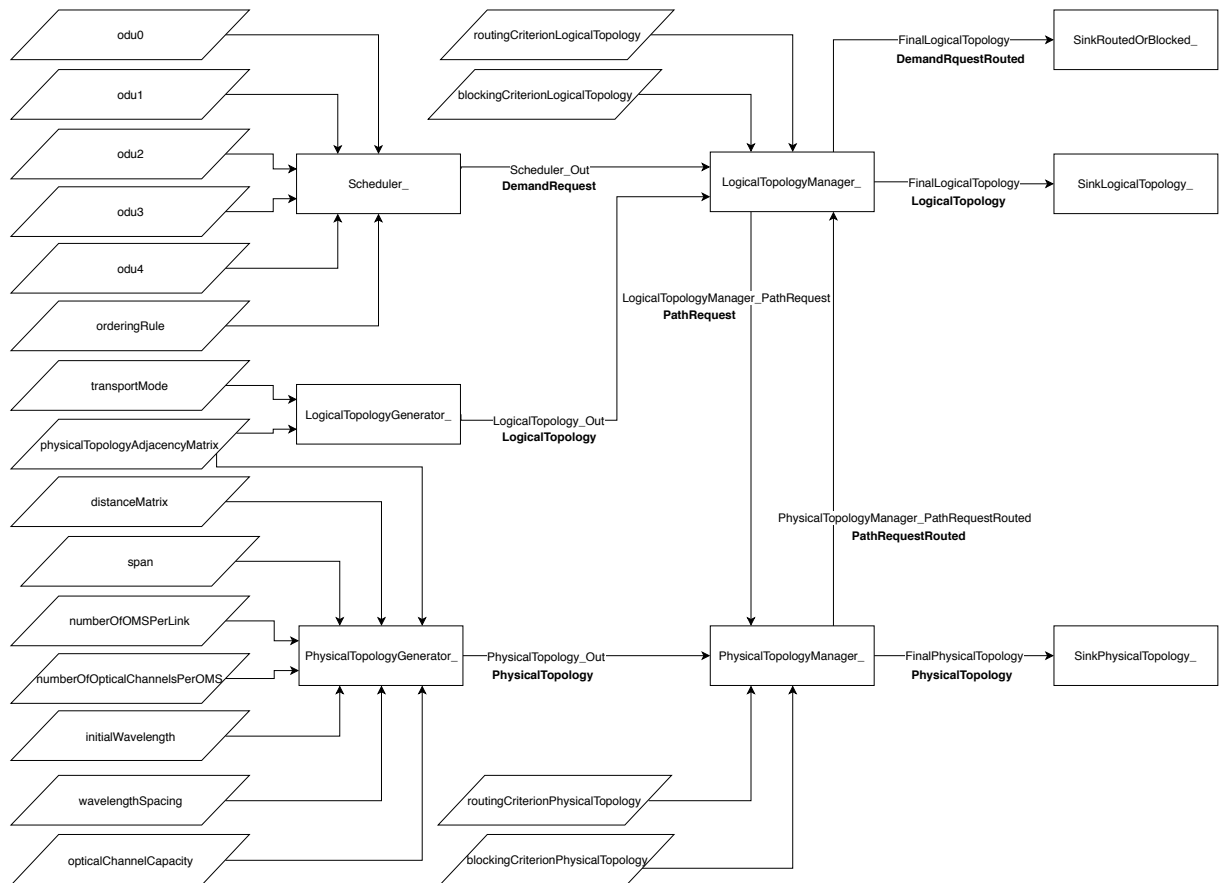


Figura 5.36: Simulation Diagram

Input Parameter	Default Value	Description
odu0	[0]	ODU0 demands matrix
odu1	[0]	ODU1 demands matrix
odu2	[0]	ODU2 demands matrix
odu3	[0]	ODU3 demands matrix
odu4	[0]	ODU4 demands matrix
orderingRule	descendingOrder	Demands ordering rule: descendingOrder - ODU4 to ODU0 ascendingOrder - ODU0 to ODU4
transportMode	opaque	Transport mode: opaque transparent translucent
physicalTopologyAdjacencyMatrix	[0]	Adjacency matrix of the physical network
distanceMatrix	[0]	Matrix with the distance (km) between adjacent nodes
span	100	Fiber span length (Km)
numberOfOMSPerLink	1	Number of OMS per link
numberOfOpticalChannelsPerOMS	100	Number of optical channels per OMS
opticalChannelCapacity	80	Capacity of each optical channel in ODU0s
routingCriterionLogicalTopology	hops	Shortest path type: hops km
blockingCriterionLogicalTopology	3	Maximum number of short paths tested between a pair of nodes
routingCriterionPhysicalTopology	hops	Shortest path type: hops km
blockingCriterionPhysicalTopology	3	Maximum number of short paths tested between a pair of nodes

Tabela 5.9: System Input Parameters

Signal Name	Signal Type
Scheduler_Out	DemandRequest
LogicalTopology_Out	LogicalTopology
PhysicalTopology_Out	PhysicalTopology
LogicalTopologyManager_PathRequest	PathRequest
PhysicalTopologyManager_PathRequestRouted	PathRequestRouted
ProcessedDemand	DemandRequestRouted
FinalLogicalTopology	LogicalTopology
FinalPhysicalTopology	PhysicalTopology

Tabela 5.10: System Signals

DemandRequest

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

Tabela 5.11: DemandRequest variable

D = numberOfDemands

N = numberOfNodes

LogicalTopology

matrix NxN logicalTopologyAdjacencyMatrix

vector paths

vector lightPaths

vector opticalChannels

Node	1	...	...	N
1	0	0/1	0/1	0/1
...	0/1	0	0/1	0/1
...	0/1	0/1	0	0/1
N	0/1	0/1	0/1	0

Tabela 5.12: logicalTopologyAdjacencyMatrix

N = numberOfNodes

0 => not logical link or 1 => logical link

paths

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0...P-1	1...N	1...N	0...OC	1...LP	[lp0,lp1,...]

Tabela 5.13: path

P = numberOfPaths

N = numberOfNodes

OC = opticalChannelCapacity

LP = numberOfLightPaths

lightPaths

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex
0...LP-1	1...N	1...N	1...OC	1...Och	[och0,och1,...]

Tabela 5.14: lightPath

LP = numberOfLightPaths

N = numberOfNodes

OC = opticalChannelCapacity

Och = numberOfOpticalChannels

opticalChannels

opticalChannelIndex	sourceNode	destinationNode	wavelength	capacity (ODU0s)	numberOfDemands	demandsIndex
0...Och-1	1...N	1...N	1...W	1...OC	0...D	[d0,d1,...]

Tabela 5.15: opticalChannel

Och = numberOfOpticalChannels

N = numberOfNodes

OC = opticalChannelCapacity

D = numberOfDemands

W = numberOfWavelengths

PhysicalTopology

matrix NxN physicalTopologyAdjacencyMatrix

vector opticalMultiplexSection

Node	1	...	...	N
1	0	0/1	0/1	0/1
...	0/1	0	0/1	0/1
...	0/1	0/1	0	0/1
N	0/1	0/1	0/1	0

Tabela 5.16: physicalTopologyAdjacencyMatrix

N = numberOfNodes

0 => not physical link or 1 => physical link

opticalMultiplexSection

OmsIndex	sourceNode	destinationNode	maximumNumberOfWavelengths	wavelengths	availableWavelengths
0	1...N	1...N	OchL	[1550 1550.8 ...]	[0/1 0/1 ...]
...	1...N	1...N	OchL	[1550 1550.8 ...]	[0/1 0/1 ...]
L-1	1...N	1...N	OchL	[1550 1550.8 ...]	[0/1 0/1 ...]

Tabela 5.17: opticalMultiplexSection

L = numberOfLinks

N = numberOfNodes

OchL = numberOfOpticalChannelsPerLink

W = numberOfWavelengths

PathRequest

requestIndex	sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes
0...R-1	1...N	1...N	0...N-2	[1, 2, ...]

Tabela 5.18: PathRequest

R = numberOfRequests

N = numberOfNodes

PathRequestRouted

pathInformation

vector lightPathsTable

requestIndex	routed	numberOfLightPaths
0...R-1	true or false	1...LP

Tabela 5.19: pathInformation

$R = \text{numberOfRequests}$

$LP = \text{numberOfLightPaths}$

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength
1...N	1...N	0...N-2	[1, 2, ...]	1...W

Tabela 5.20: lightPathsTable

$R = \text{numberOfRequests}$

$W = \text{numberOfWavelength}$

DemandRequestRouted

demandIndex	routed	pathsIndex
0...D-1	true or false	0...P-1

Tabela 5.21: DemandRequestRouted

$D = \text{numberOfDemands}$

$P = \text{numberOfPaths}$

Block	Description
Scheduler_	
LogicalTopologyGenerator_	
PhysicalTopologyGenerator_	
LogicalTopologyManager_	
PhysicalTopologyManager_	
SinkRoutedOrBlocked_	
SinkLogicalTopology_	
SinkPhysicalTopology_	

Tabela 5.22: System Blocks

Block	Input Parameters	State Variables
Scheduler_	odu0 odu1 odu2 odu3 odu4 orderingRule	odu0 odu1 odu2 odu3 odu4 demandIndex numberOfDemands
LogicalTopologyGenerator_	transportMode physicalTopologyAdjacencyMatrix	generate
PhysicalTopologyGenerator_	physicalTopologyAdjacencyMatrix distanceMatrix span numberOfOMSPerLink numberOfOpticalChannelsPerOMS initialWavelength wavelengthSpacing opticalChannelCapacity	generate
LogicalTopologyManager_	routingCriterionLogicalTopology blockingCriterionLogicalTopology	logicalTopology demand requestIndex pathDij tryAnotherPath temporaryLogicalMatrix
PhysicalTopologyManager_	routingCriterionPhysicalTopology blockingCriterionPhysicalTopology	physicalTopology
SinkRoutedOrBlocked_		
SinkLogicalTopology_		
SinkPhysicalTopology_		

Tabela 5.23: Input Parameters and State Variables

Block	Input Signals	Output Signals
Scheduler_		Sched
LogicalTopologyGenerator_		LogicalTopolo
PhysicalTopologyGenerator_		PhysicalTopolo
LogicalTopologyManager_	LogicalTopologyGenerator_Out Scheduler_Out PhysicalTopologyManager_PathRequestRouted	LogicalTopologyM FinalLogi Process
PhysicalTopologyManager_	PhysicalTopologyGenerator_Out LogicalTopologyManager_PathRequest	PhysicalTopologyMan FinalPhys
SinkRoutedOrBlocked_	ProcessedDemand	
SinkLogicalTopology_	FinalLogicalTopology	
SinkPhysicalTopology_	FinalPhysicalTopology	

Tabela 5.24: Input Signals and Output Signals


```

Input parameters for opaque transport mode example
#####

odu0 : 0 0 0 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0

odu1 : 0 0 0 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0

odu2 : 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

odu3 : 0 0 3 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0
        0 0 0 0 0 0

odu4 : 0 1 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

orderingRule : 0

transportMode : opaque

physicalTopologyAdjacencyMatrix : 0 1 0 0 0 1
                                   0 0 1 0 0 0
                                   0 0 0 0 0 0
                                   0 0 1 0 0 0
                                   0 0 1 1 0 0
                                   0 1 0 0 1 0

numberOfOMSPerLink : 1

numberOfOpticalChannelsPerOMS : 2

opticalChannelCapacity : 80

routingCriterionLogicalTopology : hops

blockingCriterionLogicalTopology : 3

routingCriterionPhysicalTopology : hops

blockingCriterionPhysicalTopology : 3

```

Figura 5.39: Input Parameters

DemandRequest

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
0	1	2	4	none
1	1	2	4	none
2	1	2	4	none
3	2	3	3	none
4	6	2	3	none
5	6	2	3	none
6	6	3	3	none
7	6	5	2	none

Tabela 5.25: DemandRequest

LogicalTopology

logicalTopologyAdjacencyMatrix

Node	1	2	3	4	5	6
1	0	1	0	0	0	1
2	0	0	1	0	0	0
3	0	0	0	0	1	0
4	0	0	1	0	0	0
5	0	0	0	1	0	1
6	0	1	0	0	0	0

Tabela 5.26: logicalTopologyAdjacencyMatrix

paths

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex

Tabela 5.27: paths

lightPaths

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex

Tabela 5.28: lightPaths

opticalChannels

opticalChannelIndex	sourceNode	destinationNode	wavelength	capacity (ODU0s)	numberOfDemands	demandsIndex

Tabela 5.29: opticalChannels

PhysicalTopology

physicalTopologyAdjacencyMatrix

Node	1	2	3	4	5	6
1	0	1	0	0	0	1
2	0	0	1	0	0	0
3	0	0	0	0	1	0
4	0	0	1	0	0	0
5	0	0	0	1	0	1
6	0	1	0	0	0	0

Tabela 5.30: physicalTopologyAdjacencyMatrix

opticalMultiplexSection

OMSIndex	sourceNode	destinationNode	maximumNumberOfWavelengths	wavelengths	availableWavelengths	numberOfAmplifiers
0	1	2	2	[1550,1550.8]	[1,1]	4
1	1	6	2	[1550,1550.8]	[1,1]	0
2	2	3	2	[1550,1550.8]	[1,1]	0
3	3	5	2	[1550,1550.8]	[1,1]	8
4	4	3	2	[1550,1550.8]	[1,1]	0
5	5	4	2	[1550,1550.8]	[1,1]	1
6	5	6	2	[1550,1550.8]	[1,1]	3
7	6	2	2	[1550,1550.8]	[1,1]	0

Tabela 5.31: opticalMultiplexSection

Demand 0**DemandRequest**

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
0	1	2	4	none

Tabela 5.32: DemandRequest

Path?

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex

Tabela 5.33: paths

No path.

sourceNode	destinationNode	shortestPath
1	2	1->2

Tabela 5.34: Dijkstra

lighPath with sourceNode 1 and destinationNode 2

There are these lightPaths?

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex

Tabela 5.35: lightPaths

Não existe o lightPath. O bloco LogicalTopologyManager envia um sinal PathRequest ao bloco PhysicalTopologyManager

PathRequest

requestIndex	sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes
0	1	2	0	[]

Tabela 5.36: PathRequest

O bloco PhysicalTopologyManager vai verificar se existe 1 wavelength disponível para o lightPath com sourceNode 1 e destinationNode 2. Neste caso tem, guarda o wavelength e atualiza o availableWavelengths no opticalMultiplexSection.

OMSIndex	sourceNode	destinationNode	maximumNumberOfWavelengths	wavelengths	availableWavelengths
0	1	2	2	[1550 1550.8]	[0 1]
1	1	6	2	[1550 1550.8]	[1 1]
2	2	3	2	[1550 1550.8]	[1 1]
3	4	3	2	[1550 1550.8]	[1 1]
4	5	3	2	[1550 1550.8]	[1 1]
5	5	4	2	[1550 1550.8]	[1 1]
6	6	2	2	[1550 1550.8]	[1 1]
7	6	5	2	[1550 1550.8]	[1 1]

Tabela 5.37: opticalMultiplexSection

O bloco PhysicalTopologyManager responde ao request do LogicalTopologyManager enviando para esse bloco 1 sinal PathRequestRouted com a informação que o routed foi possível.

PathRequestRouted

pathInformation

requestIndex	routed	numberOfLightPaths
0	true	1

Tabela 5.38: routed variable

lightPathsTable

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength
1	2	0	[]	1550

Tabela 5.39: lightPathsTable

Update paths, lightPaths and opticalChannels

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]

Tabela 5.40: paths

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex
0	1	2	0	1	[0]

Tabela 5.41: lightPaths

opticalChannelIndex	sourceNode	destinationNode	wavelength	capacity (ODU0s)	numberOfDemands	demandsIndex
0	1	2	1550	0	1	[0]

Tabela 5.42: opticalChannels

DemandRequestRouted

demandIndex	routed	pathIndex
0	true	0

Tabela 5.43: DemandRequestRouted

Demand 1**DemandRequest**

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
1	1	3	4	none

Tabela 5.44: DemandRequest

Path?

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]

Tabela 5.45: paths

No path

sourceNode	destinationNode	shortestPaths
1	3	1->2->3 1->6->2->3 1->6->5->3

Tabela 5.46: Dijkstra

lightPaths 1->2 e 2->3 with capacity to create a Path?

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex
0	1	2	0	1	[0]

Tabela 5.47: lightPaths

lightPath 1->2 without capacity and lightPath 2->3 not exist

PathRequest

requestIndex	sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes
1	1	3	1	[2]

Tabela 5.48: PathRequest

OMSIndex	sourceNode	destinationNode	maximumNumberOfWavelengths	wavelengths	availableWavelengths
0	1	2	2	[1550 1550.8]	[0 0]
1	1	6	2	[1550 1550.8]	[1 1]
2	2	3	2	[1550 1550.8]	[0 1]
3	4	3	2	[1550 1550.8]	[1 1]
4	5	3	2	[1550 1550.8]	[1 1]
5	5	4	2	[1550 1550.8]	[1 1]
6	6	2	2	[1550 1550.8]	[1 1]
7	6	5	2	[1550 1550.8]	[1 1]

Tabela 5.49: opticalMultiplexSection

PathRequestRouted

requestIndex	routed	numberOfLightPaths
1	true	2

Tabela 5.50: routed

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength
1	2	0	[]	1550.8
2	3	0	[]	1550

Tabela 5.51: lightPathsTable

Update paths, lightPaths and opticalChannels

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]
1	1	3	0	2	[1,2]

Tabela 5.52: paths

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex
0	1	2	0	1	[0]
1	1	2	0	1	[1]
2	2	3	0	1	[2]

Tabela 5.53: lightPaths

opticalChannelIndex	sourceNode	destinationNode	wavelength	capacity (ODU0s)	numberOfDemands	demandsIndex
0	1	2	1550	0	1	[0]
1	1	2	1550.8	0	1	[1]
2	2	3	1550	0	1	[1]

Tabela 5.54: opticalChannels

DemandRequestRouted

demandIndex	routed	pathIndex
1	true	1

Tabela 5.55: DemandRequestRouted

demand 2

DemandRequest

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
2	1	3	4	none

Tabela 5.56: DemandRequest

Path?

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]
1	1	3	0	2	[1,2]

Tabela 5.57: paths

Path exists but without capacity

PathRequest

requestIndex	sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes
2	1	3	2	[6,2]

Tabela 5.58: PathRequest

OMSIndex	sourceNode	destinationNode	maximumNumberOfWavelengths	wavelengths	availableWavelengths
0	1	2	2	[1550 1550.8]	[0 0]
1	1	6	2	[1550 1550.8]	[0 1]
2	2	3	2	[1550 1550.8]	[0 0]
3	4	3	2	[1550 1550.8]	[1 1]
4	5	3	2	[1550 1550.8]	[1 1]
5	5	4	2	[1550 1550.8]	[1 1]
6	6	2	2	[1550 1550.8]	[0 1]
7	6	5	2	[1550 1550.8]	[1 1]

Tabela 5.59: opticalMultiplexSection

PathRequestRouted

requestIndex	routed	numberOfLightPaths
2	true	3

Tabela 5.60: pathInformation

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength
1	6	0	[]	1550
6	2	0	[]	1550
2	3	0	[]	1550.8

Tabela 5.61: lightPathsTable

Update paths, lightPaths and opticalChannels

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]
1	1	3	0	2	[1,2]
2	1	3	0	3	[3,4,5]

Tabela 5.62: paths

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex
0	1	2	0	1	[0]
1	1	2	0	1	[1]
2	2	3	0	1	[2]
3	1	6	0	1	[3]
4	6	2	0	1	[4]
5	2	3	0	1	[5]

Tabela 5.63: lightPaths

opticalChannelIndex	sourceNode	destinationNode	wavelength	capacity (ODU0s)	numberOfDemands	demandsIndex
0	1	2	1550	0	1	[0]
1	1	2	1550.8	0	1	[1]
2	2	3	1550	0	1	[1]
3	1	6	1550	0	1	[2]
4	6	2	1550	0	1	[2]
5	2	3	1550.8	0	1	[2]

Tabela 5.64: opticalChannels

DemandRequestRouted

demandIndex	routed	pathIndex
2	true	2

Tabela 5.65: DemandRequestRouted

demand 3

DemandRequest

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
3	1	3	3	none

Tabela 5.66: DemandRequest

Path?

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]
1	1	3	0	2	[1,2]
2	1	3	0	3	[3,4,5]

Tabela 5.67: paths

No path

PathRequest

requestIndex	sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes
3	1	3	2	[6,5]

Tabela 5.68: PathRequest

OMSIndex	sourceNode	destinationNode	maximumNumberOfWavelengths	wavelengths	availableWavelengths
0	1	2	2	[1550 1550.8]	[0 0]
1	1	6	2	[1550 1550.8]	[0 0]
2	2	3	2	[1550 1550.8]	[0 0]
3	4	3	2	[1550 1550.8]	[1 1]
4	5	3	2	[1550 1550.8]	[0 1]
5	5	4	2	[1550 1550.8]	[1 1]
6	6	2	2	[1550 1550.8]	[0 1]
7	6	5	2	[1550 1550.8]	[0 1]

Tabela 5.69: opticalMultiplexSection

PathRequestRouted

requestIndex	routed	numberOfLightPaths
3	true	3

Tabela 5.70: pathInformation

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength
1	6	0	[]	1550.8
6	5	0	[]	1550
5	3	0	[]	1550

Tabela 5.71: lightPathsTable

Update paths, lightPaths and opticalChannels

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]
1	1	3	0	2	[1,2]
2	1	3	0	3	[3,4,5]
3	1	3	48	3	[6,7,8]

Tabela 5.72: paths

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex
0	1	2	0	1	[0]
1	1	2	0	1	[1]
2	2	3	0	1	[2]
3	1	6	0	1	[3]
4	6	2	0	1	[4]
5	2	3	0	1	[5]
6	1	6	48	1	[6]
7	6	5	48	1	[7]
8	5	3	48	1	[8]

Tabela 5.73: lightPaths

opticalChannelIndex	sourceNode	destinationNode	wavelength	capacity (ODU0s)	numberOfDemands	demandsIndex
0	1	2	1550	0	1	[0]
1	1	2	1550.8	0	1	[1]
2	2	3	1550	0	1	[1]
3	1	6	1550	0	1	[2]
4	6	2	1550	0	1	[2]
5	2	3	1550.8	0	1	[2]
6	1	6	1550.8	48	1	[3]
7	6	5	1550	48	1	[3]
8	5	3	1550	48	1	[3]

Tabela 5.74: opticalChannels

DemandRequestRouted

demandIndex	routed	pathIndex
3	true	3

Tabela 5.75: DemandRequestRouted

demand 4

DemandRequest

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
4	1	3	3	none

Tabela 5.76: DemandRequest

Path?

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]
1	1	3	0	2	[1,2]
2	1	3	0	3	[3,4,5]
3	1	3	48	3	[6,7,8]

Tabela 5.77: paths

Yes

Update paths, lightpaths and opticalchannels

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]
1	1	3	0	2	[1,2]
2	1	3	0	3	[3,4,5]
3	1	3	16	3	[6,7,8]

Tabela 5.78: paths

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex
0	1	2	0	1	0
1	1	2	0	1	1
2	2	3	0	1	2
3	1	6	0	1	3
4	6	2	0	1	4
5	2	3	0	1	5
6	1	6	16	1	6
7	6	5	16	1	7
8	5	3	16	1	8

Tabela 5.79: lightPaths

opticalChannelIndex	sourceNode	destinationNode	wavelength	capacity (ODU0s)	numberOfDemands	demandsIndex
0	1	2	1550	0	1	[0]
1	1	2	1550.8	0	1	[1]
2	2	3	1550	0	1	[1]
3	1	6	1550	0	1	[2]
4	6	2	1550	0	1	[2]
5	2	3	1550.8	0	1	[2]
6	1	6	1550.8	16	2	[3,4]
7	6	5	1550	16	1	[3,4]
8	5	3	1550	16	1	[3,4]

Tabela 5.80: opticalChannels

DemandRequestRouted

demandIndex	routed	pathIndex
4	true	3

Tabela 5.81: DemandRequestRouted

demand 5**DemandRequest**

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
5	1	3	3	none

Tabela 5.82: DemandRequest

Path?

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]
1	1	3	0	2	[1,2]
2	1	3	0	3	[3,4,5]
3	1	3	16	3	[6,7,8]

Tabela 5.83: paths

No path

PathRequest

requestIndex	sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes
4	1	3	2	[6,5]

Tabela 5.84: PathRequest

OmsIndex	sourceNode	destinationNode	maximumNumberOfWavelengths	wavelengths	availableWavelengths
0	1	2	2	[1550 1550.8]	[0 0]
1	1	6	2	[1550 1550.8]	[0 0]
2	2	3	2	[1550 1550.8]	[0 0]
3	4	3	2	[1550 1550.8]	[1 1]
4	5	3	2	[1550 1550.8]	[0 1]
5	5	4	2	[1550 1550.8]	[1 1]
6	6	2	2	[1550 1550.8]	[0 1]
7	6	5	2	[1550 1550.8]	[0 1]

Tabela 5.85: opticalMultiplexSection

No availableWavelengths, demand will be blocked

PathRequestRouted

requestIndex	routed	numberOfLightPaths
4	false	0

Tabela 5.86: pathInformation

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength

Tabela 5.87: lightPathsTable

DemandRequestRouted

demandIndex	routed	pathIndex
5	false	-1

Tabela 5.88: DemandRequestRouted

demand 6

DemandRequest

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
6	1	3	2	none

Tabela 5.89: DemandRequest

Path?

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]
1	1	3	0	2	[1,2]
2	1	3	0	3	[3,4,5]
3	1	3	16	3	[6,7,8]

Tabela 5.90: paths

No path

sourceNode	destinationNode	shortestPaths
1	6	1->6

Tabela 5.91: Dijkstra

lightPath 1->6 with capacity?

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex
0	1	2	0	1	0
1	1	2	0	1	1
2	2	3	0	1	2
3	1	6	0	1	3
4	6	2	0	1	4
5	2	3	0	1	5
6	1	6	16	1	6
7	6	5	16	1	7
8	5	3	16	1	8

Tabela 5.92: lightPaths

Yes. Update lightPaths and opticalChannels, create a new path and check if there are any other paths using this lightPath to check the capacity

PathRequest

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	2	0	1	[0]
1	1	3	0	2	[1,2]
2	1	3	0	3	[3,4,5]
3	1	3	8	3	[6,7,8]
4	1	6	8	1	[6]

Tabela 5.93: paths

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex
0	1	2	0	1	[0]
1	1	2	0	1	[1]
2	2	3	0	1	[2]
3	1	6	0	1	[3]
4	6	2	0	1	[4]
5	2	3	0	1	[5]
6	1	6	8	1	[6]
7	6	5	16	1	[7]
8	5	3	16	1	[8]

Tabela 5.94: lightPaths

opticalChannelIndex	sourceNode	destinationNode	wavelength	capacity (ODU0s)	numberOfDemands	demandsIndex
0	1	2	1550	0	1	[0]
1	1	2	1550.8	0	1	[1]
2	2	3	1550	0	1	[1]
3	1	6	1550	0	1	[2]
4	6	2	1550	0	1	[2]
5	2	3	1550.8	0	1	[2]
6	1	6	1550.8	8	2	[3,4,6]
7	6	5	1550	16	1	[3,4]
8	5	3	1550	16	1	[3,4]

Tabela 5.95: opticalChannels

DemandRequestRouted

demandIndex	routed	pathIndex
6	true	4

Tabela 5.96: DemandRequestRouted

Demands 0, 1, 2, 3, 4 and 6 routed

Demand 5 blocked

9 optical channels / wavelengths used

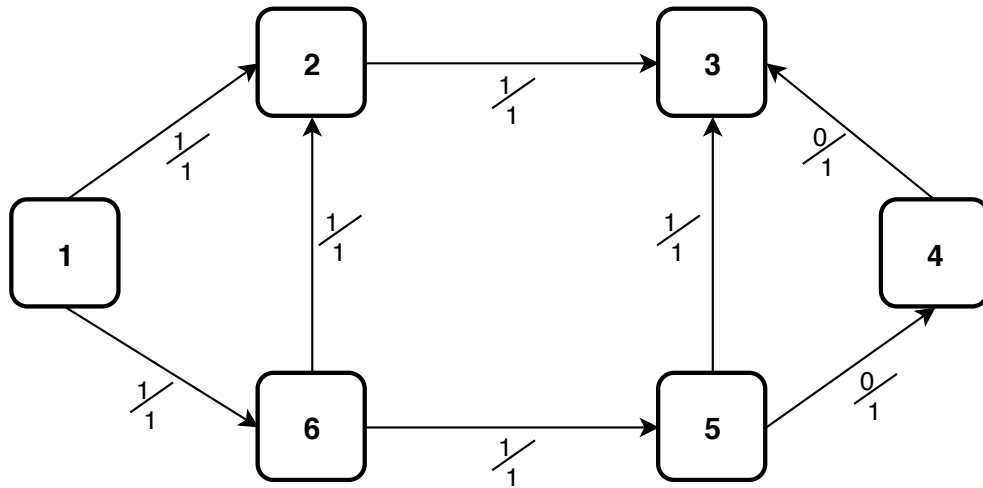


Figura 5.40: Final physical topology

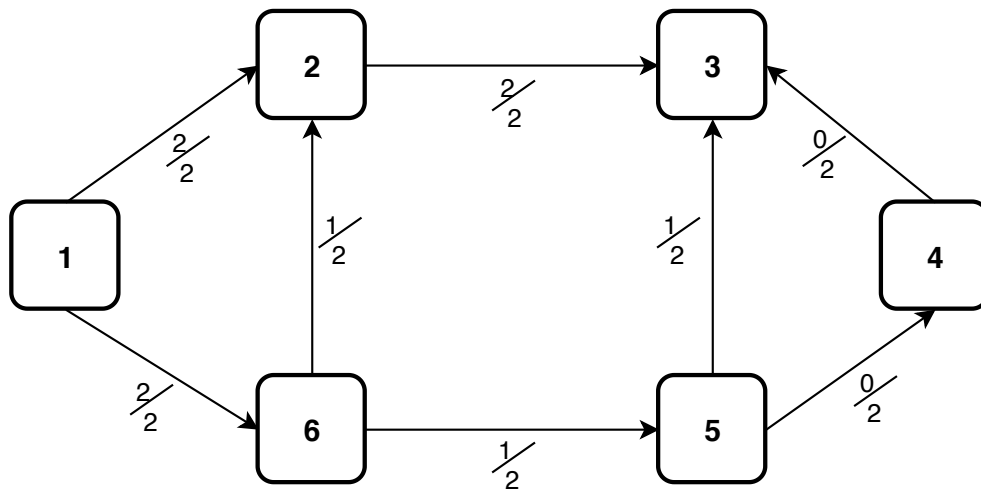


Figura 5.41: Final optical topology

File Name	Description	Status
netxpto_20190130.h		
scheduler_20190122.h		
logical_topology_generator_20190216.h		
physical_topology_generator_.h		
logical_topology_manager_.h		
physical_topology_manager_.h		
sink_20180815.h		

Tabela 5.97: Header Files

File Name	Description	Status
netxpto_20190130.cpp		
opaque_sdf.cpp		
scheduler_20190122.cpp		
logical_topology_generator_20190216.cpp		
physical_topology_generator_.cpp		
logical_topology_manager_.cpp		
physical_topology_manager_.cpp		
sink_20180815.cpp		

Tabela 5.98: Source Files

DemandRequest

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
0... ∞	1...N	1...N	0...4	none protection_1_plus_1 restoration

Tabela 5.99: DemandRequest variable

LogicalTopology**logicalTopologyAdjacencyMatrix**

Node	1	...	...	N
1	0	0/1	0/1	0/1
...	0/1	0	0/1	0/1
...	0/1	0/1	0	0/1
N	0/1	0/1	0/1	0

paths

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0... ∞	1...N	1...N	0...80	1... ∞	[lp0, lp1,...]

lightPaths

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOpticalChannels	opticalChannelsIndex
0... ∞	1...N	1...N	1...80	1...100	[och0, och1,...]

opticalChannels

opticalChannelIndex	sourceNode	destinationNode	wavelength	capacity (ODU0s)	numberOfDemands	demandsIndex
0... ∞	1...N	1...N	1550,1550.8,...	1...80	0... ∞	[d0,d1,...]

PhysicalTopology**physicalTopologyAdjacencyMatrix**

Node	1	...	...	N
1	0	0/1	0/1	0/1
...	0/1	0	0/1	0/1
...	0/1	0/1	0	0/1
N	0/1	0/1	0/1	0

opticalMultiplexSection

OMSIndex	sourceNode	destinationNode	maximumNumberOfWavelengths	wavelengths	availableWavelengths
0	1...N	1...N	OC	[1550,1550.8,...]	[0/1,0/1,...]
⋮	⋮	⋮	⋮	⋮	⋮
∞	1...N	1...N	OC	[1550,1550.8,...]	[0/1,0/1,...]

Tabela 5.100: opticalMultiplexSection

PathRequest

requestIndex	sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes
0... ∞	1...N	1...N	0...N-2	[1, 2, ...]

PathRequestRouted**pathInformation**

requestIndex	routed	numberOfLightPaths
0... ∞	true or false	1... ∞

lightPathsTable

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength
1...N	1...N	0...N-2	[1, 2, ...]	1550,1550.8,...

DemandRequestRouted

demandIndex	routed	pathsIndex
0... ∞	true or false	0... ∞

5.1.2 Opaque with 1+1 Protection

Student Name	:	Élio Coelho (08/10/2018 -)
	:	Pedro Coelho (01/03/2018 -)
Goal	:	Implement the heuristic model for the opaque transport mode with 1 plus 1 protection.

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:

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

As previously mentioned, equation 5.8 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

$$P_{exc,-1,n} = \sum_{j=1}^N w_{nj} \quad (5.8)$$

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

As previously mentioned, equation 5.9 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

$$P_{exc,c,n} = \sum_{d=1}^N D_{nd,c} \quad (5.9)$$

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, $D_{nn,c} = 0$.

To implement this heuristic approach there are used algorithms made in Java in a programming software called Eclipse and they are tested in an open-source network program called Net2Plan. In the Net2Plan guide section ?? there is an explanation on how to use and test them in this network planner.

In the next pages it will be described all the steps performed to obtain the final results in the opaque transport mode with 1+1 protection. In the figure below 5.42 it is shown a fluxogram with the description of this transport mode approach.

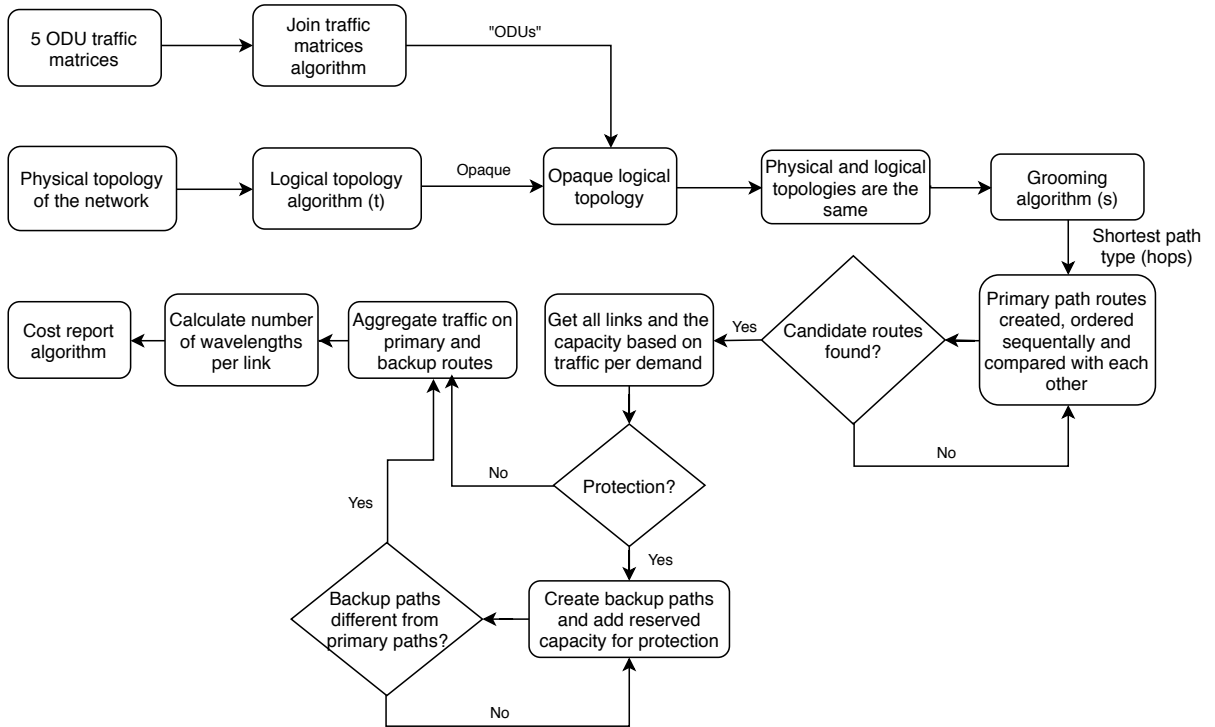


Figura 5.42: Fluxogram with the steps performed in the opaque with 1+1 protection transport mode approach.

Creation and join the traffic matrices

The first step is to create the traffic matrices based on the reference network 4.1. In order to create the 5 traffic matrices in Net2Plan it is necessary the length of all the links and the total traffic used in this network, so later it is needed to define in Net2Plan the length in all end nodes and the total traffic depends on the value of traffic used (low traffic - 0.5 Tbit/s, medium traffic - 5 Tbit/s and high traffic - 10 Tbit/s). As you can see in the figure below, it is defined the path of the 5 ODUs and they will be aggregated in just one single ODU, making it possible to join all the demands in just one file and load it later into the network. This final resulting ODU joins the multiple traffic demands from all the traffic matrices previously created and, of course, the traffic demands will depend on the values used on the creation of the matrices (low, medium and high traffic).



Figura 5.43: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.

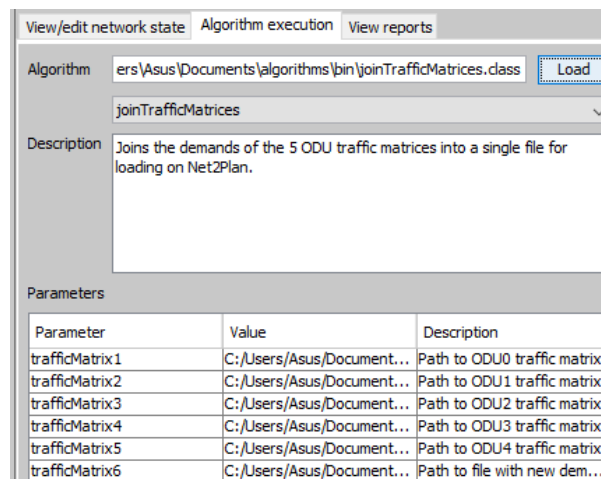


Figura 5.44: Load of the join traffic matrices algorithm for the opaque transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

The next step is to create the allowed physical topology of the network in Net2Plan. This network consists in 6 nodes and 8 bidirectional links. It is now also possible to define the length in all links. In the figure below it is shown the allowed physical topology in this transport mode.

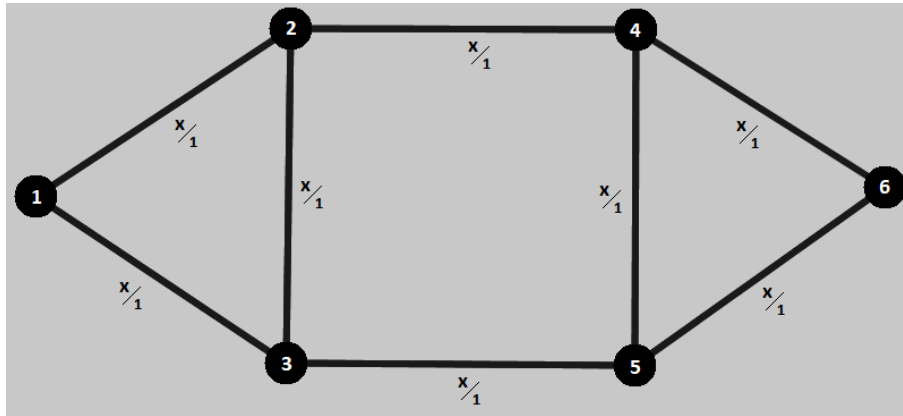


Figura 5.45: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. 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 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 physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 5.1.2 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the opaque transport mode with 1+1 protection.

```

if (netPlan.isSingleLayer() && logicalTopology.equalsIgnoreCase("Opaque"))
{
    lowerLayer = netPlan.getNetworkLayerDefault();
    upperLayer = netPlan.addLayerFrom(lowerLayer);
    netPlan.setRoutingType(RoutingType.HOP_BY_HOP_ROUTING, upperLayer);
    lowerLayer.setName("Physical Topology");
    upperLayer.setName("Logical Topology Opaque");
    upperLayer.setDescription("Opaque Logical Topology");
}

```

Figura 5.46: Java code of the logical topology approach for the opaque transport mode. The logical layer is created from the physical layer, as in this transport mode they are the same. The new layer is now the opaque logical topology of the network.

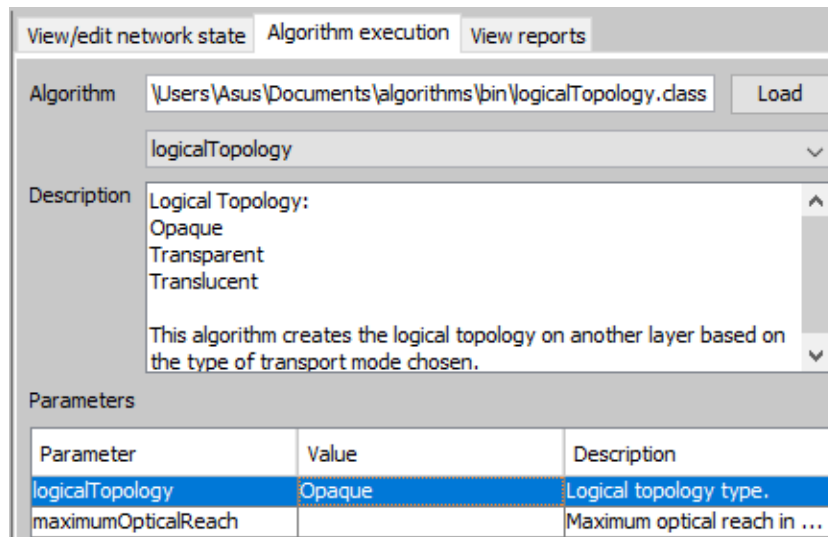


Figura 5.47: Load of the logical topology algorithm for the opaque transport mode.

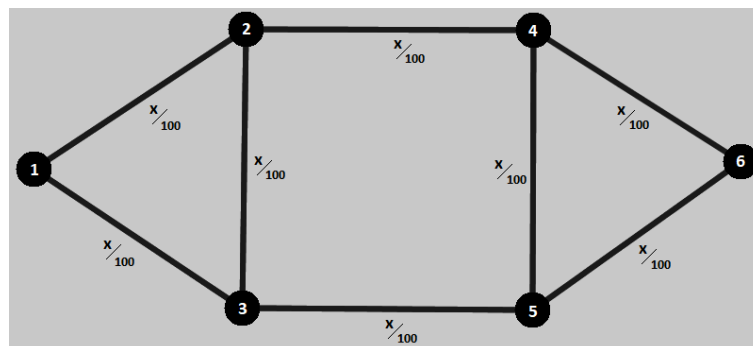


Figura 5.48: Allowed optical topology. It is assumed that each transmission system supports up to 100 optical channels.

Creation of routes and aggregation of traffic

After a network topology is created, it is now time to set the routing algorithm. In the opaque with 1+1 protection transport mode the routing algorithm starts with going through all the demands, create bidirectional routes (in this case the primary paths) based on the shortest path Dijkstra algorithm and then search the candidate routes for the respective demand. In this report it is used the shortest path type in hops. These routes are ordered sequentially and the shortest one per each demand is the primary path. The demands from the lower layer are removed and then saved in the upper layer. After this step, it is needed to set the traffic demands into the candidate routes that will integrate the network. As we also have a dedicated 1+1 protection scheme, if the network has this feature active, the algorithm will compare the previous candidate routes that will be saved to a list with the new ones that will be created. If the new routes are different from the previously created ones and if they are the next shortest path routes, then the algorithm will add these routes to the network and they will be the protection segments (backup paths) of the network. The offered traffic demands will be also set into these protection path 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.

```

case "Logical Topology Opaque":
    for (Demand d : netPlan.getDemands(lowerLayer)) {
        boolean odd=true;
        int counter=0;

        Set<Route> droutes = d.getRoutes();
        System.out.println("droutes: " + droutes.size());

        for(Route c: droutes) {
            counter++;
            boolean jump=false;

            if(odd) {
                c.setCarriedTraffic(d.getOfferedTraffic(), d.getOfferedTraffic());
                save=c;
                odd=false;
                System.out.println("Roots");
            }
            else {
                if (protection) {
                    List<Link> workingpath = save.getSeqLinksRealPath();
                    System.out.println("Protection");

                    for(Link t:workingpath) {
                        if(c.getSeqLinksRealPath().contains(t)) {
                            jump=true;
                            break;
                        }
                    }
                }
            }
        }
    }
}

```

Figura 5.49: Creation of routes and aggregation of traffic for the opaque with 1+1 protection transport mode. The candidate routes are searched by the shortest path type and the offered traffic demands are set into these routes.

```

        if(jump==false) {
            ProtectionSegment segment=netPlan.addProtectionSegment(c.getSeqLinksRealPath(),
                                                                    d.getOfferedTraffic() , null);
            save.addProtectionSegment(segment);
            odd=true;
            break;
        }

        if(jump==true && counter == droutes.size()) {
            ProtectionSegment segment=netPlan.addProtectionSegment(c.getSeqLinksRealPath(),
                                                                    d.getOfferedTraffic() , null);
            save.addProtectionSegment(segment);
            odd=true;
            throw new Net2PlanException ("Number of routes is not enough");
        }
    }
}
}
}

```

Figura 5.50: Creation of routes and aggregation of traffic for the opaque with 1+1 protection transport mode. The protection segments are added to all the primary paths that were chosen by the shortest path type method.

Function	Definition
<code>netPlan.getDemands(lowerLayer)</code>	Returns the array of demands for the lower layer.
<code>d.getRoutes()</code>	Returns all the routes associated to the demand "d".
<code>c.setCarriedTraffic()</code>	Sets the route carried traffic and the occupied capacity in the links, setting it up to be the same in all links.
<code>d.getOfferedTraffic()</code>	Returns the offered traffic of the demand "d".
<code>save.getSeqLinksRealPath()</code>	Returns the links of routes ordered sequentially.
<code>save.addProtectionSegment(segment)</code>	Add "segment" as a protection path in the route "save".

Tabela 5.101: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

The final step of the routing and grooming algorithms is to calculate the number of wavelengths per link for the whole network. This is the last and an important step because with the number of wavelengths per link in the network, it is possible to calculate other network components. In the opaque transport mode, as in the figure below shows, the algorithm starts with going through all the links and getting the capacity based on the traffic per demand. The total carried traffic in the link including protection and non-protection segments will be divided by the wavelength capacity and it is now possible to obtain the number of wavelengths per link.

```

Link p;
for(long e:linkIds) {
    p=netPlan.getLinkFromId(e);
    double sumTraffic = p.getCarriedTrafficNotIncludingProtectionSegments() + p.getReservedCapacityForProtection();
    int nw = (int) (Math.ceil(sumTraffic/wavelengthCapacity));
    String numberWavelengths = String.valueOf(nw);
    p.setCapacity(nw*wavelengthCapacity);
    p.setAttribute("nw", numberWavelengths);
}
break;

```

Figura 5.51: Calculation of the number of wavelengths per link for the opaque transport mode. The link capacity is based on the traffic per demand.

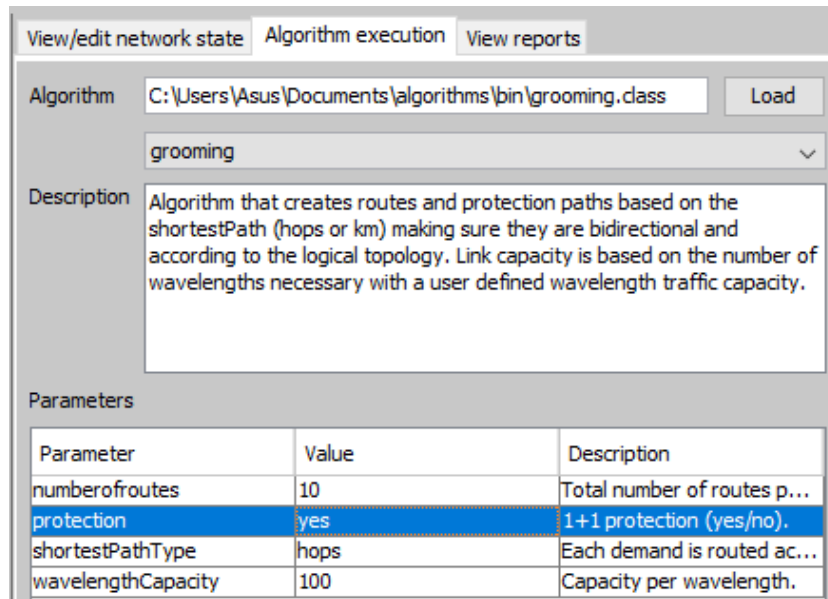


Figura 5.52: Load of the grooming algorithm for the opaque with 1+1 protection transport mode. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 5.1.2 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details. In the opaque transport mode the optical node cost is 0 because all the network ports are electrical, so it only has to be considered the electrical nodes' costs and the electrical links' costs.

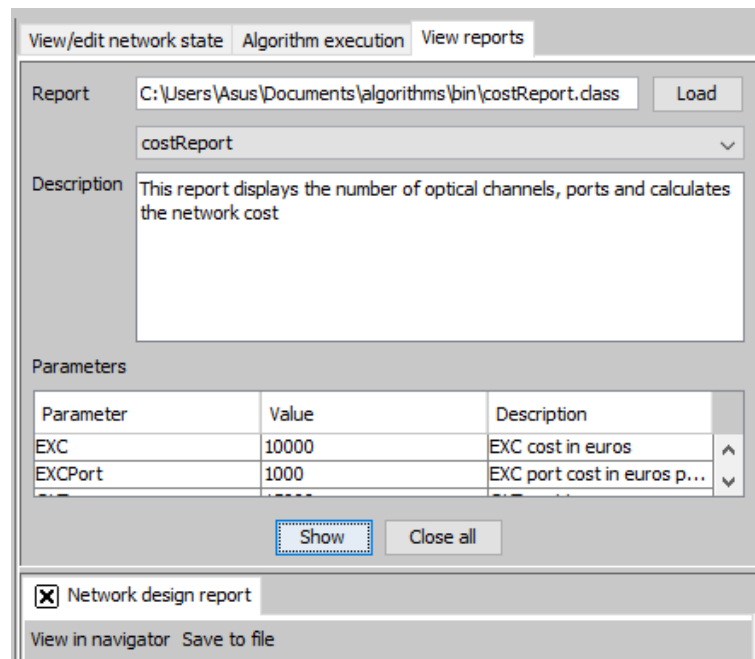


Figura 5.53: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

It is already known all the necessary formulas to obtain the CAPEX value for the reference network 4.1. 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 5.54: 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.

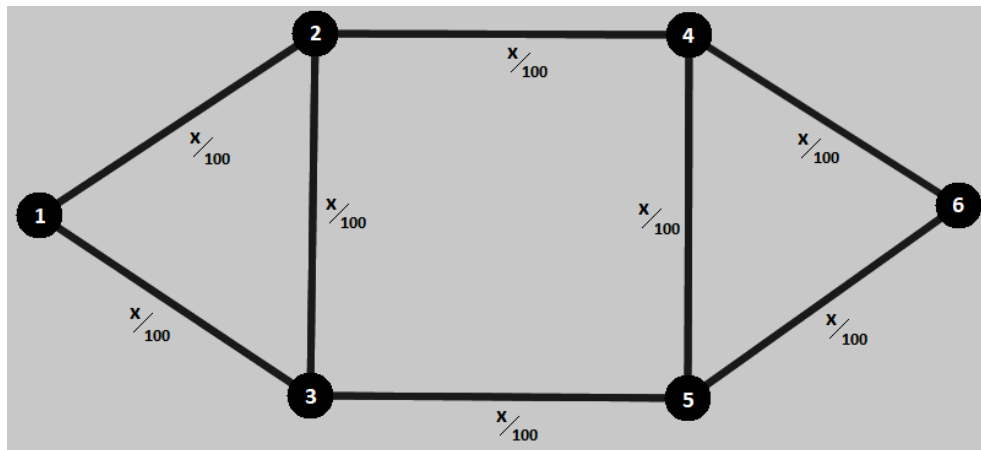


Figura 5.55: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

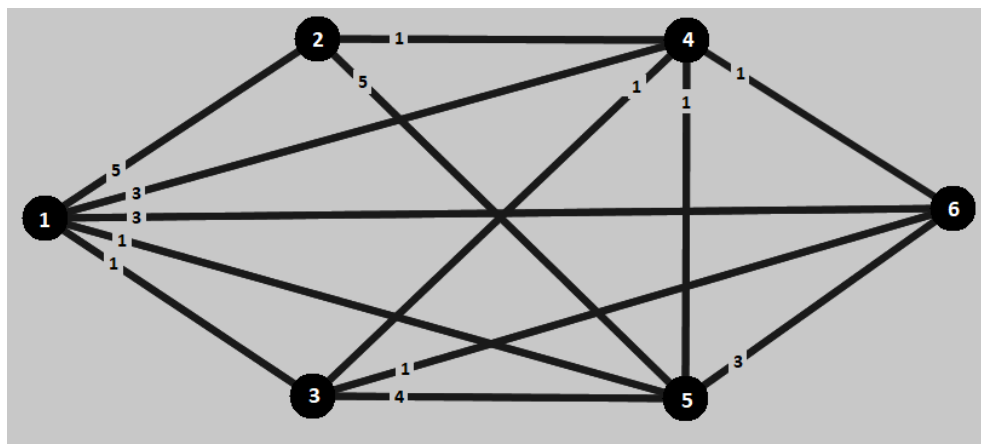


Figura 5.56: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 5.57: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 5.58: ODU2 logical topology defined by the ODU2 traffic matrix.

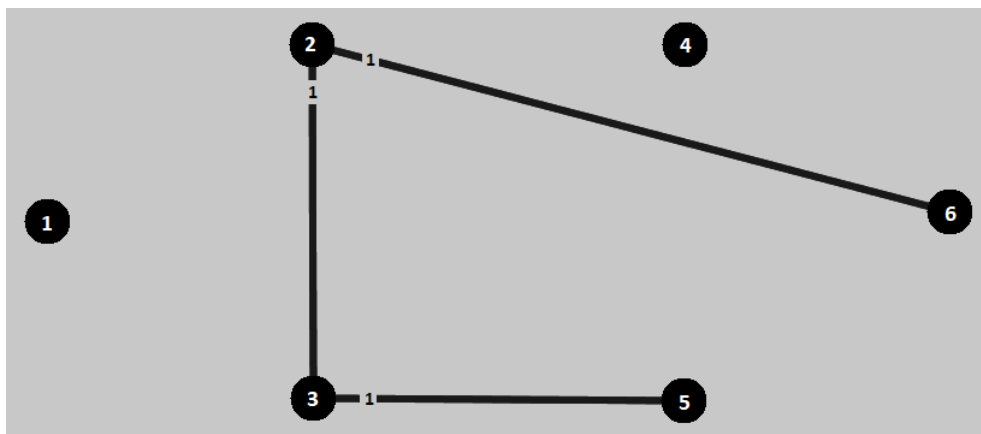


Figura 5.59: ODU3 logical topology defined by the ODU3 traffic matrix.

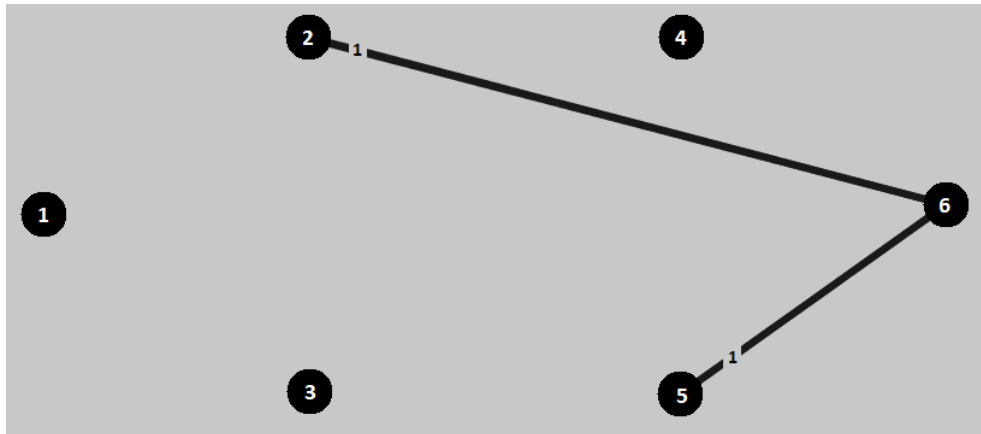


Figura 5.60: ODU4 logical topology defined by the ODU4 traffic matrix.

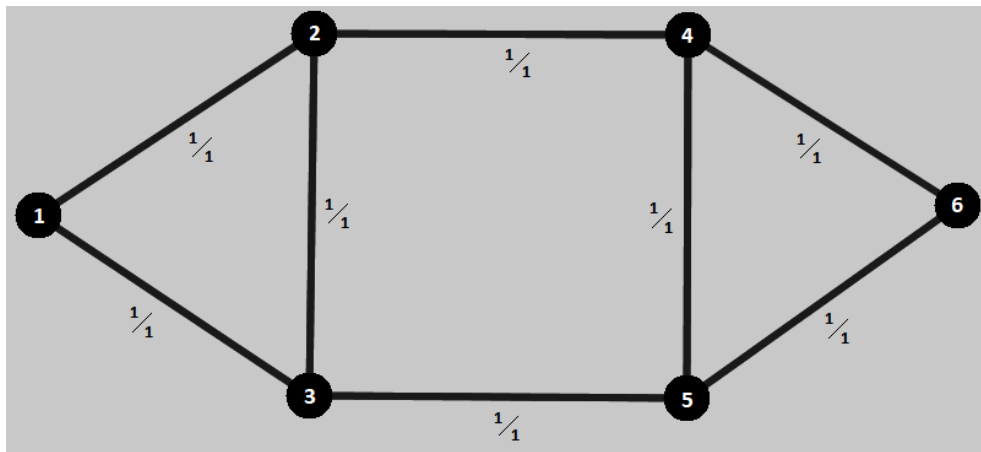


Figura 5.61: Physical topology after dimensioning.

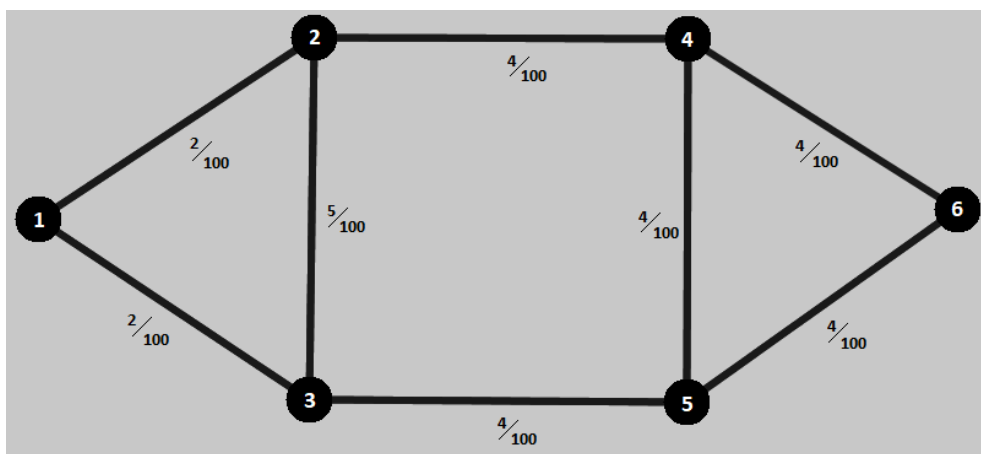


Figura 5.62: Optical topology after dimensioning.

Following all the steps mentioned in the ??, 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 5.102. In table 5.5 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 €	
	Optical	Line Ports	46	100 000 €/port	4 600 000 €	
		OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						28 182 590 €

Tabela 5.102: 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.

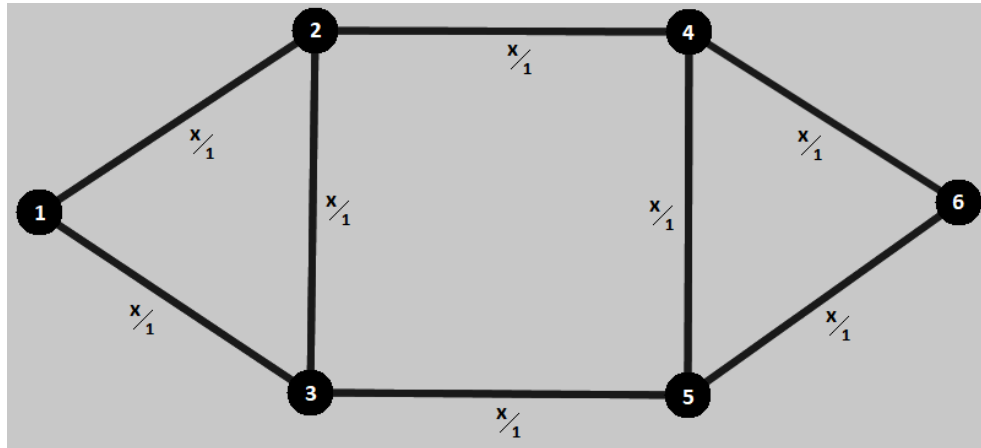


Figura 5.63: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

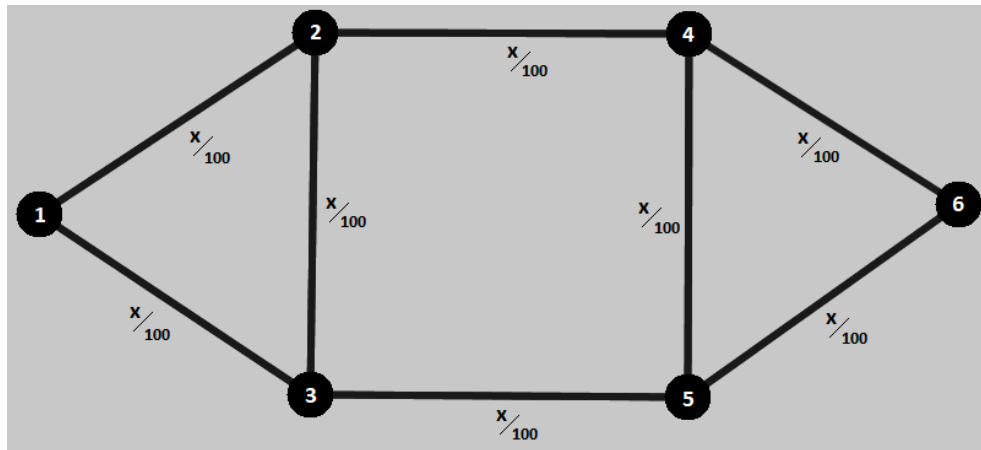


Figura 5.64: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

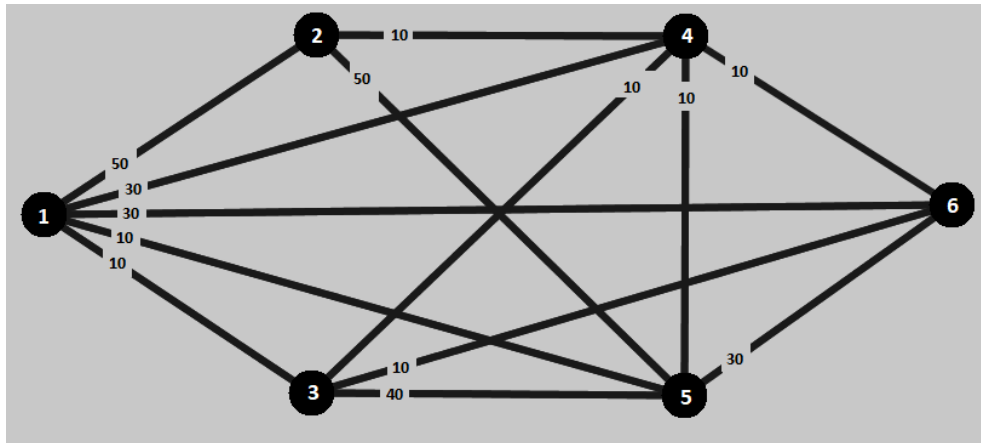


Figura 5.65: ODU0 logical topology defined by the ODU0 traffic matrix.

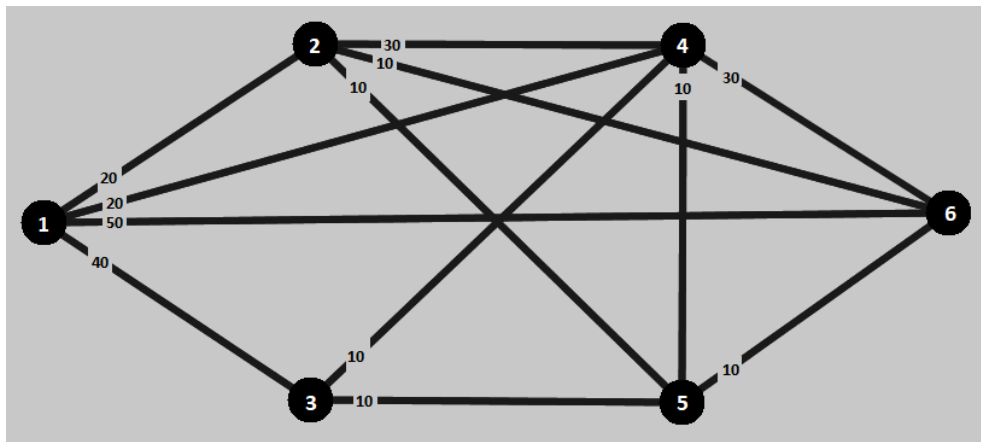


Figura 5.66: ODU1 logical topology defined by the ODU1 traffic matrix.

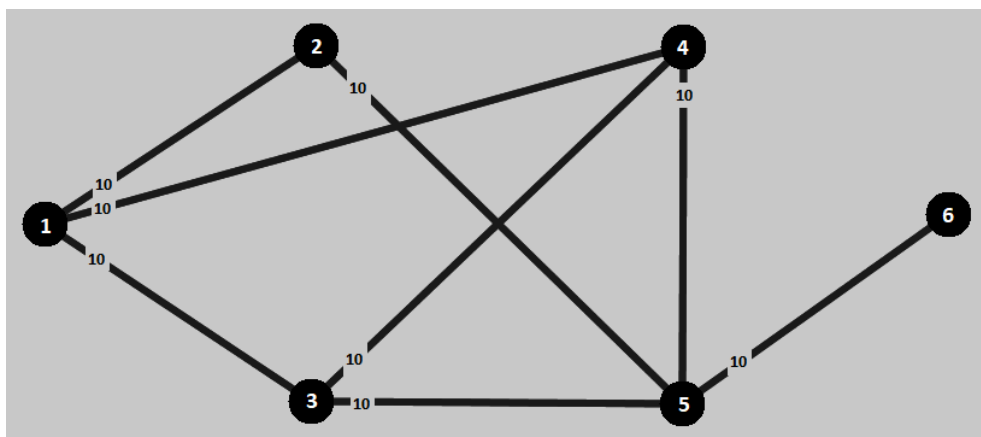


Figura 5.67: ODU2 logical topology defined by the ODU2 traffic matrix.

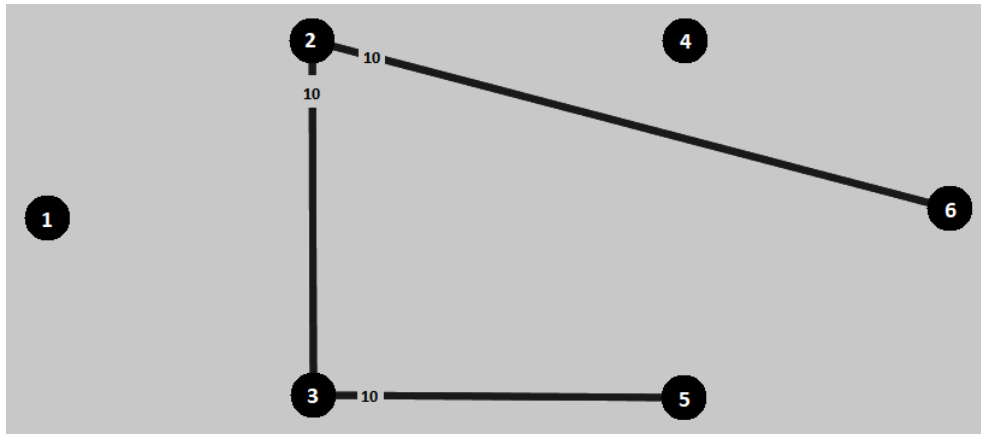


Figura 5.68: ODU3 logical topology defined by the ODU3 traffic matrix.

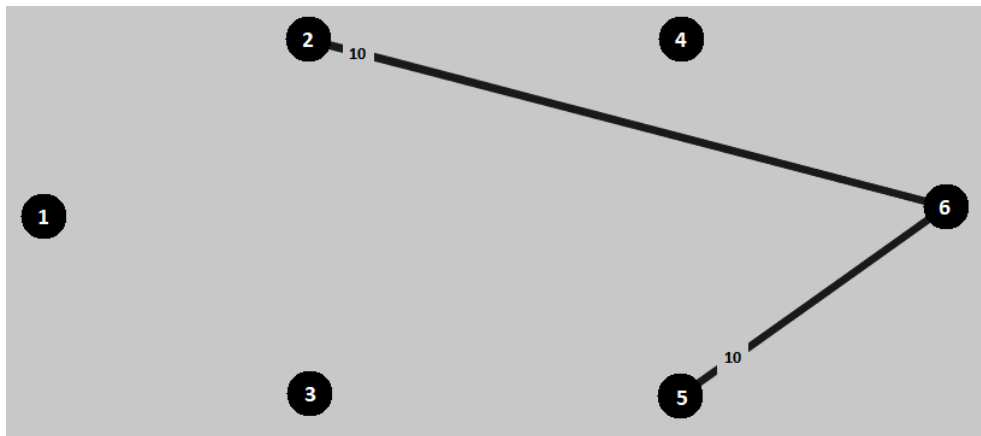


Figura 5.69: ODU4 logical topology defined by the ODU4 traffic matrix.

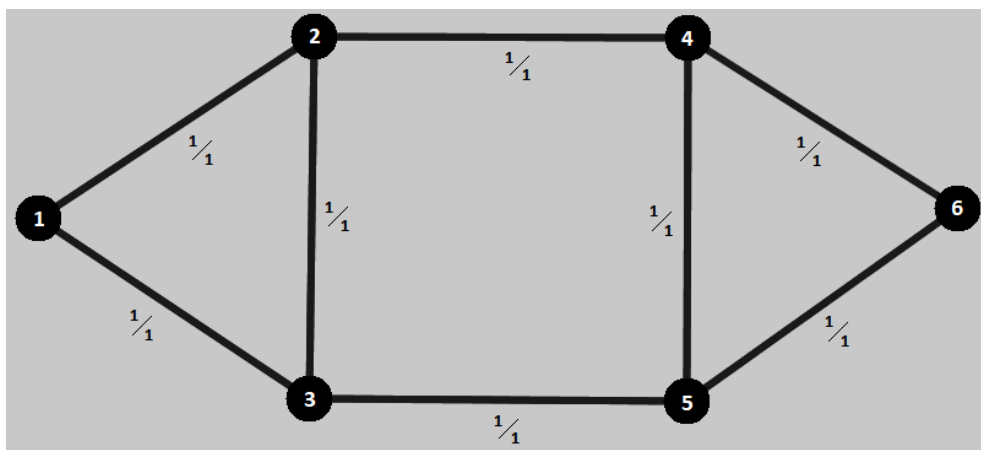


Figura 5.70: Physical topology after dimensioning.

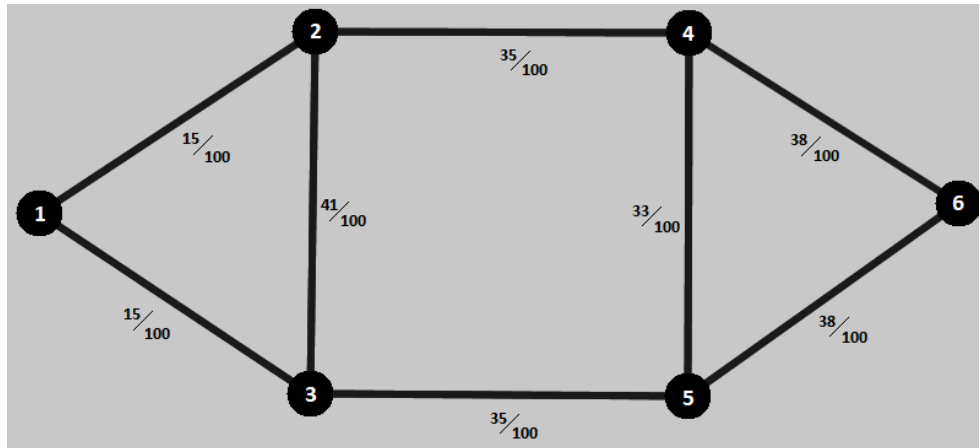


Figura 5.71: Optical topology after dimensioning.

Following all the steps mentioned in the ??, 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 5.103. In table 5.5 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	39 800 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						239 405 900 €

Tabela 5.103: 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.

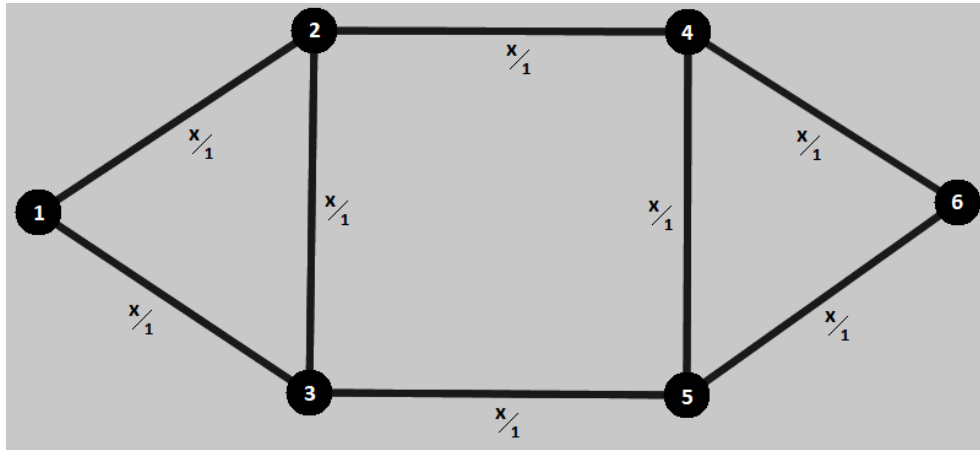


Figura 5.72: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

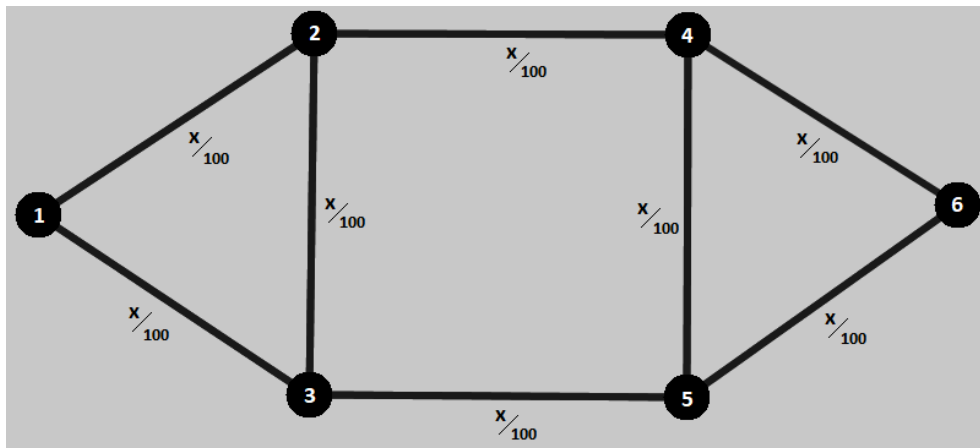


Figura 5.73: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

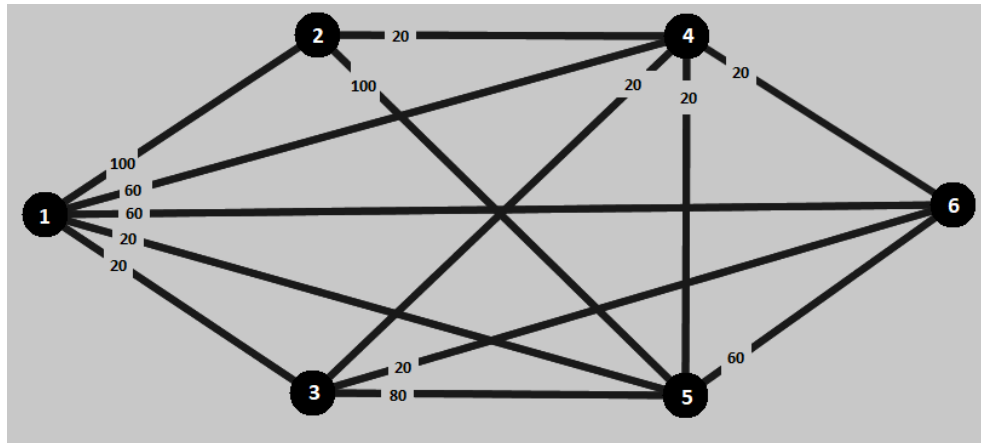


Figura 5.74: ODU0 logical topology defined by the ODU0 traffic matrix.

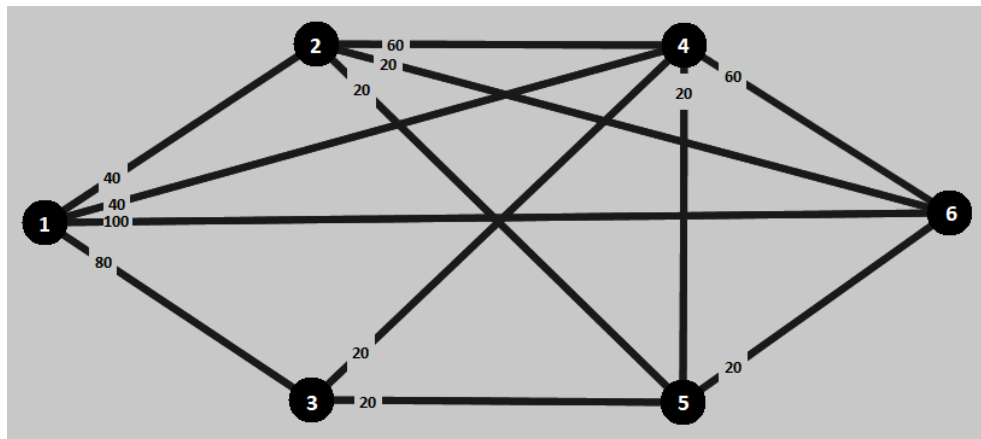


Figura 5.75: ODU1 logical topology defined by the ODU1 traffic matrix.

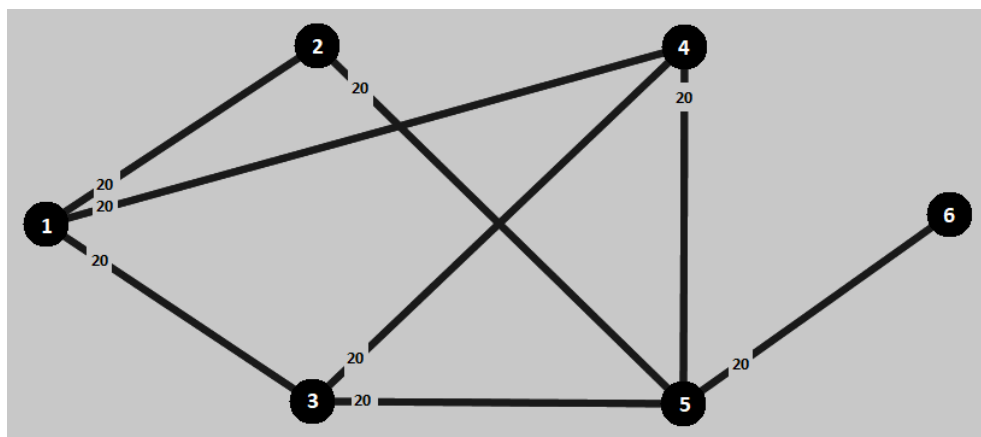


Figura 5.76: ODU2 logical topology defined by the ODU2 traffic matrix.

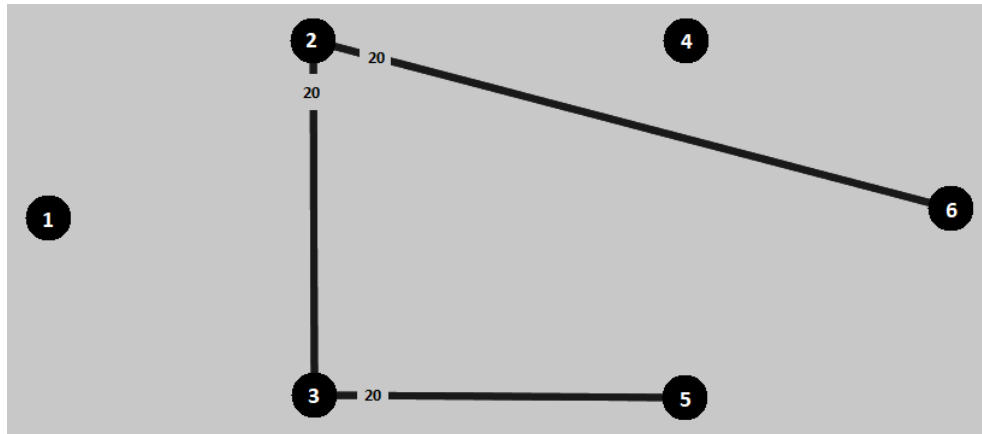


Figura 5.77: ODU3 logical topology defined by the ODU3 traffic matrix.

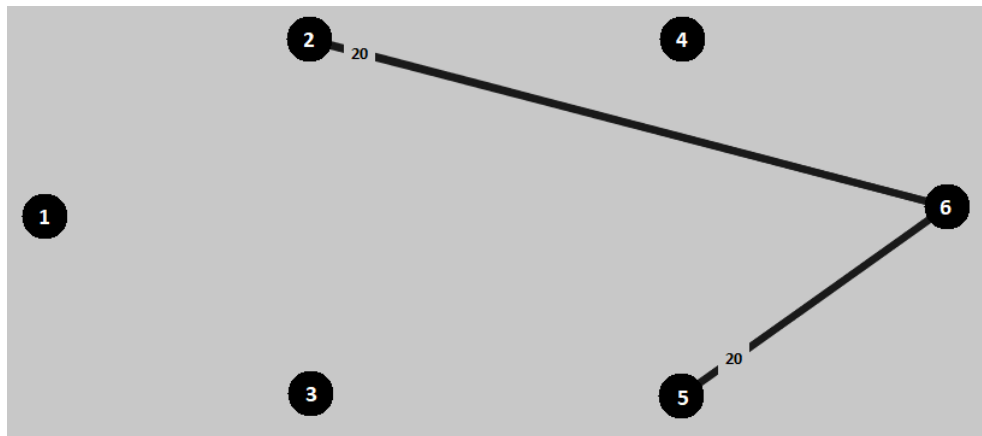


Figura 5.78: ODU4 logical topology defined by the ODU4 traffic matrix.

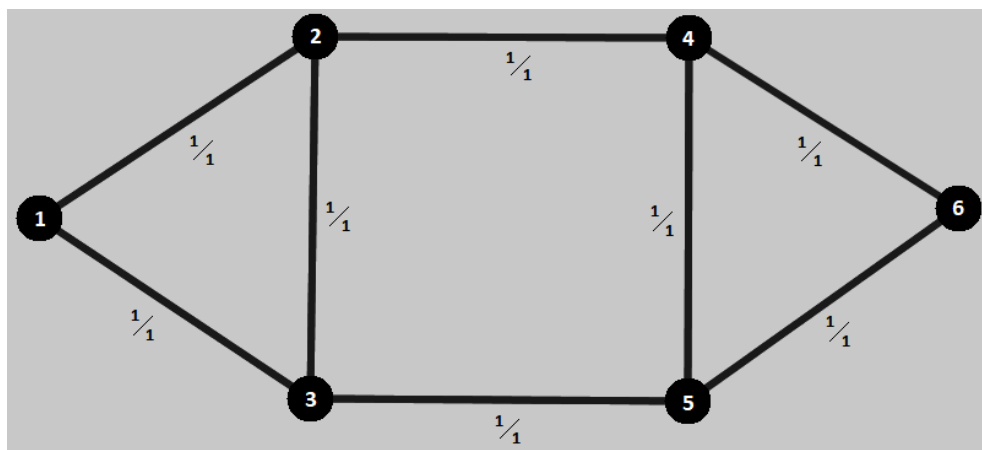


Figura 5.79: Physical topology after dimensioning.

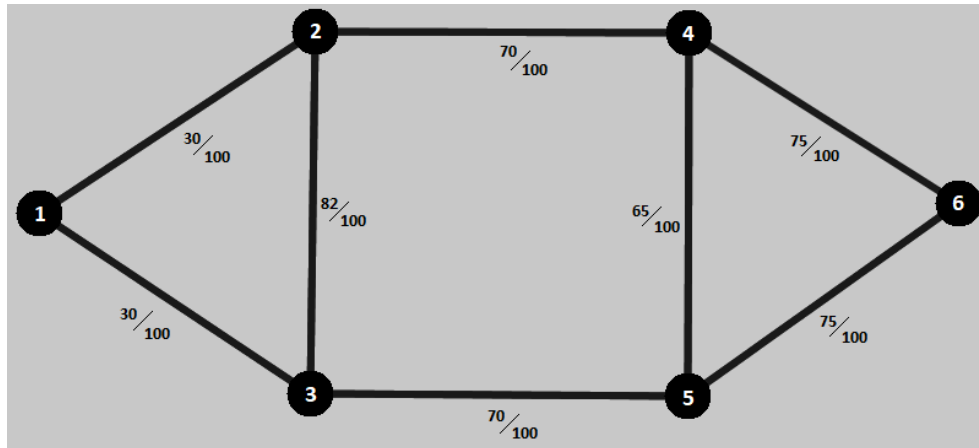


Figura 5.80: Optical topology after dimensioning.

Following all the steps mentioned in the ??, 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 5.104. In table 5.5 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 €	79 511 800 €
		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 €	
	Optical	Line Ports	794	100 000 €/port	79 400 000 €	
		OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						477 031 800 €

Tabela 5.104: 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 5.105 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 €	178 831 800 €
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 €	79 511 800 €
CAPEX	28 182 590 €	239 405 900 €	477 031 800 €
CAPEX/Gbit/s	56 365 €/Gbit/s	47 881 €/Gbit/s	47 703 €/Gbit/s

Tabela 5.105: 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.

5.1.3 Transparent without Survivability

Student Name	:	Eduardo Fernandes (20/10/2018 -)
	:	Pedro Coelho (01/03/2018 -)
Goal	:	Implement the heuristic model for the transparent transport mode without survivability.

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:

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

The minimization of the network CAPEX is made through the equation 5.1 where in this case for the cost of nodes we have in consideration the electric cost 5.4 and the optical cost 5.5.

In this case the value of $P_{exc,c,n}$ is obtained by equation 5.10 for short-reach and by the equation 5.11 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 5.12.

The equation 5.10 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

$$P_{exc,c,n} = \sum_{d=1}^N D_{nd,c} \quad (5.10)$$

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 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 add ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^N f_{nj}^{od} \quad (5.11)$$

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

The equation 5.12 refers to the number of line ports and the number of adding ports of node n which can be calculated as

$$P_{oxc,n} = \sum_{j=1}^N 2f_{nj}^{od} + \sum_{j=1}^N \lambda_{nj} \quad (5.12)$$

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

To implement this heuristic approach there are used algorithms made in Java in a programming software called Eclipse and they are tested in an open-source network program called Net2Plan. In the Net2Plan guide section ?? there is an explanation on how to use and test them in this network planner.

In the next pages it will be described all the steps performed to obtain the final results in the transparent transport mode without survivability. In the figure below 5.81 it is shown a fluxogram with the description of this transport mode approach.

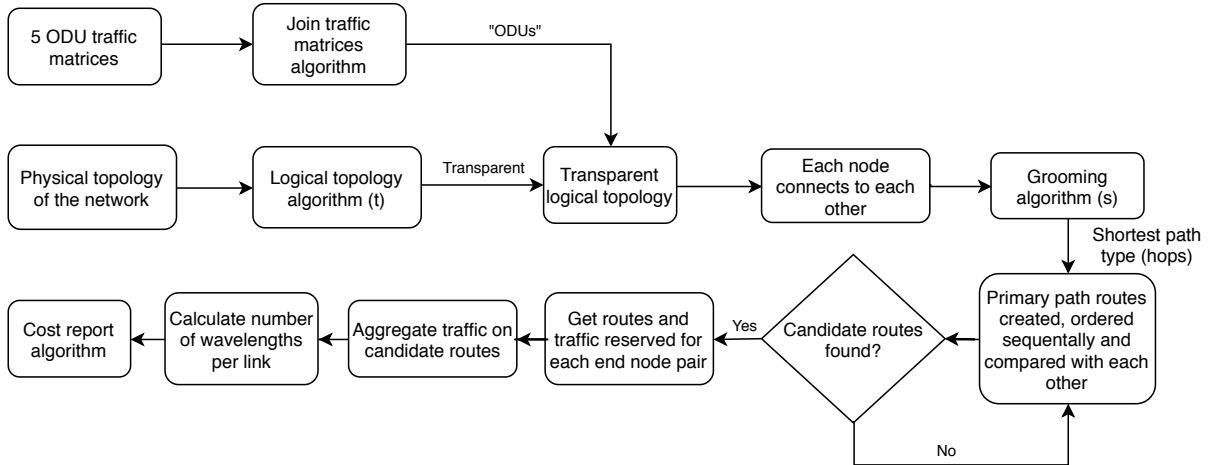


Figura 5.81: Fluxogram with the steps performed in the transparent without survivability transport mode approach.

Creation and join the traffic matrices

The first step is to create the traffic matrices based on the reference network 4.1. In order to create the 5 traffic matrices in Net2Plan it is necessary the length of all the links and the total traffic used in this network, so later it is needed to define in Net2Plan the length in all end nodes and the total traffic depends on the value of traffic used (low traffic - 0.5 Tbit/s, medium traffic - 5 Tbit/s and high traffic - 10 Tbit/s). As you can see in the figure below, it is defined the path of the 5 ODUs and they will be aggregated in just one single ODU, making it possible to join all the demands in just one file and load it later into the network. This final resulting ODU joins the multiple traffic demands from all the traffic matrices previously created and, of course, the traffic demands will depend on the values used on the creation of the matrices (low, medium and high traffic).

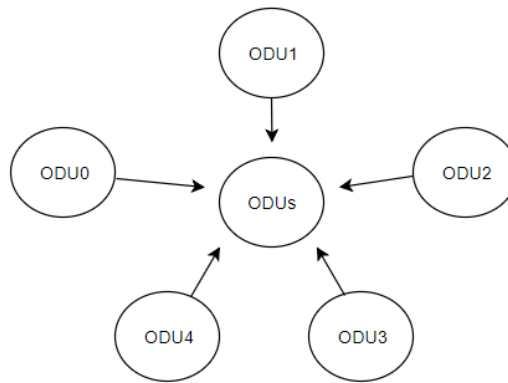


Figura 5.82: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.

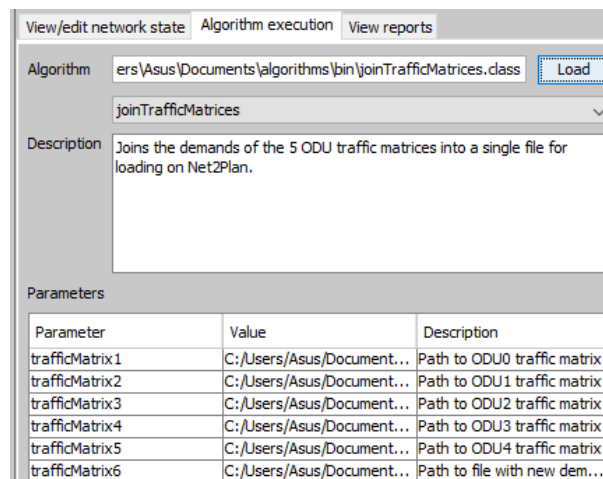


Figura 5.83: Load of the join traffic matrices algorithm for the transparent transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

The next step is to create the allowed physical topology of the network in Net2Plan. This network consists in 6 nodes and 8 bidirectional links. It is now also possible to define the length in all links. In the figure below it is shown the allowed physical topology in this transport mode.

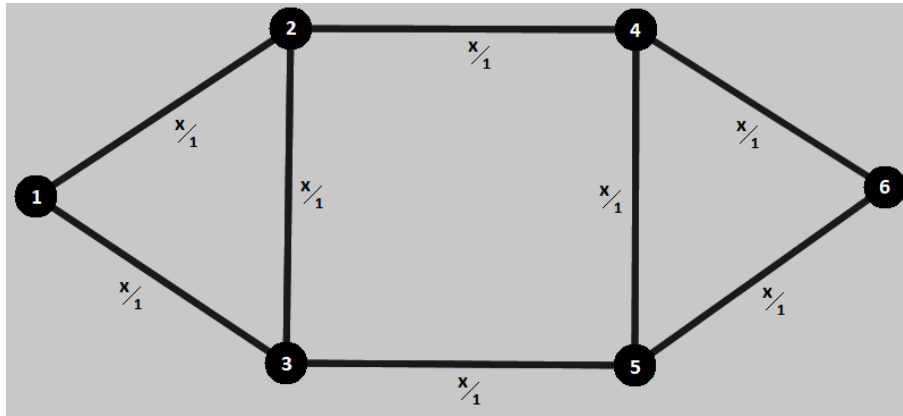


Figura 5.84: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. 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 one, then creates a shortest and direct link between them. These additions of links between end 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 physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 5.1.3 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the transparent transport mode without survivability.

```

if(netPlan.isSingleLayer() && logicalTopology.equalsIgnoreCase("Transparent"))
{
    this.lowerLayer = netPlan.getNetworkLayerDefault();
    lowerLayer.setName("Physical Topology");
    this.upperLayer = netPlan.addLayer("Logical Topology Transparent","Upper layer of the design","ODU","ODU",null);
    upperLayer.setDescription("Transparent Logical Topology");
    netPlan.removeAllLinks(upperLayer);

    for (Node i : netPlan.getNodes()) {
        for (Node j : netPlan.getNodes()) {
            if (i.getIndex() != j.getIndex())
            {
                netPlan.addLink(i, j, 0 , netPlan.getNodePairEuclideanDistance(i, j), 200000 , null , upperLayer);
            }
        }
    }
}

```

Figura 5.85: Java code of the logical topology approach for the transparent transport mode. The logical layer is created by adding direct links between all end nodes. The new layer is now the transparent logical topology of the network.

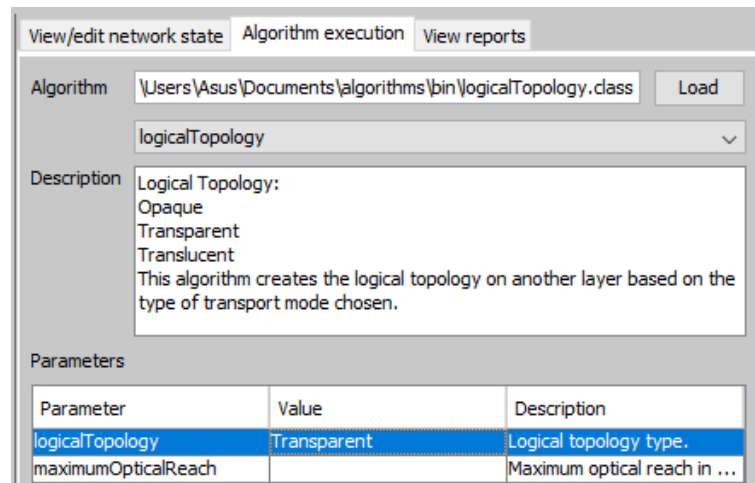


Figura 5.86: Load of the logical topology algorithm for the transparent transport mode.

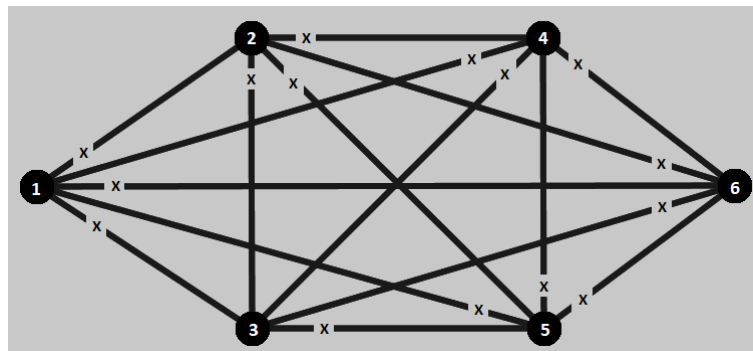


Figura 5.87: Allowed optical topology. It is assumed that each connections between demands supports up to 100 lightpaths.

Creation of routes and aggregation of traffic

After a network topology is created, it is now time to set the routing algorithm. In the transparent without survivability transport mode the routing algorithm is similar with the one used in opaque transport mode. It starts with going through all the demands and nodes which have different index between them (end nodes), create bidirectional routes (in this case the primary paths) based on the shortest path Dijkstra algorithm and then search the candidate routes for the respective demand. In this report it is used the shortest path type in hops. These routes are ordered sequentially and the shortest one per each demand is the primary path. The demands from the lower layer are removed and then saved in the upper layer. After this step, the routes are saved to a "Set" of routes and in each link of end nodes it is set the traffic demands into these routes that will integrate the whole network.

```
case "Logical Topology Transparent":

    for (Demand d : netPlan.getDemands(lowerLayer)) {
        boolean odd=true;
        int counter=0;

        Set<Route> droutes = d.getRoutes();
        System.out.println("droutes: " + droutes.size());

        for(Route c: droutes) {
            counter++;
            boolean jump=false;

            if(odd) {
                c.setCarriedTraffic(d.getOfferedTraffic(), d.getOfferedTraffic());
                save=c;
                odd=false;
                System.out.println("Roots");
            }
        }
    }
}
```

Figura 5.88: Creation of routes and aggregation of traffic for the transparent without survivability transport mode. The candidate routes are searched by the shortest path type method and the offered traffic demands are set into these routes.


```

ArrayList<Long> tNodeIds = netPlan.getNodeIds();
Node in;
Node out;
Set<Route> groomRoute;
Set<ProtectionSegment> protectRoutes;
Route compare=null;
ProtectionSegment compare1=null;
List<Link> path;
int nw=0;

for (long tNodeId : tNodeIds) {
    in = netPlan.getNodeFromId(tNodeId);
    for (long tNodeId1 : tNodeIds) {

        if(tNodeId==tNodeId1)continue;

        out = netPlan.getNodeFromId(tNodeId1);
        double totaltraffic=0;

        groomRoute=netPlan.getNodePairRoutes(in,out,false,lowerLayer);
        protectRoutes=netPlan.getNodePairProtectionSegments(in,out,false,lowerLayer);

        for(Route d:groomRoute)
        {
            totaltraffic = totaltraffic + d.getCarriedTraffic();
            compare=d;
        }
    }
}

```

Figura 5.89: Creation of routes and aggregation of traffic for the transparent without survivability transport mode. The traffic demands are set into the candidate primary path routes found earlier.

Function	Definition
netPlan.getDemands(lowerLayer)	Returns the array of demands for the lower layer.
d.getRoutes()	Returns all the routes associated to the demand "d".
c.setCarriedTraffic()	Sets the route carried traffic and the occupied capacity in the links, setting it up to be the same in all links.
d.getOfferedTraffic()	Returns the offered traffic of the demand "d".
netPlan.getNodeIds()	Returns the array of the nodes' indexes.
netPlan.getNodeFromId(tNodeId)	Returns the node with the index "tNodeId".
netPlan.getNodePairRoutes (in,out,false,lowerLayer)	Returns the routes at "lowerLayer" from nodes "in" and "out".

Tabela 5.106: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

The final step of the routing and grooming algorithms is to calculate the number of wavelengths per link for the whole network. This is the last and an important step because with the number of wavelengths per link in the network, it is possible to calculate other network components. In the transparent transport mode, as in the figure below shows, the algorithm starts with going through all the nodes which have different index between them (end nodes) and in all the links that crosses between these pairs of nodes is reserved a link capacity based on the previous traffic aggregation. The total carried traffic in the link including protection and non-protection segments will be divided by the wavelength capacity and it is now possible to obtain the number of wavelengths per link.

```

for (Link link:path)
{
    String nw = link.getAttribute("nw");
    nw=0;

    if(nw!=null)
    {
        nw = Integer.parseInt(nw);
        nw = (int) (nw+Math.ceil(totaltraffic/wavelengthCapacity));
        link.setAttribute("nw",String.valueOf(nw));
    }else {
        nw = (int) Math.ceil(totaltraffic/wavelengthCapacity);
        link.setAttribute("nw",String.valueOf(nw));
    }
}

```

Figura 5.90: Calculation of the number of wavelengths per link for the transparent transport mode. The link capacity is reserved based on the previous traffic aggregation.

View/edit network state Algorithm execution View reports

Algorithm

Description
Algorithm that creates routes and protection paths based on the shortestPath (hops or km) making sure they are bidirectional and according to the logical topology. Link capacity is based on the number of wavelengths necessary with a user defined wavelength traffic capacity.

Parameters

Parameter	Value	Description
numberofroutes	10	Total number of routes p...
protection	no	1+1 protection (yes/no).
shortestPathType	hops	Each demand is routed ac...
wavelengthCapacity	100	Capacity per wavelength.

Figura 5.91: Load of the grooming algorithm for the transparent without survivability transport mode. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 5.1.3 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details.



Figura 5.92: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

It is already known all the necessary formulas to obtain the CAPEX value for the reference network 4.1. 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.

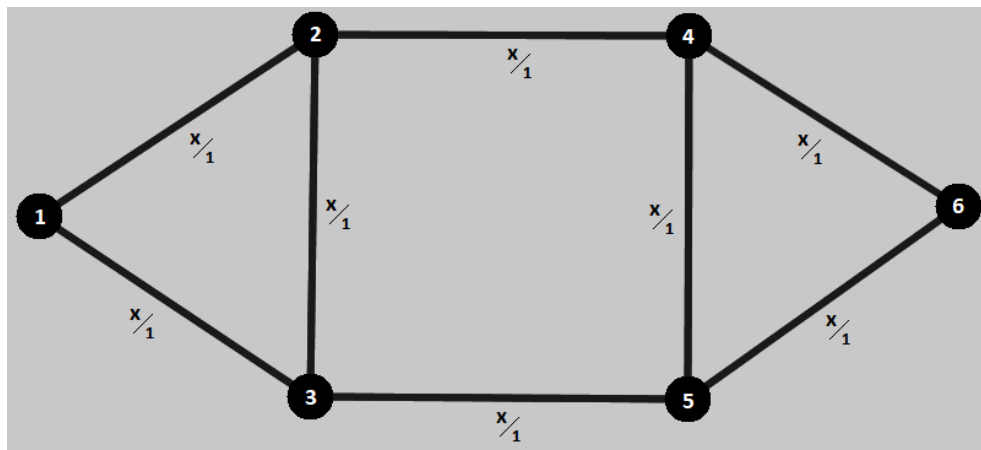


Figura 5.93: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 5.94: 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.

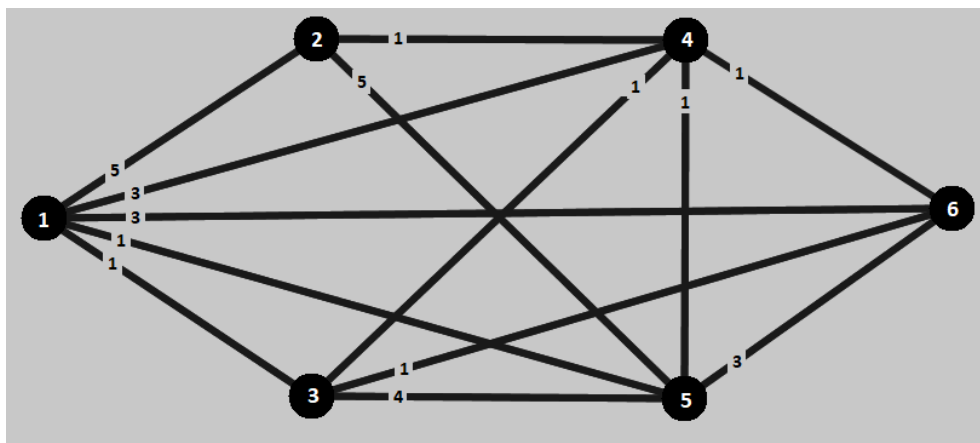


Figura 5.95: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 5.96: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 5.97: ODU2 logical topology defined by the ODU2 traffic matrix.

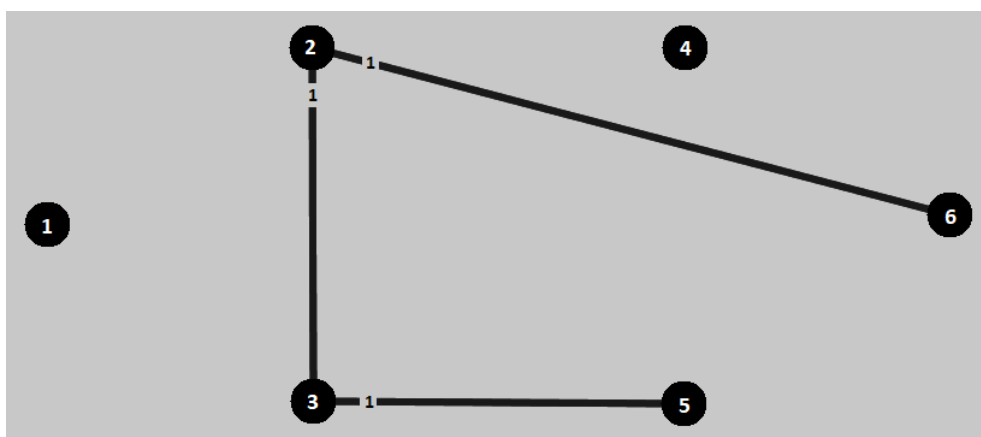


Figura 5.98: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 5.99: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 5.100: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 5.107.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	26 520 000 €
	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 €	3 797 590 €
		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	52	2 500 €/port	130 000 €	
		Add Ports	34	2 500 €/port	85 000 €	
Total Network Cost						30 317 590 €

Tabela 5.107: Table with detailed description of CAPEX of Vasco's 2016 results.

All the values calculated in the previous table were obtained through the equations 5.2 and 5.3 referred to in section 5.1, but for a more detailed analysis we created table 5.108 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	$\sum_{n=1}^N \sum_{j=1}^N N_{exc,n} \lambda_{od} \gamma_{e1,-1}$
OXC	$\sum_{n=1}^N N_{oxc,n} \gamma_{o0}$
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 5.108: Table with description of calculation

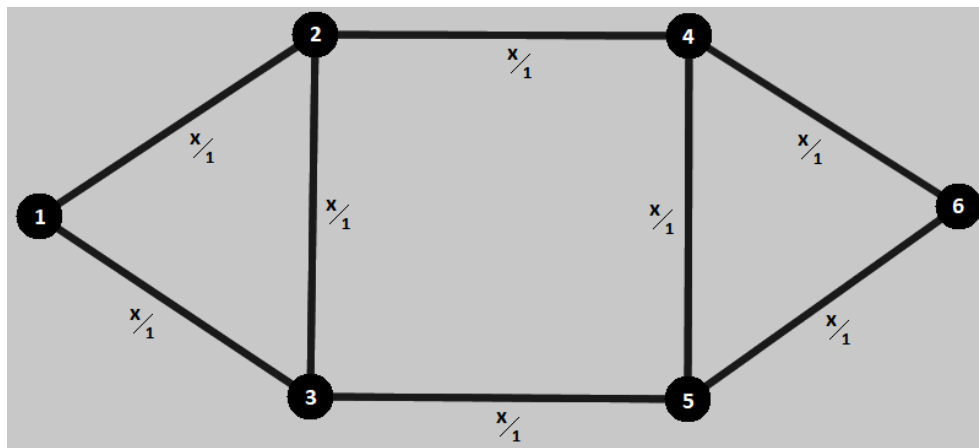


Figura 5.101: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional



Figura 5.102: 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 5.103: ODU0 logical topology defined by the ODU0 traffic matrix.

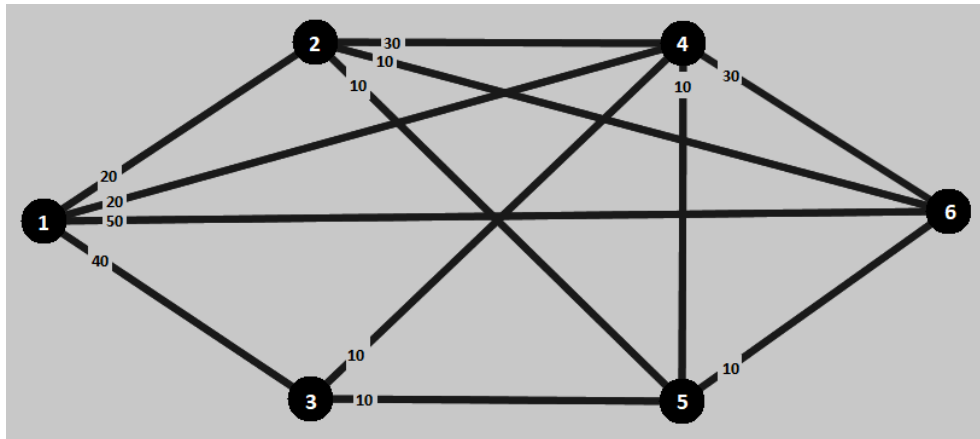


Figura 5.104: ODU1 logical topology defined by the ODU1 traffic matrix.

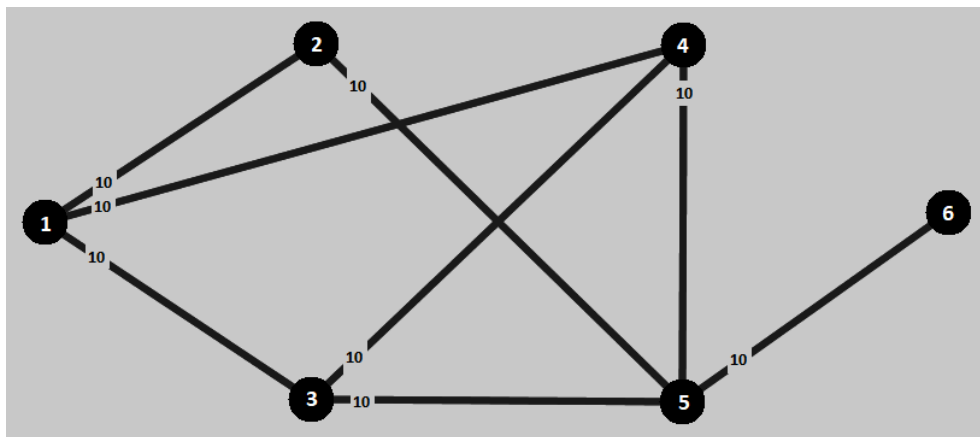


Figura 5.105: ODU2 logical topology defined by the ODU2 traffic matrix.

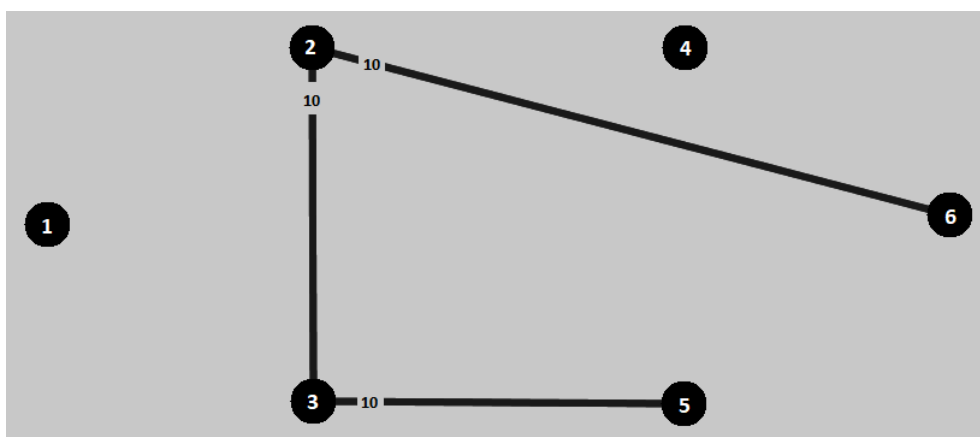


Figura 5.106: ODU3 logical topology defined by the ODU3 traffic matrix.

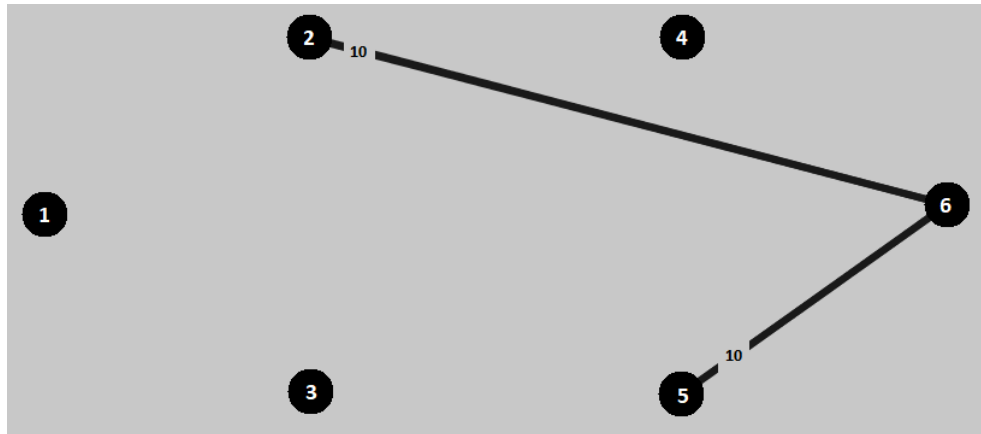


Figura 5.107: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 5.108: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 5.109. In table 5.108 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 €	84 520 000 €
	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 €	15 180 900 €
		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	142	100 000 €/port	14 200 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	168	2 500 €/port	420 000 €	
		Add Ports	142	2 500 €/port	355 000 €	
Total Network Cost						99 700 900 €

Tabela 5.109: 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.

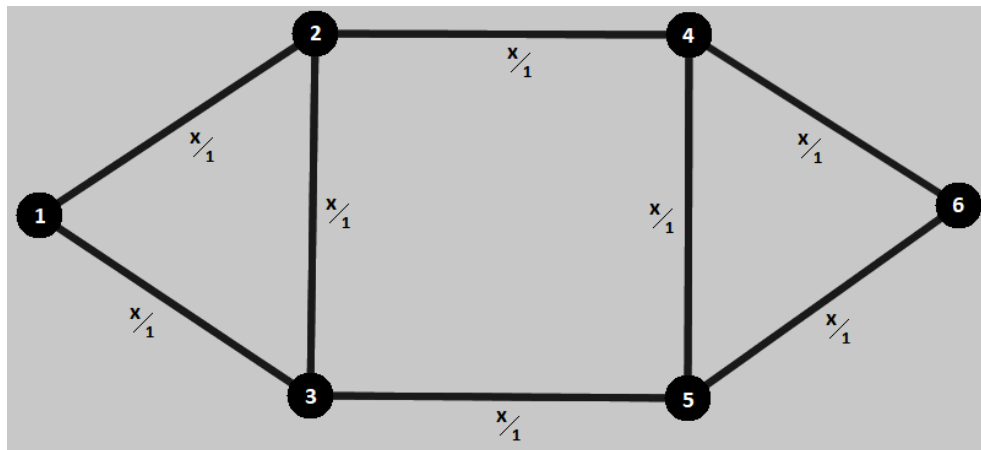


Figura 5.109: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 5.110: 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.

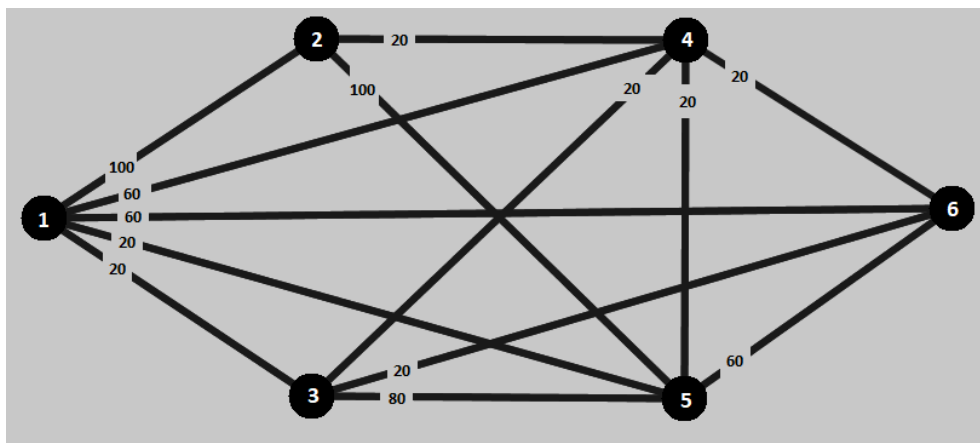


Figura 5.111: ODU0 logical topology defined by the ODU0 traffic matrix.

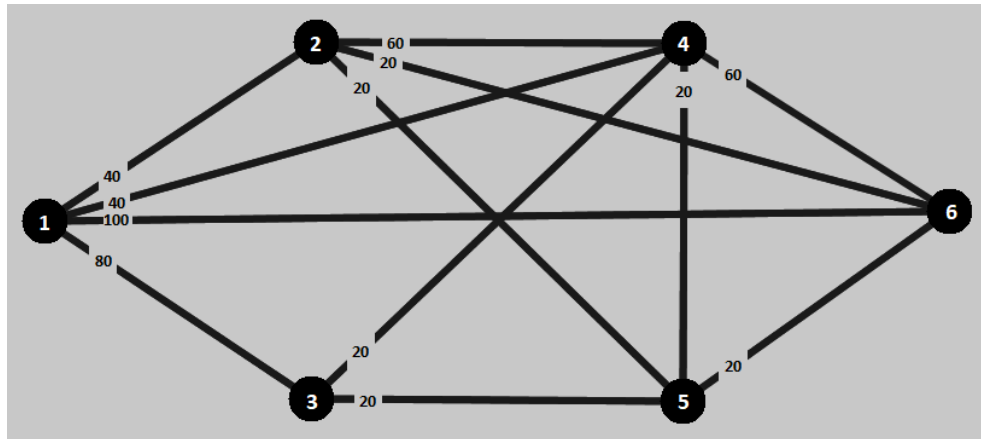


Figura 5.112: ODU1 logical topology defined by the ODU1 traffic matrix.

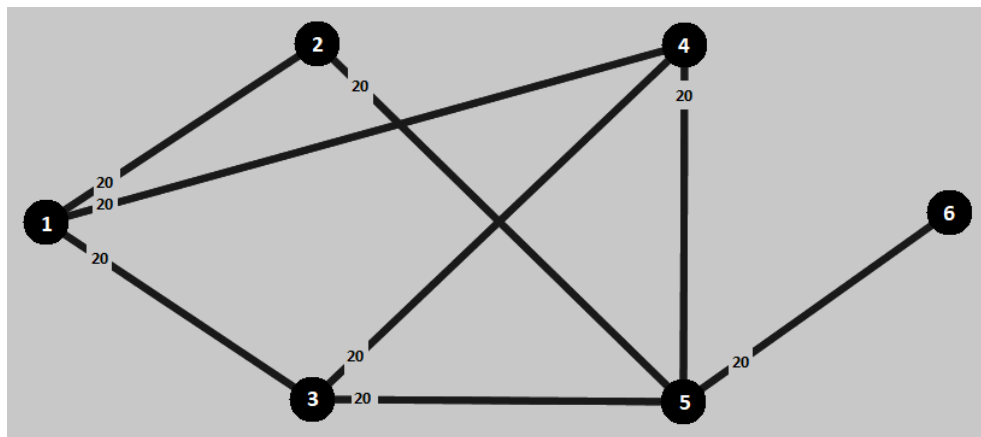


Figura 5.113: ODU2 logical topology defined by the ODU2 traffic matrix.

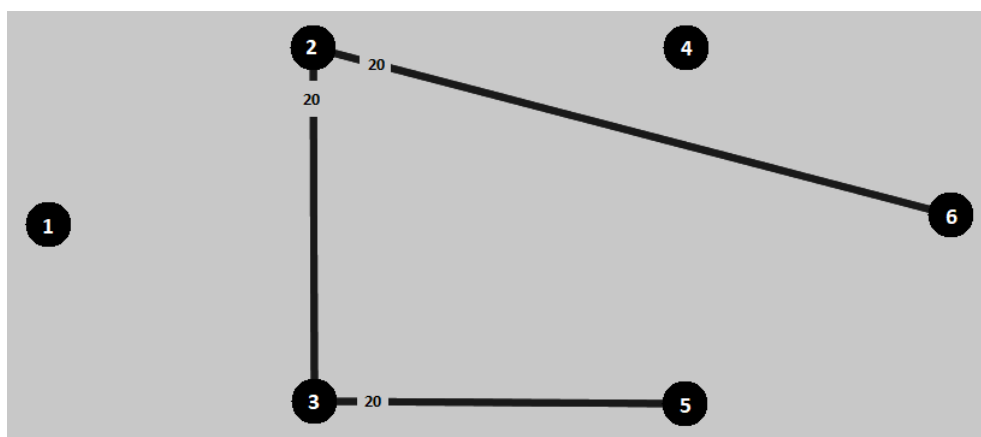


Figura 5.114: ODU3 logical topology defined by the ODU3 traffic matrix.

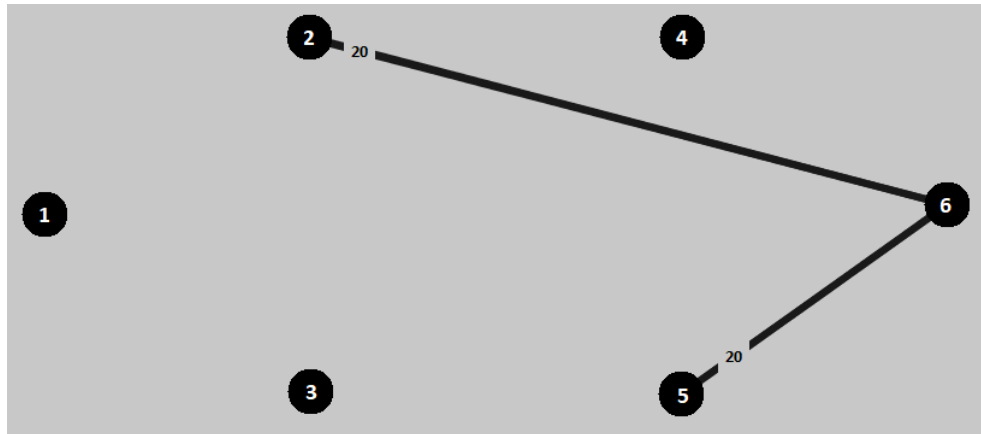


Figura 5.115: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 5.116: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 5.110. In table 5.108 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 €	28 486 800 €
		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	268	100 000 €/port	26 800 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	314	2 500 €/port	785 000 €	
		Add Ports	268	2 500 €/port	670 000 €	
Total Network Cost						186 006 800 €

Tabela 5.110: 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 5.111 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	142	268
Number of Line ports	52	168	314
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	52	168	314
Link Cost	26 520 000 €	84 520 000 €	157 520 000 €
Node Cost	3 797 590 €	15 180 900 €	28 486 800 €
CAPEX	30 317 590 €	99 700 900 €	186 006 800 €
CAPEX/Gbit/s	60 635 €/Gbit/s	19 940 €/Gbit/s	18 600 €/Gbit/s

Tabela 5.111: 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.

Capítulo 6

Transparent transport mode

Student Name : Eduardo Fernandes (09/11/2018 -)
Goal : Allows blocking, i.e., creation of a model that supports a partial solution where some demands are not routed (are blocked).

In figure 1.112 a top level diagram is presented in which it is represented the heuristics approach implemented behind the developed algorithms.

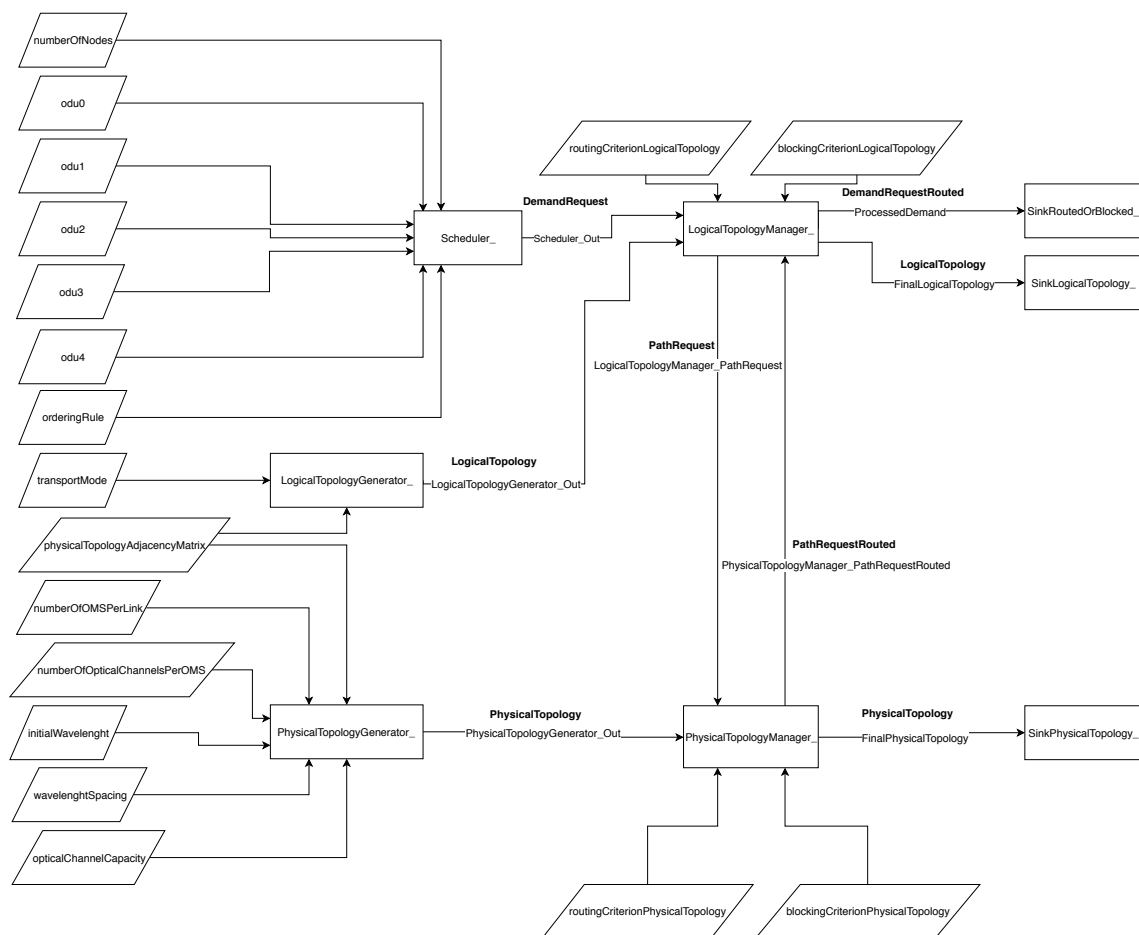


Figura 6.1: High level diagram of the heuristic algorithm performed.

6.1 Concepts

This section serves to introduce some of the terminology used throughout the dissertation.

6.1.1 Network Nodes

The circles in the network graphs presented above represent nodes, these are points in the network that terminate and switch traffic.

6.1.2 Network Links

The lines connecting network nodes can be mentioned both as physical links or optical multiplexing systems and they are typically depicted with just a single line and are formed by one fiber that carries traffic in a certain direction.

6.2 System inputs

Parameter	Default value	Description
numberOfNodes	0	Number of existing nodes in the network.
odu0	[0]	N by N matrix containing ODU0 demands.
odu1	[0]	N by N matrix containing ODU1 demands.
odu2	[0]	N by N matrix containing ODU2 demands.
odu3	[0]	N by N matrix containing ODU3 demands.
odu4	[0]	N by N matrix containing ODU4 demands.
orderingRule	descendingOrder	descendingOrder (ODU4 to ODU0) ascendingOrder (ODU0 to ODU4)
transportMode	transparent	"opaque", "transparent" or "translucent".
physicalTopologyAdjacencyMatrix	[0]	Physical connections of the network.
numberOfOMSPerLink	1	Number of optical multiplexing systems existing in each physical link.
numberOfOpticalChannelsPerOMS	100	Number of optical channels per optical multiplexing system
initialWavelength	1550	Initial value of the wavelength used expressed in nanometers (nm).
wavelengthSpacing	0.8	Interval between used wavelengths (nm).
opticalChannelCapacity	100 Gbps	Physical capacity of each optical channel.
routingCriterionLogicalTopology	Hops	Shortest path type.
routingCriterionPhysicalTopology	Hops	Shortest path type.
blockingCriterionLogicalTopology	3	Number of attempted paths before blocking a demand.
blockingCriterionPhysicalTopology	3	Number of attempts before discarding a possible path.

Tabela 6.1: System input parameters.

6.3 System signals

Signal name	Signal type
Scheduler_Out	DemandRequest
LogicalTopologyGenerator_Out	LogicalTopology
PhysicalTopologyGenerator_Out	PhysicalTopology
LogicalTopologyManager_PathRequest	PathRequest
PhysicalTopologyManager_PathRequestRouted	PathRequestRouted
ProcessedDemand	DemandRequestRouted
FinalLogicalTopology	LogicalTopology
FinalPhysicalTopology	PhysicalTopology

Tabela 6.2: System Signals.

Table 6.2 presents the system signals as well as their type.

6.4 Type signals structure

6.4.1 LogicalTopology

The logical topology of the network is an approach that defines how components are connected. Each node may be optical directly connected to each other, or only optical connected to adjacent nodes or optical connected to suitable nodes. These possibilities are demonstrated below on table ??, where 0/1 indicates the possibility of establishing a logical connection between nodes.

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

logicalTopologyMatrix

Nodes	1	2	...	N
1	0	0/1	...	0/1
2	0/1	0	...	0/1
.
.
.
N	0/1	0/1	...	0

Tabela 6.3: Allowed logical topology for a matrix of N nodes.

N represents the number of nodes present in the network.

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

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

paths

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

Tabela 6.4: Structure of a path variable.

lightPaths

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

Tabela 6.5: Structure of a light path variable.

opticalChannels

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

Tabela 6.6: Structure of an optical channel variable.

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

6.4.2 PhysicalTopology

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

connection between a pair of nodes, and each site supports up to 1 node.

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

physicalTopologyMatrix

Nodes	1	2	...	N
1	0	0/1	...	0/1
2	0/1	0	...	0/1
.
.
.
N	0/1	0/1	...	0

Tabela 6.7: Allowed physical topology for a matrix of N nodes.

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

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

opticalMultiplexingSystems

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

Tabela 6.8: Structure of the opticalMultiplexingSystems variables.

OC represents the number of optical channels present in a physical link.

L represent the total number of existent unidirectional physical links in the network.

w_1 and w_2 represent values of possible wavelengths to be used.

In the availableWavelengths array 0/1 dictates if the corresponding wavelength value of wavelengths array is available or not to be used, 1 and 0 respectively.

All Optical Multiplexing Systems existent in the network are created in the PhysicalTopologyGenerator_ block. They all contain an index in order to be identified all the time, source and destination nodes, numberOfWavelengths which translates in capacity

in terms of quantity of available wavelenghts, and finally the actual values of wavelenghts and a matrix wich specifies which of them are still available to be used, initially all.

6.4.3 DemandRequest

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

Tabela 6.9: Constitution of a DemandRequest type signal.

D represents the total number of demand requests entering the network. It is possible to know this value for the fact that we are dealing with static traffic and so all the traffic requests are known. In the situation where all requests for traffic are not known, this traffic is said to be dynamic.

6.4.4 PathRequest

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

Tabela 6.10: PathRequest type signal.

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

6.4.5 PathRequestRouted

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

pathInformation

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

Tabela 6.11: pathInformation variable structure.

lightPathsTable

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength
1...N	1...N	0...N-2	[1...N ... 1...N]	W
...

Tabela 6.12: lightPathsTable variable structure.

The lightPathsTable structure will numberOfLightPaths-1 elements.

This signal represents the response that the PhysicalTopologyManager_ block sends back to the LogicalTopologyManager_ block when asked to establish a path. There is an requestIndex variable that identifies this signal as a reponse to the pathRequest signal with the same requestIndex. It is also formed by one boolean variable "routed" which will return true in the case a demand is routed correctly through the network, validating the remaining information on the lighPathsTable, or false in the case it is not, which means no path is possible to be created to route the demand and so the other fields of this signal will be void or fill with invalid information. Furthermore, this signal contains, in the lightPathsTable, various information about each of the light paths needed to establish the path required in the case it is possible to do so.

6.4.6 DemandRequestRouted

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

Tabela 6.13: DemandRequestRouted type signal.

This signal contains information regarding one demand and whether it was routed or not. In the case variable "routed" assumes a true value it is presented in the final block (SinkRoutedOrBlocked_) of the diagram of figure 6.1 information about the path used. In the case where variable "routed" assumes value false only the information about the demandIndex is presented meaning that that demand was blocked. In the case a demand is routed combining the information of the DemandRequestRouted signal with the one present in the LogicalTopologyManager_ block it is possible to know every piece of information about the route taken by the demand, lighPaths and opticalChannels used as well as waveleghts.

6.5 Blocks input parameters and signals

Block	Input Parameters	Input Signals
Scheduler_	odu0, odu1, odu2, odu3, odu4, orderingRule	None
LogicalTopologyGenerator_	transportMode, adjacencyMatrix	None
PhysicalTopologyGenerator_	transportSystems, opticalChannels, opticalChannelCapacity	None
LogicalTopologyManager_	routingCriterionLogicalTopology, blockingCriterionLogicalTopology	Scheduler_Out, LogicalTopologyGenerator_Out, PhysicalTopologyManagerOut
PhysicalTopologyManager_	routingCriterionPhysicalTopology, blockingCriterionPhysicalTopology	PhysicalGeneratorOut, LogicalManagerRequest
SinkRoutedOrBlocked_	None	LogicalManagerOut
SinkLogicalTopology_	None	currentLogicalTopology
SinkPhysicalTopology_	None	currentPhysicalTopology

Tabela 6.14: Blocks input parameters and signals.

6.6 Blocks state variables and output signals

Block	State Variables	Output Signals
Scheduler_	odu0, odu1, odu2, odu3, odu4, demandIndex, numberOfDemands	SchedulerOut
LogicalTopologyGenerator_	generate	LogicalTopologyOut
PhysicalTopologyGenerator_	generate	PhysicalTopologyOut
LogicalTopologyManager_	paths, lightPaths, opticalChannels	LogicalManagerRequest, LogicalManagerOut
PhysicalTopologyManager_	opticalMultiplexingSystems	PhysicalManagerOut
SinkRoutedOrBlocked_	None	None

Tabela 6.15: Blocks state variables and output signals.

6.7 Network example

6.7.1 Physical topology matrix

Considering a network with the following adjacence matrix represented on table 6.50, it becomes evident that our test network consists in 6 nodes and 16 unidirectional optical multiplexing systems.

Nodes	1	2	3	4	5	6
1	0	1	0	0	0	1
2	1	0	1	0	0	1
3	0	1	0	1	1	0
4	0	0	1	0	1	0
5	0	0	1	1	0	1
6	1	1	0	0	1	0

Tabela 6.16: Allowed physical topology matrix.

Below we have a graphical representation of the same network physical topology. Each arrow represents an optical multiplexing system connecting two nodes in a certain direction and all of them have a number which represents its own index for further identification purposes.

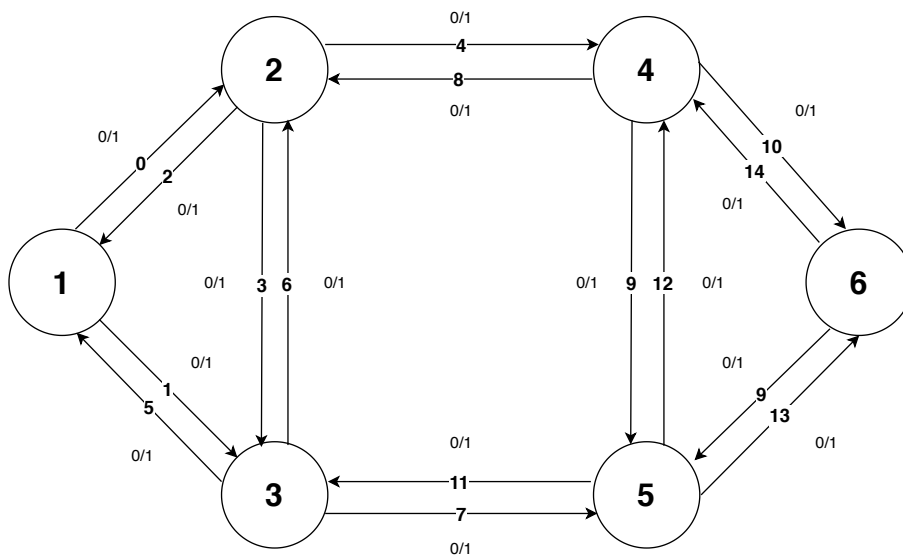


Figura 6.2: Allowed physical topology.

6.7.2 Logical topology matrix

The network logical topology represents how the links and the nodes may interconnect with each other. In this particular case it is considered the transparent transport mode, and so each of the nodes will connect to others creating direct links between all nodes of the network. The same can be seen below represented in a matrix in table 6.17 and graphically in figure 6.3.

Nodes	1	2	3	4	5	6
1	0	1	1	1	1	1
2	1	0	1	1	1	1
3	1	1	0	1	1	1
4	1	1	1	0	1	1
5	1	1	1	1	0	1
6	1	1	1	1	1	0

Tabela 6.17: Allowed logical topology matrix for transparent transport mode.

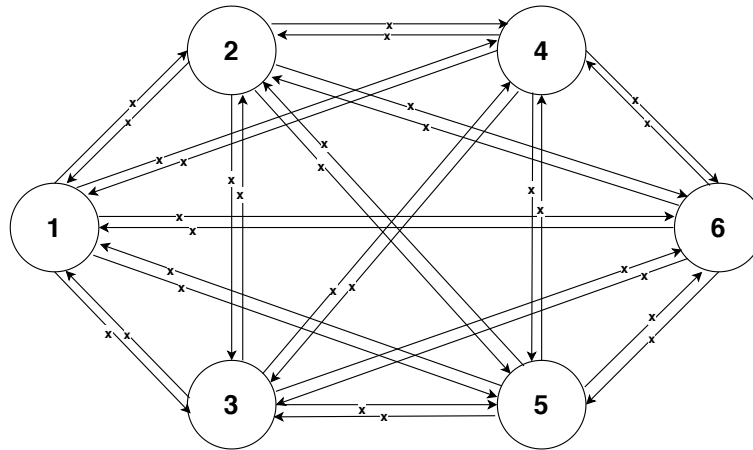


Figura 6.3: Allowed logical topology graph.

6.7.3 Traffic scenario

The traffic matrices below 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.

Considering just 2 optical channels per opticalMultiplexingSystem, each with a capacity of 100 Gbps (80 ODU0s), and the following set of demands.

$$\begin{aligned}
ODU0 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} & ODU1 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \\
ODU2 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} & ODU3 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \\
ODU4 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}
\end{aligned}$$

6.7.4 Theoretical resolution

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

$$T_1^0 = 0 \times 1.25 = 0 \text{ Gbits/s} \quad T_1^1 = 0 \times 2.5 = 0 \text{ Gbits/s} \quad T_1^2 = 0 \times 10 = 0 \text{ Gbits/s}$$

$$T_1^3 = 2 \times 40 = 80 \text{ Gbits/s} \quad T_1^4 = 5 \times 100 = 500 \text{ Gbits/s}$$

$$T_1 = 0 + 0 + 0 + 80 + 500 = 580 \text{ Gbits/s}$$

Where the variable T_1^x represents the unidirectional traffic of the ODU x , 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.

Ordering demands

The demands are first ordered in the Scheduler_ block considering the entry variable, orderingRule, in a single queue. It is assumed orderingRule to be equal to its default value descendingOrder, which will organize demand requests from ODU4 type demands to ODU0 type. These demands will constitute the Scheduler_Out signal, which is a DemandRequest

type signal.

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
0	1	5	4	none
1	1	5	4	none
2	1	5	4	none
3	1	5	4	none
4	1	5	4	none
5	3	5	3	none
6	3	5	3	none

Tabela 6.18: Demands ordered by Scheduler_block.

Demand 0

Generate a DemandRequest type signal

Demand 0 is sent in a DemandRequest type signal from the Scheduler_block to the LogicalTopologyManager_block.

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
0	1	5	4	none

Tabela 6.19: DemandRequest sent by Scheduler_block for demand 0.

There, a search is made by an available path from source to destination node, in this case nodes 1 and 5, respectively.

Search for an available path

pathIndex	sourceNode	destinationNode	capacity (ODU0s)	lightPathsIndex

Tabela 6.20: Paths state variable from LogicalTopologyManager_block.

As initially no path exists, one must be created in order to route this demand and so a pathRequest type signal is sent from the LogicalTopologyManager_ to the PhysicalTopologyManager_block.

Apply Dijkstra algorithm to discover shortest logical paths

The logical topology matrix of table 6.17 is applied as an entry parameter to the Dijkstra algorithm. Considering the entry variables `routingCriterionLogicalTopology` as "Hops"(gives the shortest paths in terms of hops) and `blockingCriterionLogicalTopology` equal to 3, once in transparent transport mode only direct logical connections will concern us, the output gives only the possibility of the direct logical connection (1->5) to establish a path between source and destination nodes, 1 and 5 respectively.

Generate a pathRequest signal

requestIndex	sourceNode	intermediateNodes	destinationNode
0	1	-1	5

Tabela 6.21: pathRequest signal for demand 0.

As the transport mode assumed is the transparent, only direct logical connections are used to route demands, and consequently there are no intermediate nodes.

Apply Dijkstra algorithm to discover shortest physical paths

The physical topology matrix of table 6.50 is applied as an entry parameter to the Dijkstra algorithm. Here it is intended to convert the required light path (1->5) into a restricted variety of sets of physical connections, in this specific case 3. Considering `blockingCriterionPhysicalTopology` equal to 3 (number of paths to be tested before declaring a possible blocked state) and `routingCriterionPhysicalTopology` to be "Hops", then the final result of Dijkstra algorithm will be the one presented below.

lightPath from nodes 1 to 5				
	sourceNode	destinationNode	opticalChannels	
			sourceNode	destinationNode
Shortest path 1	1	5	1	6
			6	5
Shortest path 2	1	5	1	2
			2	3
			3	5
Shortest path 3	1	5	1	2
			2	6
			6	5

Tabela 6.22: Result of Dijkstra algorithm applied to the ajacence matrix.

Test shortest path 1

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
1	1	6	2	[1310 1550]	[1 1]
15	6	5	2	[1310 1550]	[1 1]

Tabela 6.23: Initial values of opticalMultiplexingSystems going from node 1 to 6 and 6 to 5.

As both opticalMultiplexingSystems have the required capacity and wavelengths a PathRequestRouted signal will be generated informing the LogicalTopologyManager_block that it is possible to establish a path to route demand 0 through a lightPath using the opticalChannels above, and the physical capacity of the opticalMultiplexingSystems of the network will be updated.

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
1	1	6	2	[1310 1550]	[0 1]
15	6	5	2	[1310 1550]	[0 1]

Tabela 6.24: After values of opticalMultiplexingSystems going from node 1 to 6 and 6 to 5.

In both Optical Multiplexing Systems an Optical Channel is going to be used in the creation of a Light Path in order to route demand 0. In this specific case the wavelength used is 1310 nm which will remain unavailable for other demands that will not use this Light Path.

Generate a PathRequestRouted type signal

requestIndex	routed	numberOfLightPaths
0	true	1

Tabela 6.25: pathInformation variable from PathRequestRouted signal.

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength (nm)
1	5	1	[6]	1310

Tabela 6.26: lightPathsTable variable from PathRequestRouted signal.

Update LogicalTopologyManager_ block state variables

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0

Tabela 6.27: Paths variable updated.

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOptical-Channels	opticalChannles-Index
0	1	5	0	2	[0,1]

Tabela 6.28: LightPaths variable updated.

opticalChannel-Index	sourceNode	destination-Node	capacity (ODU0s)	wavelength (nm)	numberOf-Demands	demands-Index
0	1	6	0	1310	1	[0]
1	6	5	0	1310	1	[0]

Tabela 6.29: OpticalChannels variable updated.

Nodes	1	2	3	4	5	6
1	0	1	1	1	1	1
2	1	0	1	1	1	1
3	1	1	0	1	1	1
4	1	1	1	0	1	1
5	1	1	1	1	0	1
6	1	1	1	1	1	0

Tabela 6.30: logicalTopologyMatrix variable updated.

Generate a DemandRequestRouted type signal

demandIndex	routed	pathsIndex
0	true	0

Tabela 6.31: DemandRequestRouted signal.

Finally this signal is sent to the last block of the diagram, SinkRoutedOrBlocked_.

6.7.5 Demand 1**Generate a DemandRequest type signal**

Demand 1 is sent in a DemandRequest type signal from the Scheduler_ block to the LogicalTopologyManager_ block.

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
1	1	5	4	none

Tabela 6.32: DemandRequest sent by Scheduler_ block for demand 1.

There, a search is made by an available path from source to destination node, in this case nodes 1 and 5, respectively.

Search for an available path

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0

Tabela 6.33: Paths state variable from LogicalTopologyManager_ block.

As there is no path available with remaining capacity to route an ODU4 demand, one must be created in order to route this demand 1 and so a pathRequest type signal is sent from the LogicalTopologyManager_ to the PhysicalTopologyManager_ block.

Apply Dijkstra algorithm to discover shortest logical paths

The logical topology matrix of table 6.110 is applied as an entry parameter to the Dijkstra algorithm. Considering the entry variables routingCriterionLogicalTopology as "Hops"(gives the shortest paths in terms of hops) and blockingCriterionLogicalTopology equal to 3, once in transparent transport mode only direct logical connections will concern us, the output gives only the possibility of the direct logical connection (1->5) to establish a path between source and destination nodes, 1 and 5 respectively.

Generate a pathRequest signal

requestIndex	sourceNode	intermediateNodes	destinationNode
1	1	-1	5

Tabela 6.34: pathRequest signal for demand 0.

As the transport mode assumed is the transparent, only direct logical connections are used to route demands, and consequently there are no intermediate nodes.

Apply Dijkstra algorithm to discover shortest physical paths

The physical topology matrix of table 6.50 is applied as an entry parameter to the Dijkstra algorithm. Here it is intended to convert the required light path (1->5) into a restricted variety of sets of physical connections, in this specific case 3. Considering blockingCriterionPhysicalTopology equal to 3 (number of paths to be tested before declaring a possible blocked state) and routingCriterionPhysicalTopology to be "Hops", then the final result of Dijkstra algorithm will be the one presented below.

lightPath from nodes 1 to 5				
	sourceNode	destinationNode	opticalChannels	
			sourceNode	destinationNode
Shortest path 1	1	5	1	6
			6	5
Shortest path 2	1	5	1	2
			2	3
			3	5
Shortest path 3	1	5	1	2
			2	6
			6	5

Tabela 6.35: Result of Dijkstra algorithm applied to the ajacence matrix.

Test shortest path 1

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
1	1	6	2	[1310 1550]	[0 1]
15	6	5	2	[1310 1550]	[0 1]

Tabela 6.36: Initial values of opticalMultiplexingSystems going from node 1 to 6 and 6 to 5.

As both opticalMultiplexingSystems have the required capacity and wavelengths a PathRequestRouted signal will be generated informing the LogicalTopologyManager_block that it is possible to establish a path to route demand 1 through a lightPath using the opticalChannels above, and the physical capacity of the opticalMultiplexingSystems of the network will be updated.

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
1	1	6	2	[1310 1550]	[0 0]
15	6	5	2	[1310 1550]	[0 0]

Tabela 6.37: After values of opticalMultiplexingSystems going from node 1 to 6 and 6 to 5.

In both Optical Multiplexing Systems an Optical Channel is going to be used in the creation of a Light Path in order to route demand 1. In this specific case the wavelength used is 1550 nm which will remain unavailable for other demands that will not use this Light Path.

Generate a PathRequestRouted type signal

requestIndex	routed	numberOfLightPaths
1	true	1

Tabela 6.38: pathInformation variable from PathRequestRouted signal.

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength (nm)
1	5	1	[6]	1550

Tabela 6.39: lightPathsTable variable from PathRequestRouted signal.

Update LogicalTopologyManager_ block state variables

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1

Tabela 6.40: Paths variable updated.

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOptical-Channels	opticalChannles-Index
0	1	5	0	2	[0,1]
1	1	5	0	2	[2,3]

Tabela 6.41: LightPaths variable updated.

opticalChannel-Index	sourceNode	destination-Node	capacity (ODU0s)	wavelength (nm)	numberOf-Demands	demands-Index
0	1	6	0	1310	1	[0]
1	6	5	0	1310	1	[0]
2	1	6	0	1550	1	[1]
3	6	5	0	1550	1	[1]

Tabela 6.42: OpticalChannels variable updated.

Nodes	1	2	3	4	5	6
1	0	1	1	1	1	1
2	1	0	1	1	1	1
3	1	1	0	1	1	1
4	1	1	1	0	1	1
5	1	1	1	1	0	1
6	1	1	1	1	1	0

Tabela 6.43: logicalTopologyMatrix variable updated.

Generate a DemandRequestRouted type signal

demandIndex	routed	pathsIndex
1	true	1

Tabela 6.44: DemandRequestRouted signal.

Finally this signal is sent to the last block of the diagram, SinkRoutedOrBlocked_.

6.7.6 Demand 2**Generate a DemandRequest type signal**

Demand 2 is sent in a DemandRequest type signal from the Scheduler_ block to the LogicalTopologyManager_ block.

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
2	1	5	4	none

Tabela 6.45: DemandRequest sent by Scheduler_ block for demand 2.

There, a search is made by an available path from source to destination node, in this case nodes 1 and 5, respectively.

Search for an available path

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1

Tabela 6.46: Paths state variable from LogicalTopologyManager_ block.

As there is no path available with remaining capacity to route an ODU4 demand, one must be created in order to route this demand 2 and so a pathRequest type signal is sent from the LogicalTopologyManager_ to the PhysicalTopologyManager_ block.

Apply Dijkstra algorithm to discover shortest logical paths

The logical topology matrix of table 6.110 is applied as an entry parameter to the Dijkstra algorithm. Considering the entry variables routingCriterionLogicalTopology as "Hops"(gives the shortest paths in terms of hops) and blockingCriterionLogicalTopology equal to 3, once in transparent transport mode only direct logical connections will concern us, the output gives only the possibility of the direct logical connection (1->5) to establish a path between source and destination nodes, 1 and 5 respectively.

Generate a pathRequest signal

requestIndex	sourceNode	intermediateNodes	destinationNode
2	1	-1	5

Tabela 6.47: pathRequest signal for demand 0.

As the transport mode assumed is the transparent, only direct logical connections are used to route demands, and consequently there are no intermediate nodes.

Apply Dijkstra algorithm to discover shortest physical paths

The physical topology matrix of table 6.50 is applied as an entry parameter to the Dijkstra algorithm. Here it is intended to convert the required light path (1->5) into a restricted variety of sets of physical connections, in this specific case 3. Considering blockingCriterionPhysicalTopology equal to 3 (number of paths to be tested before declaring a possible blocked state) and routingCriterionPhysicalTopology to be "Hops", then the final result of Dijkstra algorithm will be the one presented below.

lightPath from nodes 1 to 5				
	sourceNode	destinationNode	opticalChannels	
			sourceNode	destinationNode
Shortest path 1	1	5	1	6
			6	5
Shortest path 2	1	5	1	2
			2	3
			3	5
Shortest path 3	1	5	1	2
			2	6
			6	5

Tabela 6.48: Result of Dijkstra algorithm applied to the ajacence matrix.

Test shortest path 1

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
1	1	6	2	[1310 1550]	[0 0]
15	6	5	2	[1310 1550]	[0 0]

Tabela 6.49: Initial values of opticalMultiplexingSystems going from node 1 to 6 and 6 to 5.

As both opticalMultiplexingSystems are already completely full then they will remain unavailable for demands to use and so the physical topology must be updated so that Dijkstra algorithm does not take into account this Optical Multiplexing Systems for shortest path creating processes in further iterations.

Update physical topology matrix

Nodes	1	2	3	4	5	6
1	0	1	0	0	0	0
2	1	0	1	0	0	1
3	0	1	0	1	1	0
4	0	0	1	0	1	0
5	0	0	1	1	0	1
6	1	1	0	0	0	0

Tabela 6.50: Updated physical topology matrix.

Test shortest path 2

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
0	1	2	2	[1310 1550]	[1 1]
3	2	3	2	[1310 1550]	[1 1]
7	3	5	2	[1310 1550]	[1 1]

Tabela 6.51: Initial values of opticalMultiplexingSystems going from nodes 1 to 2, 2 to 3 and 3 to 5.

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
0	1	2	2	[1310 1550]	[0 1]
3	2	3	2	[1310 1550]	[0 1]
7	3	5	2	[1310 1550]	[0 1]

Tabela 6.52: After values of opticalMultiplexingSystems going from nodes 1 to 2, 2 to 3 and 3 to 5.

In both Optical Multiplexing Systems an Optical Channel is going to be used in the creation of a Light Path in order to route demand 2. In this specific case the wavelength used is 1310 nm which will remain unavailable for other demands that will not use this Light Path.

Generate a PathRequestRouted type signal

requestIndex	routed	numberOfLightPaths
2	true	1

Tabela 6.53: pathInformation variable from PathRequestRouted signal.

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength (nm)
1	5	2	[2 3]	1310

Tabela 6.54: lightPathsTable variable from PathRequestRouted signal.

Update LogicalTopologyManager_ block state variables

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1
2	1	5	0	1	2

Tabela 6.55: Paths variable updated.

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOptical-Channels	opticalChannles-Index
0	1	5	0	2	[0,1]
1	1	5	0	2	[2,3]
2	1	5	0	3	[4,5,6]

Tabela 6.56: LightPaths variable updated.

opticalChannel-Index	sourceNode	destination-Node	capacity (ODU0s)	wavelength (nm)	numberOf-Demands	demands-Index
0	1	6	0	1310	1	[0]
1	6	5	0	1310	1	[0]
2	1	6	0	1550	1	[1]
3	6	5	0	1550	1	[1]
4	1	2	0	1310	1	[2]
5	2	3	0	1310	1	[2]
6	3	5	0	1310	1	[2]

Tabela 6.57: OpticalChannels variable updated.

Nodes	1	2	3	4	5	6
1	0	1	1	1	1	1
2	1	0	1	1	1	1
3	1	1	0	1	1	1
4	1	1	1	0	1	1
5	1	1	1	1	0	1
6	1	1	1	1	1	0

Tabela 6.58: logicalTopologyMatrix variable updated.

Generate a DemandRequestRouted type signal

demandIndex	routed	pathsIndex
2	true	2

Tabela 6.59: DemandRequestRouted signal.

Finally this signal is sent to the last block of the diagram, SinkRoutedOrBlocked_.

6.7.7 Demand 3

Generate a DemandRequest type signal

Demand 3 is sent in a DemandRequest type signal from the Scheduler_ block to the LogicalTopologyManager_ block.

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
3	1	5	4	none

Tabela 6.60: DemandRequest sent by Scheduler_ block for demand 3.

There, a search is made by an available path from source to destination node, in this case nodes 1 and 5, respectively.

Search for an available path

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1
2	1	5	0	1	2

Tabela 6.61: Paths state variable from LogicalTopologyManager_ block.

As there is no path available with remaning capacity to route an ODU4 demand, one must be created in order to route this demand 1 and so a pathRequest type signal is sent from the LogicalTopologyManager_ to to the PhysicalTopologyManager_ block.

Apply Dijkstra algorithm to discover shortest logical paths

The logical topology matrix of table 6.110 is applied as an entry parameter to the Dijkstra algorithm. Considering the entry variables routingCriterionLogicalTopology as "Hops"(gives the shortest paths in terms of hops) and blockingCriterionLogicalTopology

equal to 3, once in transparent transport mode only direct logical connections will concern us, the output gives only the possibility of the direct logical connection (1->5) to establish a path between source and destination nodes, 1 and 5 respectively.

Generate a pathRequest signal

requestIndex	sourceNode	intermediateNodes	destinationNode
3	1	-1	5

Tabela 6.62: pathRequest signal for demand 0.

As the transport mode assumed is the transparent, only direct logical connections are used to route demands, and consequently there are no intermediate nodes.

Apply Dijkstra algorithm to discover shortest physical paths

The physical topology matrix already updated before of table xxx is applied as an entry parameter to the Dijkstra algorithm. Here it is intended to convert the required light path (1->5) into a restricted variety of sets of physical connections, in this specific case 3. Considering blockingCriterionPhysicalTopology equal to 3 (number of paths to be tested before declaring a possible blocked state) and routingCriterionPhysicalTopology to be "Hops", then the final result of Dijkstra algorithm will be the one presented below. Notice that once our entry physical topology is now different then the final output of Dijkstra algorithm will also differ.

lightPath from nodes 1 to 5				
	sourceNode	destinationNode	opticalChannels	
			sourceNode	destinationNode
Shortest path 1	1	5	1	2
			2	3
			3	5
Shortest path 2	1	5	1	2
			2	6
			6	5
Shortest path 3	1	5	1	2
			2	3
			3	4
			4	5

Tabela 6.63: Result of Dijkstra algorithm applied to the ajacence matrix.

Test shortest path 1

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
0	1	2	2	[1310 1550]	[0 1]
3	2	3	2	[1310 1550]	[0 1]
7	3	5	2	[1310 1550]	[0 1]

Tabela 6.64: Initial values of opticalMultiplexingSystems going from node 1 to 2, 2 to 3 and 3 to 5.

As both opticalMultiplexingSystems have the required capacity and wavelengths a PathRequestRouted signal will be generated informing the LogicalTopologyManager_ block that it is possible to establish a path to route demand 1 through a lightPath using the opticalChannels above, and the physical capacity of the opticalMultiplexingSystems of the network will be updated.

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
0	1	2	2	[1310 1550]	[0 0]
3	2	3	2	[1310 1550]	[0 0]
7	3	5	2	[1310 1550]	[0 0]

Tabela 6.65: After values of opticalMultiplexingSystems going from node 1 to 2, 2 to 3 and 3 to 5.

In both Optical Multiplexing Systems an Optical Channel is going to be used in the creation of a Light Path in order to route demand 3. In this specific case the wavelength used is 1550 nm which will remain unavailable for other demands that will not use this Light Path.

Generate a PathRequestRouted type signal

requestIndex	routed	numberOfLightPaths
3	true	1

Tabela 6.66: pathInformation variable from PathRequestRouted signal.

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength (nm)
1	5	2	[2 3]	1550

Tabela 6.67: lightPathsTable variable from PathRequestRouted signal.

Update LogicalTopologyManager_ block state variables

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1
2	1	5	0	1	2
3	1	5	0	1	3

Tabela 6.68: Paths variable updated.

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOptical-Channels	opticalChannles-Index
0	1	5	0	2	[0,1]
1	1	5	0	2	[2,3]
2	1	5	0	3	[4,5,6]
3	1	5	0	3	[7,8,9]

Tabela 6.69: LightPaths variable updated.

opticalChannel-Index	sourceNode	destination-Node	capacity (ODU0s)	wavelength (nm)	numberOf-Demands	demands-Index
0	1	6	0	1310	1	[0]
1	6	5	0	1310	1	[0]
2	1	6	0	1550	1	[1]
3	6	5	0	1550	1	[1]
4	1	2	0	1310	1	[2]
5	2	3	0	1310	1	[2]
6	3	5	0	1310	1	[2]
7	1	2	0	1550	1	[3]
8	2	3	0	1550	1	[3]
9	3	5	0	1550	1	[3]

Tabela 6.70: OpticalChannels variable updated.

Nodes	1	2	3	4	5	6
1	0	1	1	1	1	1
2	1	0	1	1	1	1
3	1	1	0	1	1	1
4	1	1	1	0	1	1
5	1	1	1	1	0	1
6	1	1	1	1	1	0

Tabela 6.71: logicalTopologyMatrix variable updated.

Generate a DemandRequestRouted type signal

demandIndex	routed	pathsIndex
3	true	3

Tabela 6.72: DemandRequestRouted signal.

Finally this signal is sent to the last block of the diagram, SinkRoutedOrBlocked_.

6.7.8 Demand 4**Generate a DemandRequest type signal**

Demand 3 is sent in a DemandRequest type signal from the Scheduler_ block to the LogicalTopologyManager_ block.

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
4	1	5	4	none

Tabela 6.73: DemandRequest sent by Scheduler_ block for demand 4.

There, a search is made by an available path from source to destination node, in this case nodes 1 and 5, respectively.

Search for an available path

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1
2	1	5	0	1	2
3	1	5	0	1	3

Tabela 6.74: Paths state variable from LogicalTopologyManager_ block.

As there is no path available with remaning capacity to route an ODU4 demand, one must be created in order to route this demand 4 and so a pathRequest type signal is sent from the LogicalTopologyManager_ to to the PhysicalTopologyManager_ block.

Apply Dijkstra algorithm to discover shortest logical paths

The logical topology matrix of table 6.110 is applied as an entry parameter to the Dijkstra algorithm. Considering the entry variables routingCriterionLogicalTopology as "Hops"(gives the shortest paths in terms of hops) and blockingCriterionLogicalTopology equal to 3, once in transparent transport mode only direct logical connections will concerne us, the output gives only the possibility of the direct logical connection (1->5) to establish a path between source and destination nodes, 1 and 5 respectively.

Generate a pathRequest signal

requestIndex	sourceNode	intermediateNodes	destinationNode
4	1	-1	5

Tabela 6.75: pathRequest signal for demand 4.

As the transport mode assumed is the transparent, only direct logical connections are used to route demands, and consequently there are no intermediate nodes.

Apply Dijkstra algorithm to discover shortest physical paths

The physical topology matrix already updated before of table xxx is applied as an entry parameter to the Dijkstra algorithm. Here it is intended to convert the required light path (1->5) into a restricted variety of sets of physical connections, in this specific case 3. Considering

blockingCriterionPhysicalTopology equal to 3 (number of paths to be tested before declaring a possible blocked state) and routingCriterionPhysicalTopology to be "Hops", then the final result of Dijkstra algorithm will be the one presented below. Notice that once our entry physical topology is now different then the final output of Dijkstra algorithm will also differ.

lightPath from nodes 1 to 5				
	sourceNode	destinationNode	opticalChannels	
			sourceNode	destinationNode
Shortest path 1	1	5	1	2
			2	3
			3	5
Shortest path 2	1	5	1	2
			2	6
			6	5
Shortest path 3	1	5	1	2
			2	3
			3	4
			4	5

Tabela 6.76: Result of Dijkstra algorithm applied to the ajacence matrix.

Test shortest path 1

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
0	1	2	2	[1310 1550]	[0 0]
3	2	3	2	[1310 1550]	[0 0]
7	3	5	2	[1310 1550]	[0 0]

Tabela 6.77: Initial values of opticalMultiplexingSystems going from node 1 to 2, 2 to 3 and 3 to 5.

As all opticalMultiplexingSystems are already completely full then they will remain unavailable for other demands to use and so the physical topology matrix must be updated so that Dijkstra algorithm does not take into account this Optical Multiplexing Systems for shortest path creating processes in further iterations.

Update physical topology matrix

Nodes	1	2	3	4	5	6
1	0	0	0	0	0	0
2	1	0	0	0	0	1
3	0	1	0	1	0	0
4	0	0	1	0	1	0
5	0	0	1	1	0	1
6	1	1	0	0	0	0

Tabela 6.78: Updated physical topology matrix.

Test shortest paths 2 and 3

As both shortest paths share common Optical Multiplexing Systems with the first then all of them will be discarded and so it will not be possible to create a path between nodes 1 and 5 to route demand 4.

Generate a PathRequestRouted type signal

requestIndex	routed	numberOfLightPaths
4	false	0

Tabela 6.79: pathInformation variable from PathRequestRouted signal.

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength (nm)
			[]	

Tabela 6.80: lightPathsTable variable from PathRequestRouted signal.

Update LogicalTopologyManager_ block state variables

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1
2	1	5	0	1	2
3	1	5	0	1	3

Tabela 6.81: Paths variable updated.

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOptical-Channels	opticalChannles-Index
0	1	5	0	2	[0,1]
1	1	5	0	2	[2,3]
2	1	5	0	3	[4,5,6]
3	1	5	0	3	[7,8,9]

Tabela 6.82: LightPaths variable updated.

opticalChannel-Index	sourceNode	destination-Node	capacity (ODU0s)	wavelength (nm)	numberOf-Demands	demands-Index
0	1	6	0	1310	1	[0]
1	6	5	0	1310	1	[0]
2	1	6	0	1550	1	[1]
3	6	5	0	1550	1	[1]
4	1	2	0	1310	1	[2]
5	2	3	0	1310	1	[2]
6	3	5	0	1310	1	[2]
7	1	2	0	1550	1	[3]
8	2	3	0	1550	1	[3]
9	3	5	0	1550	1	[3]

Tabela 6.83: OpticalChannels variable updated.

Nodes	1	2	3	4	5	6
1	0	1	1	1	0	1
2	1	0	1	1	1	1
3	1	1	0	1	1	1
4	1	1	1	0	1	1
5	1	1	1	1	0	1
6	1	1	1	1	1	0

Tabela 6.84: logicalTopologyMatrix variable updated.

Generate a DemandRequestRouted type signal

demandIndex	routed	pathsIndex
4	false	

Tabela 6.85: DemandRequestRouted signal.

Finally this signal is sent to the last block of the diagram, SinkRoutedOrBlocked_.

6.7.9 Demand 5

Generate a DemandRequest type signal

Demand 5 is sent in a DemandRequest type signal from the Scheduler_ block to the LogicalTopologyManager_ block.

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
5	3	5	3	none

Tabela 6.86: DemandRequest sent by Scheduler_ block for demand 5.

There, a search is made by an available path from source to destination node, in this case nodes 3 and 5, respectively.

Search for an available path

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1
2	1	5	0	1	2
3	1	5	0	1	3

Tabela 6.87: Paths state variable from LogicalTopologyManager_ block.

As there is no path available to route demand 5 from nodes 3 to 5 one must be created and so a pathRequest type signal is sent from the LogicalTopologyManager_ to the PhysicalTopologyManager_ block.

Apply Dijkstra algorithm to discover shortest logical paths

The logical topology matrix of table 6.110 is applied as an entry parameter to the Dijkstra algorithm. Considering the entry variables routingCriterionLogicalTopology as "Hops"(gives the shortest paths in terms of hops) and blockingCriterionLogicalTopology equal to 3, once in transparent transport mode only direct logical connections will concern us, the output gives only the possibility of the direct logical connection (3->5) to establish a path between source and destination nodes, 3 and 5 respectively.

Generate a pathRequest signal

requestIndex	sourceNode	intermediateNodes	destinationNode
5	3	-1	5

Tabela 6.88: pathRequest signal for demand 5.

As the transport mode assumed is the transparent, only direct logical connections are used to route demands, and consequently there are no intermediate nodes.

Apply Dijkstra algorithm to discover shortest physical paths

The physical topology matrix already updated before of table xxx is applied as an entry parameter to the Dijkstra algorithm. Here it is intended to convert the required light path (3->5) into a restricted variety of sets of physical connections, in this specific case 3. Considering blockingCriterionPhysicalTopology equal to 3 (number of paths to be tested before declaring a possible blocked state) and routingCriterionPhysicalTopology to be "Hops", then the final result of Dijkstra algorithm will be the one presented below.

lightPath from nodes 1 to 5			
	sourceNode	destinationNode	opticalChannels
			sourceNode destinationNode
Shortest path 1	3	5	3 4
			4 5

Tabela 6.89: Result of Dijkstra algorithm applied to the physical topology matrix.

Based on our current physical topology matrix only one path is possible to be established between nodes 3 and 5.

Test shortest path 1

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
6	3	4	2	[1310 1550]	[1 1]
9	4	5	2	[1310 1550]	[1 1]

Tabela 6.90: Initial values of opticalMultiplexingSystems going from node 3 to 4 and 4 to 5.

As both opticalMultiplexingSystems have the required capacity and wavelengths a PathRequestRouted signal will be generated informing the LogicalTopologyManager_ block that it is possible to establish a path to route demand 5 through a lightPath using the opticalChannels above, and the physical capacity of the opticalMultiplexingSystems of the network will be updated.

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
6	3	4	2	[1310 1550]	[0 1]
9	4	5	2	[1310 1550]	[0 1]

Tabela 6.91: After values of opticalMultiplexingSystems going from node 3 to 4 and 4 to 5.

In both Optical Multiplexing Systems an Optical Channel is going to be used in the creation of a Light Path in order to route demand 5. In this specific case the wavelength used is 1310 nm which will remain unavailable for other demands that will not use this Light Path.

Generate a PathRequestRouted type signal

requestIndex	routed	numberOfLightPaths
5	true	1

Tabela 6.92: pathInformation variable from PathRequestRouted signal.

sourceNode	destinationNode	numberOfIntermediateNodes	intermediateNodes	wavelength (nm)
3	5	1	[4]	1310

Tabela 6.93: lightPathsTable variable from PathRequestRouted signal.

Update LogicalTopologyManager_ block state variables

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1
2	1	5	0	1	2
3	1	5	0	1	3
4	3	5	48	1	4

Tabela 6.94: Paths variable updated.

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOptical- Channels	opticalChannles- Index
0	1	5	0	2	[0,1]
1	1	5	0	2	[2,3]
2	1	5	0	3	[4,5,6]
3	1	5	0	3	[7,8,9]
4	3	5	48	2	[10,11]

Tabela 6.95: LightPaths variable updated.

opticalChannel- Index	sourceNode	destination- Node	capacity (ODU0s)	wavelength (nm)	numberOf- Demands	demands- Index
0	1	6	0	1310	1	[0]
1	6	5	0	1310	1	[0]
2	1	6	0	1550	1	[1]
3	6	5	0	1550	1	[1]
4	1	2	0	1310	1	[2]
5	2	3	0	1310	1	[2]
6	3	5	0	1310	1	[2]
7	1	2	0	1550	1	[3]
8	2	3	0	1550	1	[3]
9	3	5	0	1550	1	[3]
10	3	4	48	1310	1	[5]
11	3	5	48	1310	1	[5]

Tabela 6.96: OpticalChannels variable updated.

Nodes	1	2	3	4	5	6
1	0	1	1	1	0	1
2	1	0	1	1	1	1
3	1	1	0	1	1	1
4	1	1	1	0	1	1
5	1	1	1	1	0	1
6	1	1	1	1	1	0

Tabela 6.97: logicalTopologyMatrix variable updated.

Generate a DemandRequestRouted type signal

demandIndex	routed	pathsIndex
5	true	4

Tabela 6.98: DemandRequestRouted signal.

Finally this signal is sent to the last block of the diagram, SinkRoutedOrBlocked_.

6.7.10 Demand 6**Generate a DemandRequest type signal**

Demand 6 is sent in a DemandRequest type signal from the Scheduler_ block to the LogicalTopologyManager_ block.

demandIndex	sourceNode	destinationNode	oduType	survivabilityMethod
6	3	5	3	none

Tabela 6.99: DemandRequest sent by Scheduler_ block for demand 5.

There, a search is made by an available path from source to destination node, in this case nodes 3 and 5, respectively.

Search for an available path

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1
2	1	5	0	1	2
3	1	5	0	1	3
4	3	5	48	1	4

Tabela 6.100: Paths state variable from LogicalTopologyManager_ block.

As path with index equal to 4 has the same source and destination nodes and there are still capacity available to route an ODU3 type demand, this will then be used to route demand 6 through the network. There will be no necessity to create a pathRequest type signal.

Update LogicalTopologyManager_ block state variables

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1
2	1	5	0	1	2
3	1	5	0	1	3
4	3	5	16	1	4

Tabela 6.101: Paths variable updated.

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOptical-Channels	opticalChannles-Index
0	1	5	0	2	[0,1]
1	1	5	0	2	[2,3]
2	1	5	0	3	[4,5,6]
3	1	5	0	3	[7,8,9]
4	3	5	16	2	[10,11]

Tabela 6.102: LightPaths variable updated.

opticalChannel-Index	sourceNode	destination-Node	capacity (ODU0s)	wavelength (nm)	numberOf-Demands	demands-Index
0	1	6	0	1310	1	[0]
1	6	5	0	1310	1	[0]
2	1	6	0	1550	1	[1]
3	6	5	0	1550	1	[1]
4	1	2	0	1310	1	[2]
5	2	3	0	1310	1	[2]
6	3	5	0	1310	1	[2]
7	1	2	0	1550	1	[3]
8	2	3	0	1550	1	[3]
9	3	5	0	1550	1	[3]
10	3	4	16	1310	2	[5,6]
11	3	5	16	1310	2	[5,6]

Tabela 6.103: OpticalChannels variable updated.

Nodes	1	2	3	4	5	6
1	0	1	1	1	0	1
2	1	0	1	1	1	1
3	1	1	0	1	1	1
4	1	1	1	0	1	1
5	1	1	1	1	0	1
6	1	1	1	1	1	0

Tabela 6.104: logicalTopologyMatrix variable updated.

Generate a DemandRequestRouted type signal

demandIndex	routed	pathsIndex
6	true	4

Tabela 6.105: DemandRequestRouted signal.

Finally this signal is sent to the last block of the diagram, SinkRoutedOrBlocked_.

6.7.11 Final Report

demandIndex	routed	pathsIndex
0	true	0
1	true	1
2	true	2
3	true	3
4	false	-1
5	true	4
6	true	4

Tabela 6.106: Final information stored in SinkRoutedOrBlocked_block.

Final Logical Topology

pathIndex	sourceNode	destinationNodes	capacity (ODU0s)	numberOfLightPaths	lightPathsIndex
0	1	5	0	1	0
1	1	5	0	1	1
2	1	5	0	1	2
3	1	5	0	1	3
4	3	5	16	1	4

Tabela 6.107: Final Paths variable value.

lightPathIndex	sourceNode	destinationNode	capacity (ODU0s)	numberOfOptical- Channels	opticalChannles- Index
0	1	5	0	2	[0,1]
1	1	5	0	2	[2,3]
2	1	5	0	3	[4,5,6]
3	1	5	0	3	[7,8,9]
4	3	5	16	2	[10,11]

Tabela 6.108: Final LightPaths variable value.

opticalChannel-Index	sourceNode	destination-Node	capacity (ODU0s)	wavelength (nm)	numberOf-Demands	demands-Index
0	1	6	0	1310	1	[0]
1	6	5	0	1310	1	[0]
2	1	6	0	1550	1	[1]
3	6	5	0	1550	1	[1]
4	1	2	0	1310	1	[2]
5	2	3	0	1310	1	[2]
6	3	5	0	1310	1	[2]
7	1	2	0	1550	1	[3]
8	2	3	0	1550	1	[3]
9	3	5	0	1550	1	[3]
10	3	4	16	1310	2	[5,6]
11	4	5	16	1310	2	[5,6]

Tabela 6.109: Final OpticalChannels variable value.

Nodes	1	2	3	4	5	6
1	0	1	1	1	0	1
2	1	0	1	1	1	1
3	1	1	0	1	1	1
4	1	1	1	0	1	1
5	1	1	1	1	0	1
6	1	1	1	1	1	0

Tabela 6.110: Final logical topology matrix value.

Final Physical Topology

Nodes	1	2	3	4	5	6
1	0	0	0	0	0	0
2	1	0	0	0	0	1
3	0	1	0	1	0	0
4	0	0	1	0	1	0
5	0	0	1	1	0	1
6	1	1	0	0	0	0

Tabela 6.111: Final physical topology matrix value.

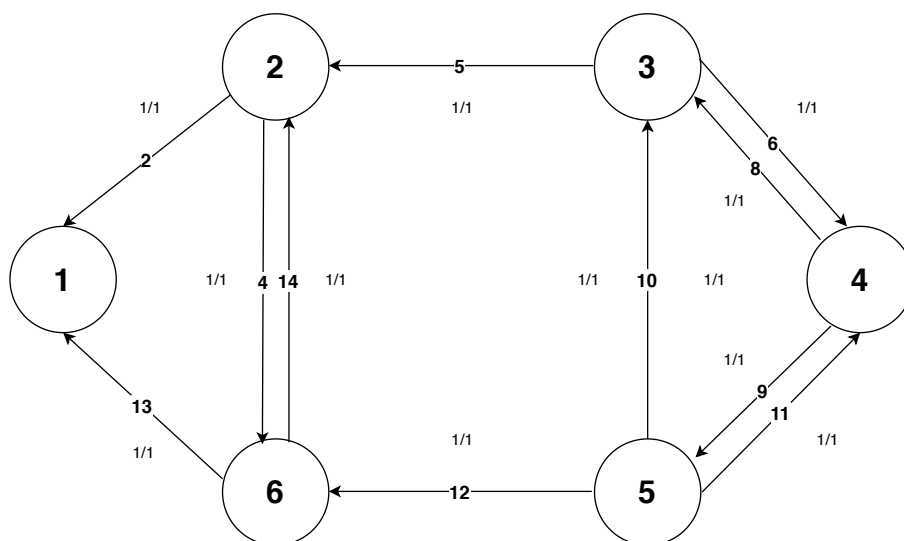


Figura 6.4: Final physical topology graph.

opticalMultiplexing-SystemIndex	sourceNode	destination-Node	numberOf-Wavelengths	wavelengths (nm)	available-Wavelengths
0	1	2	2	[1310 1550]	[0 0]
1	1	6	2	[1310 1550]	[0 0]
2	2	1	2	[1310 1550]	[1 1]
3	2	3	2	[1310 1550]	[0 0]
4	2	6	2	[1310 1550]	[1 1]
5	3	2	2	[1310 1550]	[1 1]
6	3	4	2	[1310 1550]	[0 1]
7	3	5	2	[1310 1550]	[0 0]
8	4	3	2	[1310 1550]	[1 1]
9	4	5	2	[1310 1550]	[0 1]
10	5	3	2	[1310 1550]	[1 1]
11	5	4	2	[1310 1550]	[1 1]
12	5	6	2	[1310 1550]	[1 1]
13	6	1	2	[1310 1550]	[1 1]
14	6	2	2	[1310 1550]	[1 1]
15	6	5	2	[1310 1550]	[0 0]

Tabela 6.112: Final opticalMultiplexingSystems variable values.

6.8 Heuristics vs ILP

6.8.1 Low traffic scenario

The traffic matrices below 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.

Considering 100 optical channels per opticalMultiplexingSystem, each with a capacity of 100 Gbps (80 ODU0s), and the following set of demands.

$$\begin{aligned}
 ODU0 &= \begin{bmatrix} 0 & 5 & 1 & 3 & 1 & 3 \\ 5 & 0 & 0 & 1 & 5 & 0 \\ 1 & 0 & 0 & 1 & 4 & 1 \\ 3 & 1 & 1 & 0 & 1 & 1 \\ 1 & 5 & 4 & 1 & 0 & 3 \\ 3 & 0 & 1 & 1 & 3 & 0 \end{bmatrix} & ODU1 &= \begin{bmatrix} 0 & 2 & 4 & 2 & 0 & 5 \\ 2 & 0 & 0 & 3 & 1 & 1 \\ 4 & 0 & 0 & 1 & 1 & 0 \\ 2 & 3 & 1 & 0 & 1 & 3 \\ 0 & 1 & 1 & 1 & 0 & 1 \\ 5 & 1 & 0 & 3 & 1 & 0 \end{bmatrix} \\
 ODU2 &= \begin{bmatrix} 0 & 1 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} & ODU3 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \\
 ODU4 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix}
 \end{aligned}$$

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

$$T_1^0 = 60 \times 1.25 = 75 \text{ Gbits/s} \quad T_1^1 = 50 \times 2.5 = 125 \text{ Gbits/s} \quad T_1^2 = 16 \times 10 = 160 \text{ Gbits/s}$$

$$T_1^3 = 6 \times 40 = 240 \text{ Gbits/s} \quad T_1^4 = 4 \times 100 = 400 \text{ Gbits/s}$$

$$T_1 = 75 + 125 + 160 + 240 + 400 = 1000 \text{ Gbits/s}$$

Where the variable T_1^x represents the unidirectional traffic of the ODU x , 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.

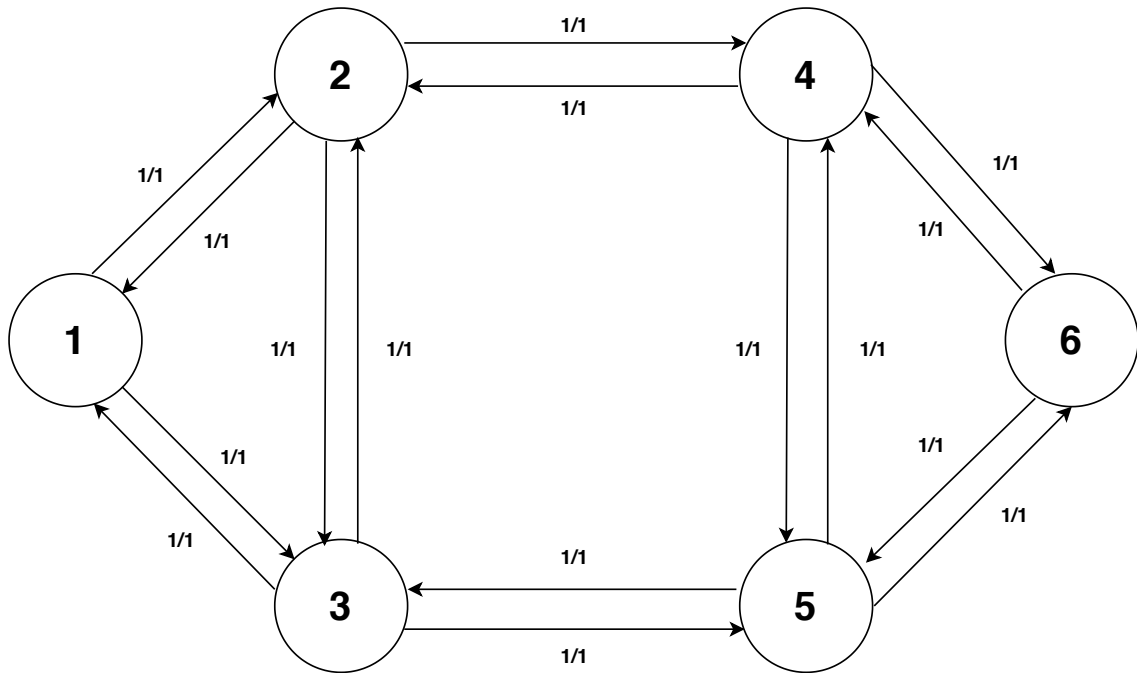


Figura 6.5: Transparent without survivability in low scenario: physical topology after dimensioning.

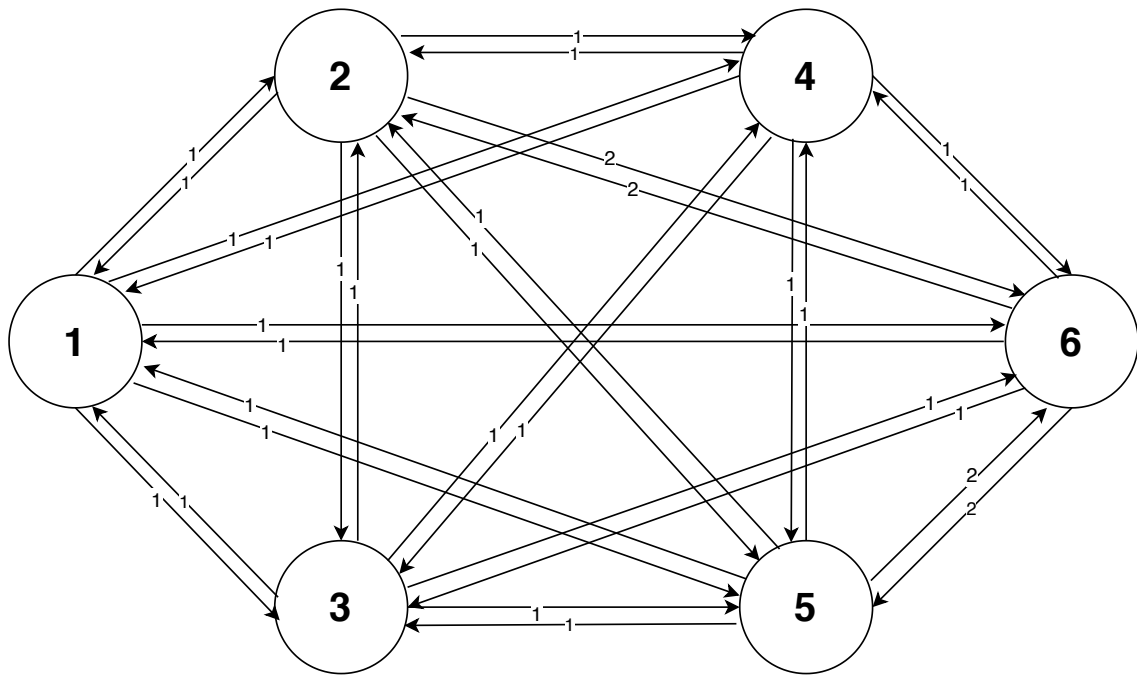


Figura 6.6: Transparent without survivability in low scenario: optical topology after dimensioning.

Information regarding links		
Unidirectional link	Optical channels	Amplifiers
Node 1 ->2	3	4
Node 1 ->3	2	6
Node 2 ->1	3	4
Node 2 ->3	3	0
Node 2 ->4	6	6
Node 3 ->1	2	6
Node 3 ->2	3	0
Node 3 ->5	4	8
Node 4 ->2	6	6
Node 4 ->5	1	1
Node 4 ->6	4	7
Node 5 ->4	1	8
Node 5 ->6	3	1
Node 5 ->3	4	3
Node 6 ->4	4	7
Node 6 ->5	3	3

Tabela 6.113: Table with information regarding links for transparent mode without survivability in low scenario.

Information regarding nodes					
		Electrical part		Optical part	
Node	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 6.114: Table with information regarding nodes for transparent mode without survivability in low scenario.

Routing							
Source node	Destination node	Links	ODU0	ODU1	ODU2	ODU3	ODU4
1	2	{(1,2)}	5	2	1	0	0
1	3	{(1,3)}	1	4	1	0	0
1	4	{(1,2),(2,4)}	3	2	1	0	0
1	5	{(1,3),(3,5)}	1	0	0	0	0
1	6	{(1,2),(2,4),(4,6)}	3	5	0	0	0
2	1	{(2,1)}	5	2	1	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),(2,6)}	0	1	0	1	1
3	1	{(1,3)}	1	4	1	0	0
3	2	{(3,2)}	0	0	0	1	0
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	1	{(4,2),(2,1)}	3	2	1	0	0
4	2	{(4,2)}	1	3	0	0	0
4	3	{(4,2),(2,3)}	1	1	1	0	0
4	5	{(4,5)}	1	1	1	0	0
4	6	{(4,6)}	1	3	0	0	0
5	1	{(5,3),(3,1)}	1	0	0	0	0
5	2	{(5,3),(3,2)}	5	1	1	0	0
5	3	{(5,3)}	4	1	1	1	0
5	4	{(5,4)}	1	1	1	0	0
5	6	{(5,6)}	3	1	1	0	1
6	1	{(6,4),(4,2),(2,1)}	3	5	0	0	0
6	2	{(6,4),(4,2)}	0	1	0	1	1
6	3	{(6,5),(5,3)}	1	0	0	0	0
6	4	{(6,4)}	1	3	0	0	0
6	5	{(6,5)}	3	1	1	0	1

Tabela 6.115: Transparent without survivability in low scenario: description of routing.

Network CAPEX						
			Quantity	Unit price	Cost	Total
Link cost	OLTs		16	15 000 €	240 000 €	26 520 000 €
	100 Gbit/s Transceivers		52	5 000 €/Gbit/s	26 000 000 €	
	Amplifiers		70	10 000 €	280 000 €	
Node Cost	Electrical part	EXCs	6	10 000 €	60 000 €	3 797 590 €
		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 part	OXCs	6	20 000 €	120 000 €	
		Add ports	34	2500 €/port	85 000 €	
		Line ports	52	2500 €/ port	130 000 €	
Total Network Cost						30 317 590 €

Tabela 6.116: Transparent without survivability in low scenario: detailed description of CAPEX for this scenario.

6.8.2 Medium traffic scenario

$$\begin{aligned}
 ODU0 &= \begin{bmatrix} 0 & 50 & 10 & 30 & 10 & 30 \\ 50 & 0 & 0 & 10 & 50 & 0 \\ 10 & 0 & 0 & 10 & 40 & 10 \\ 30 & 10 & 10 & 0 & 10 & 10 \\ 10 & 50 & 40 & 10 & 0 & 30 \\ 30 & 0 & 10 & 10 & 30 & 0 \end{bmatrix} & ODU1 &= \begin{bmatrix} 0 & 20 & 40 & 20 & 0 & 50 \\ 20 & 0 & 0 & 30 & 10 & 10 \\ 40 & 0 & 0 & 10 & 10 & 0 \\ 20 & 30 & 10 & 0 & 10 & 30 \\ 0 & 10 & 10 & 10 & 0 & 10 \\ 50 & 10 & 0 & 30 & 10 & 0 \end{bmatrix} \\
 ODU2 &= \begin{bmatrix} 0 & 10 & 10 & 10 & 0 & 0 \\ 10 & 0 & 0 & 0 & 10 & 0 \\ 10 & 0 & 0 & 10 & 10 & 0 \\ 10 & 0 & 10 & 0 & 10 & 0 \\ 0 & 10 & 10 & 10 & 0 & 10 \\ 0 & 0 & 0 & 0 & 10 & 0 \end{bmatrix} & ODU3 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 10 \\ 0 & 10 & 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 & 0 \end{bmatrix} \\
 ODU4 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \\ 0 & 10 & 0 & 0 & 10 & 0 \end{bmatrix}
 \end{aligned}$$

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

$$T_1^0 = 600 \times 1.25 = 750 \text{ Gbits/s} \quad T_1^1 = 500 \times 2.5 = 1250 \text{ Gbits/s} \quad T_1^2 = 160 \times 10 = 1600 \text{ Gbits/s}$$

$$T_1^3 = 60 \times 40 = 2400 \text{ Gbits/s} \quad T_1^4 = 40 \times 100 = 4000 \text{ Gbits/s}$$

$$T_1 = 750 + 1250 + 1600 + 2400 + 4000 = 10000 \text{ Gbits/s}$$

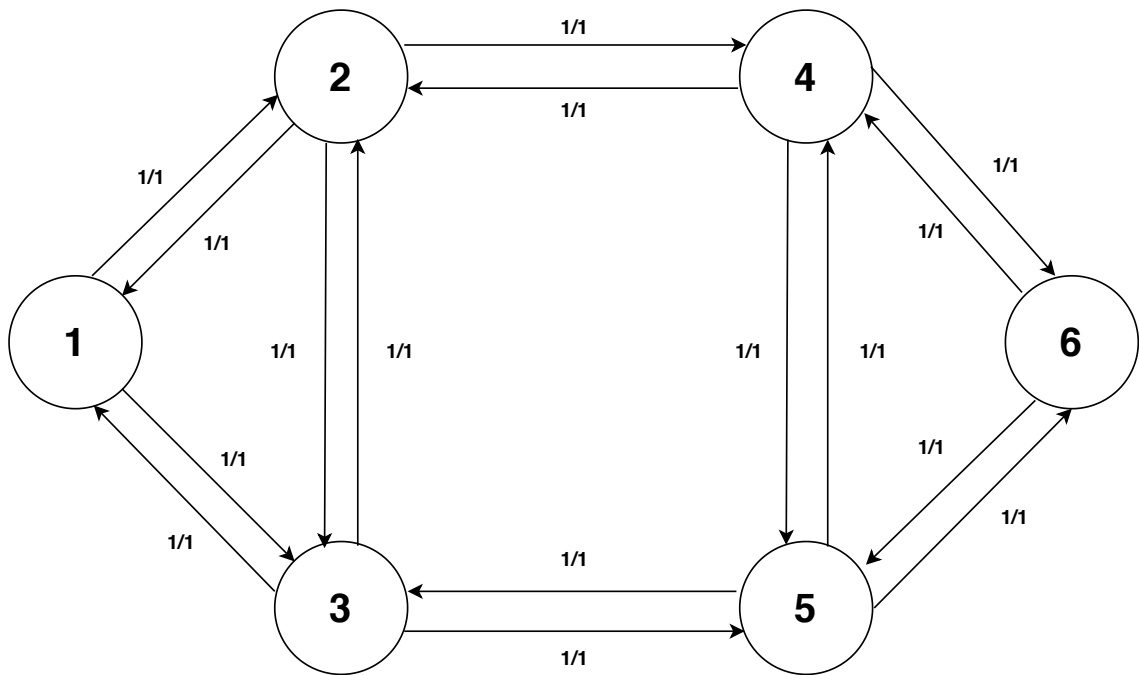


Figura 6.7: Transparent without survivability in medium scenario: physical topology after dimensioning.

Information regarding links		
Unidirectional link	Optical channels	Amplifiers
Node 1 ->2	7	4
Node 1 ->3	4	6
Node 2 ->1	7	4
Node 2 ->3	9	0
Node 2 ->4	22	6
Node 3 ->1	4	6
Node 3 ->2	9	0
Node 3 ->5	10	8
Node 4 ->2	22	6
Node 4 ->5	2	1
Node 4 ->6	18	7
Node 5 ->4	2	1
Node 5 ->6	13	3
Node 5 ->3	10	8
Node 6 ->4	18	7
Node 6 ->5	13	3

Tabela 6.117: Table with information regarding links for transparent mode without survivability in medium traffic scenario.

Information regarding nodes					
		Electrical part		Optical part	
Node	Nodal degree	Tributary ports	LR transponders	Add ports	Line ports
1	2	290	11	11	11
2	3	230	26	26	38
3	3	180	17	17	23
4	3	200	8	8	42
5	3	240	23	23	25
6	2	220	31	31	31

Tabela 6.118: Table with information regarding nodes for transparent mode without survivability in medium traffic scenario.

Network CAPEX						
			Quantity	Unit price	Cost	Total
Link cost	OLTs		16	15 000 €	240 000 €	85 520 000 €
	100 Gbit/s Transceivers		170	5 000 €/Gbit/s	85 000 000 €	
	Amplifiers		70	10 000 €	280 000 €	
Node Cost	Electrical part	EXCs	6	10 000 €	60 000 €	12 520 900 €
		ODU0 ports	600	10 €/ port	6000 €	
		ODU1 ports	500	15 €/ port	7500 €	
		ODU2 ports	160	30 €/ port	4800 €	
		ODU3 ports	60	60 €/ port	3600 €	
		ODU4 ports	40	100 €/ port	4000 €	
		Transponders	116	100 000 €/ port	11 600 000 €	
	Optical part	OXCs	6	20 000 €	120 000 €	
		Add ports	116	2500 €/port	290 000 €	
		Line ports	170	2500 €/ port	425 000 €	
Total Network Cost						98 040 900 €

Tabela 6.119: Transparent without survivability in medium traffic scenario: detailed description of CAPEX for this scenario.

6.8.3 High traffic scenario

$$\begin{aligned}
 ODU0 &= \begin{bmatrix} 0 & 100 & 20 & 60 & 20 & 60 \\ 100 & 0 & 0 & 20 & 100 & 0 \\ 20 & 0 & 0 & 20 & 80 & 20 \\ 60 & 20 & 20 & 0 & 20 & 20 \\ 20 & 100 & 80 & 20 & 0 & 60 \\ 60 & 0 & 20 & 20 & 60 & 0 \end{bmatrix} & ODU1 &= \begin{bmatrix} 0 & 40 & 80 & 40 & 0 & 100 \\ 40 & 0 & 0 & 60 & 20 & 20 \\ 80 & 0 & 0 & 20 & 20 & 0 \\ 40 & 60 & 20 & 0 & 20 & 60 \\ 0 & 20 & 20 & 20 & 0 & 20 \\ 100 & 20 & 0 & 60 & 20 & 0 \end{bmatrix} \\
 ODU2 &= \begin{bmatrix} 0 & 20 & 20 & 20 & 0 & 0 \\ 20 & 0 & 0 & 0 & 20 & 0 \\ 20 & 0 & 0 & 20 & 20 & 0 \\ 20 & 0 & 20 & 0 & 20 & 0 \\ 0 & 20 & 20 & 20 & 0 & 20 \\ 0 & 0 & 0 & 0 & 20 & 0 \end{bmatrix} & ODU3 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 20 & 0 & 0 & 20 \\ 0 & 20 & 0 & 0 & 20 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 20 & 0 & 0 & 0 \\ 0 & 20 & 0 & 0 & 0 & 0 \end{bmatrix} \\
 ODU4 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20 \\ 0 & 20 & 0 & 0 & 20 & 0 \end{bmatrix}
 \end{aligned}$$

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

$$T_1^0 = 600 \times 1.25 = 750 \text{ Gbits/s} \quad T_1^1 = 500 \times 2.5 = 1250 \text{ Gbits/s} \quad T_1^2 = 160 \times 10 = 1600 \text{ Gbits/s}$$

$$T_1^3 = 60 \times 40 = 2400 \text{ Gbits/s} \quad T_1^4 = 40 \times 100 = 4000 \text{ Gbits/s}$$

$$T_1 = 750 + 1250 + 1600 + 2400 + 4000 = 10000 \text{ Gbits/s}$$

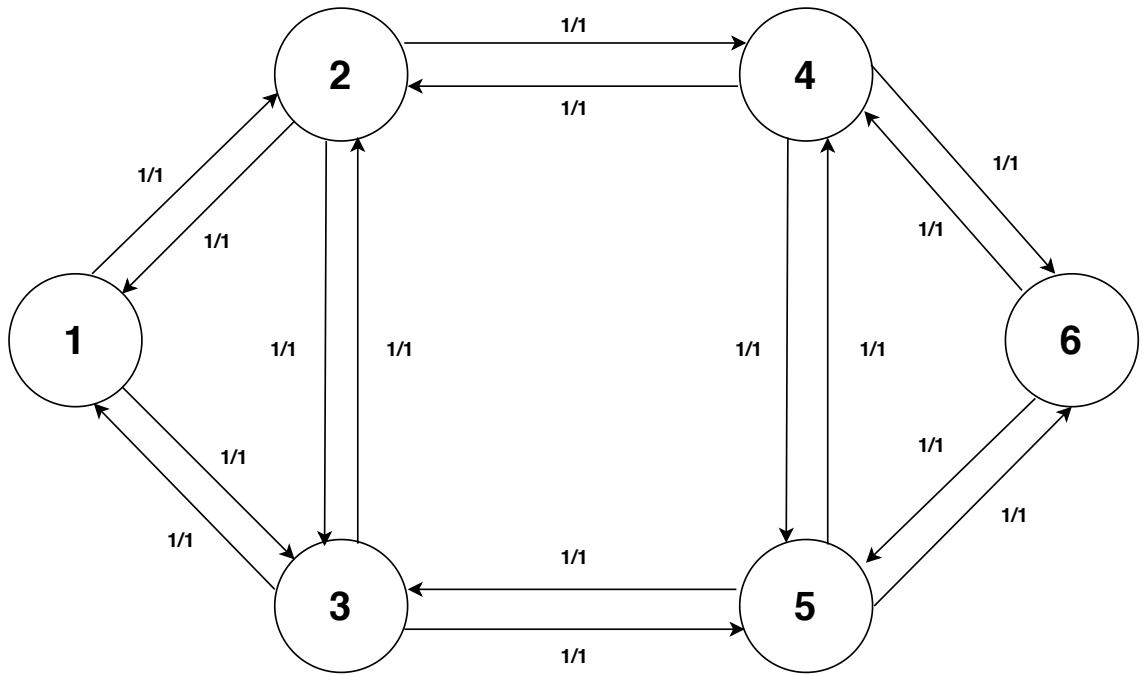


Figura 6.8: Transparent without survivability in high scenario: physical topology after dimensioning.

Information regarding links		
Unidirectional link	Optical channels	Amplifiers
Node 1 ->2	13	4
Node 1 ->3	6	6
Node 2 ->1	13	4
Node 2 ->3	17	0
Node 2 ->4	43	6
Node 3 ->1	6	6
Node 3 ->2	17	0
Node 3 ->5	18	8
Node 4 ->2	43	6
Node 4 ->5	3	1
Node 4 ->6	36	7
Node 5 ->3	18	8
Node 5 ->4	3	1
Node 5 ->6	25	3
Node 6 ->4	36	7
Node 6 ->5	25	3

Tabela 6.120: Table with information regarding links for transparent mode without survivability in high traffic scenario.

Information regarding nodes					
		Electrical part		Optical part	
Node	Nodal degree	Tributary ports	LR transponders	Add ports	Line ports
1	2	580	19	19	19
2	3	460	51	51	73
3	3	360	31	31	41
4	3	400	14	14	82
5	3	480	44	44	46
6	2	440	61	61	61

Tabela 6.121: Table with information regarding nodes for transparent mode without survivability in high traffic scenario.

Network CAPEX						
			Quantity	Unit price	Cost	Total
Link cost	OLTs		16	15 000 €	240 000 €	161 520 000 €
	100 Gbit/s Transceivers		322	5 000 €/Gbit/s	110 000 000 €	
	Amplifiers		70	10 000 €	280 000 €	
Node Cost	Electrical part	EXCs	6	10 000 €	60 000 €	23 586 800 €
		ODU0 ports	1200	10 €/ port	12 000 €	
		ODU1 ports	1000	15 €/ port	15 000 €	
		ODU2 ports	320	30 €/ port	9600 €	
		ODU3 ports	120	60 €/ port	7200 €	
		ODU4 ports	80	100 €/ port	8000 €	
		Transponders	220	100 000 €/ port	22 000 000 €	
	Optical part	OXCs	6	20 000 €	120 000 €	
		Add ports	220	2500 €/port	550 000 €	
		Line ports	322	2500 €/ port	805 000 €	
Total Network Cost						185 106 800 €

Tabela 6.122: Transparent without survivability in high traffic scenario: detailed description of CAPEX for this scenario.

		ILP	Other Heuristics	My Heuristics
Low traffic	Link cost	26 520 000 €	26 520 000 €	26 520 000 €
	Node Cost	3 797 590 €	3 797 590 €	3 797 590 €
	CAPEX	30 317 590 €	30 317 590 €	30 317 590 €
Medium traffic	Link cost	84 520 000 €	84 520 000 €	85 520 000 €
	Node Cost	12 310 900 €	15 180 900 €	12 520 900 €
	CAPEX	96 830 900 €	99 700 900 €	98 040 900 €
High traffic	Link cost	157 520 000 €	157 520 000 €	161 520 000 €
	Node Cost	22 951 800 €	28 486 800 €	23 586 800 €
	CAPEX	180 471 800 €	186 006 800 €	185 106 800 €

Tabela 6.123: Transparent without survivability: Table with different value of CAPEX for all scenarios

6.8.4 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.

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:

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

The minimization of the network CAPEX is made through the equation 5.1 where in this case for the cost of nodes we have in consideration the electric cost 5.4 and the optical cost 5.5.

In this case the value of $P_{exc,c,n}$ is obtained by equation 6.1 for short-reach and by the equation 6.2 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 6.3.

The equation 6.1 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

$$P_{exc,c,n} = \sum_{d=1}^N D_{nd,c} \quad (6.1)$$

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 6.2 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

$$P_{exc,-1,n} = \sum_{j=1}^N f_{nj}^{od} \quad (6.2)$$

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

The equation 6.3 refers to the number of line ports and the number of adding ports of node n which can be calculated as

$$P_{oxc,n} = \sum_{j=1}^N 2f_{nj}^{od} + \sum_{j=1}^N \lambda_{nj} \quad (6.3)$$

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.

To implement this heuristic approach there are used algorithms made in Java in a programming software called Eclipse and they are tested in an open-source network program called Net2Plan. In the Net2Plan guide section ?? there is an explanation on how to use and test them in this network planner.

In the next pages it will be described all the steps performed to obtain the final results in the transparent transport mode with 1+1 protection. In the figure below 6.9 it is shown a fluxogram with the description of this transport mode approach.

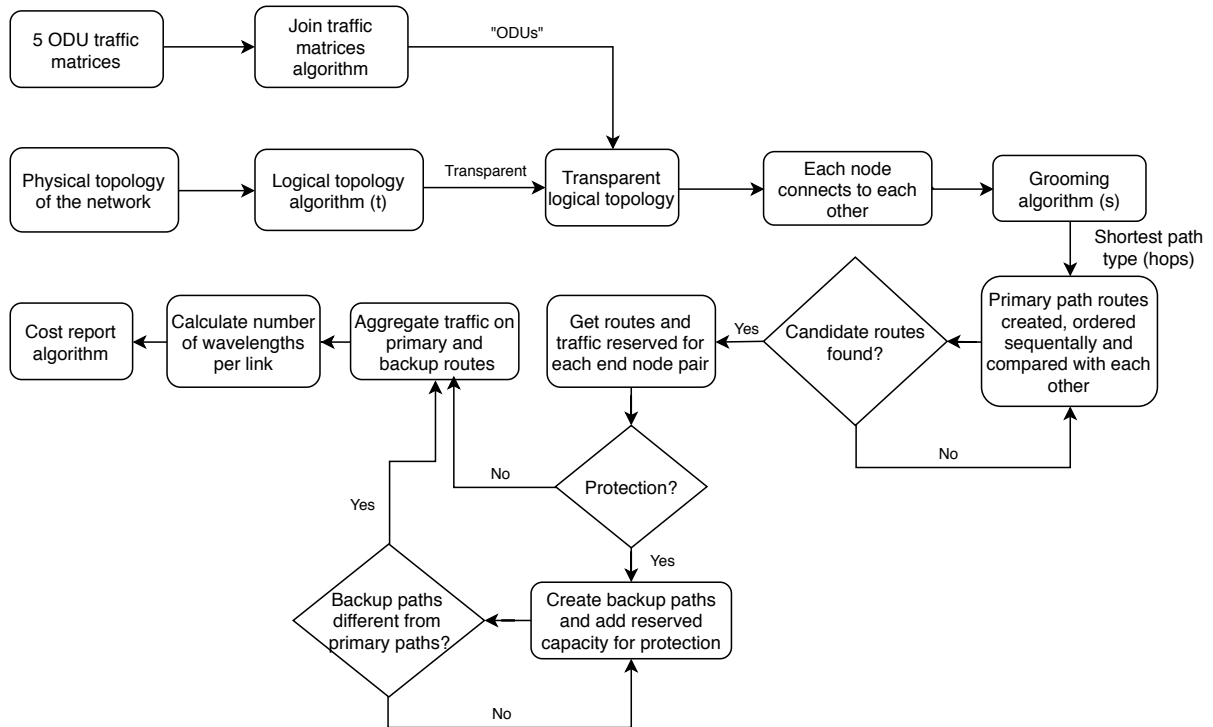


Figura 6.9: Fluxogram with the steps performed in the transparent with 1+1 protection transport mode approach.

Creation and join the traffic matrices

The first step is to create the traffic matrices based on the reference network 4.1. In order to create the 5 traffic matrices in Net2Plan it is necessary the length of all the links and the total traffic used in this network, so later it is needed to define in Net2Plan the length in all end nodes and the total traffic depends on the value of traffic used (low traffic - 0.5 Tbit/s, medium traffic - 5 Tbit/s and high traffic - 10 Tbit/s). As you can see in the figure below, it is defined the path of the 5 ODUs and they will be aggregated in just one single ODU, making it possible to join all the demands in just one file and load it later into the network. This final resulting ODU joins the multiple traffic demands from all the traffic matrices previously created and, of course, the traffic demands will depend on the values used on the creation of the matrices (low, medium and high traffic).

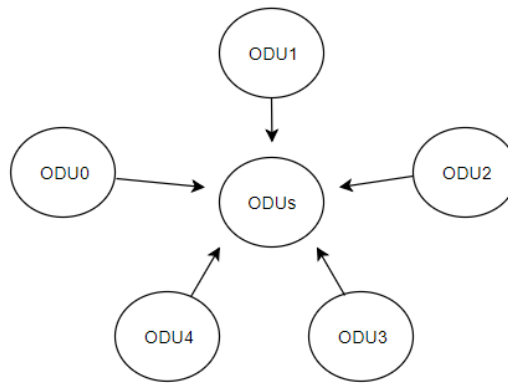


Figura 6.10: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.

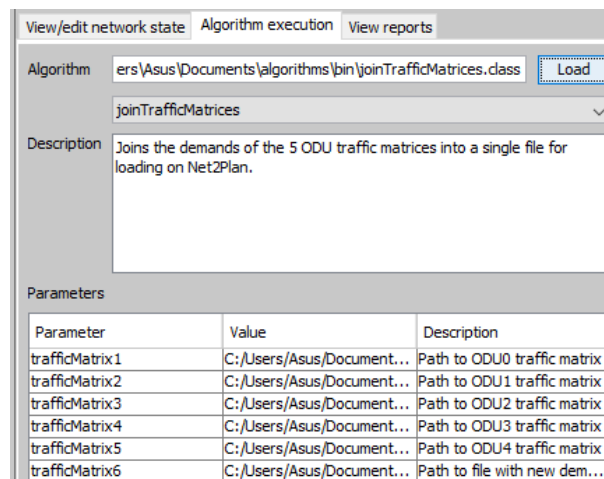


Figura 6.11: Load of the join traffic matrices algorithm for the transparent transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

The next step is to create the allowed physical topology of the network in Net2Plan. This network consists in 6 nodes and 8 bidirectional links. It is now also possible to define the length in all links. In the figure below it is shown the allowed physical topology in this transport mode.



Figura 6.12: 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.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. 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 one, then creates a shortest and direct link between them. These additions of links between end 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 physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 6.8.4 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the transparent transport mode with 1+1 protection.


```

if(netPlan.isSingleLayer() && logicalTopology.equalsIgnoreCase("Transparent"))
{
    this.lowerLayer = netPlan.getNetworkLayerDefault();
    lowerLayer.setName("Physical Topology");
    this.upperLayer = netPlan.addLayer("Logical Topology Transparent","Upper layer of the design","ODU","ODU",null);
    upperLayer.setDescription("Transparent Logical Topology");
    netPlan.removeAllLinks(upperLayer);

    for (Node i : netPlan.getNodes()) {
        for (Node j : netPlan.getNodes()) {
            if (i.getIndex() != j.getIndex())
            {
                netPlan.addLink(i, j, 0 , netPlan.getNodePairEuclideanDistance(i, j), 200000 , null , upperLayer);
            }
        }
    }
}

```

Figura 6.13: Java code of the logical topology approach for the transparent transport mode. The logical layer is created by adding direct links between all end nodes. The new layer is now the transparent logical topology of the network.



Figura 6.14: Load of the logical topology algorithm for the transparent transport mode.

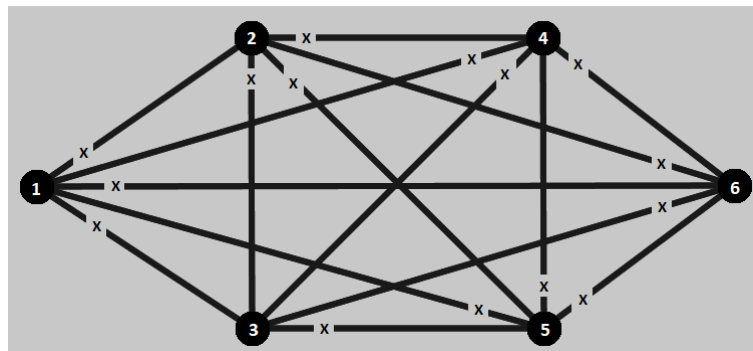


Figura 6.15: Allowed optical topology. It is assumed that each connections between demands supports up to 100 lightpaths.

Creation of routes and aggregation of traffic

After a network topology is created, it is now time to set the routing algorithm. In the transparent with 1+1 protection transport mode the routing algorithm is similar with the one used in opaque transport mode. It starts with going through all the demands and nodes which have different index between them (end nodes), create bidirectional routes (in this case the primary paths) based on the shortest path Dijkstra algorithm and then search the candidate routes for the respective demand. In this report it is used the shortest path type in hops. These routes are ordered sequentially and the shortest one per each demand is the primary path. The demands from the lower layer are removed and then saved in the upper layer. As we also have a dedicated 1+1 protection scheme, if the network has this feature active, the algorithm will compare the previous candidate routes that will be saved to a list with the new ones that will be created. If the new routes are different from the previously created ones and if they are the next shortest path routes, then the algorithm will add these routes to the network and they will be the protection segments (backup paths) of the network. The offered traffic demands will be also set into these protection path routes. The routes are saved to a "Set" of routes and in each link of end nodes it is set the traffic demands into these routes that will integrate the whole network. 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.

```
case "Logical Topology Transparent":

    for (Demand d : netPlan.getDemands(lowerLayer)) {
        boolean odd=true;
        int counter=0;

        Set<Route> droutes = d.getRoutes();
        System.out.println("droutes: " + droutes.size());

        for(Route c: droutes) {
            counter++;
            boolean jump=false;

            if(odd) {
                c.setCarriedTraffic(d.getOfferedTraffic(), d.getOfferedTraffic());
                save=c;
                odd=false;
                System.out.println("Roots");
            }
        }
    }
}
```

Figura 6.16: Creation of routes and aggregation of traffic for the transparent with 1+1 protection transport mode. The candidate routes are searched by the shortest path type and the offered traffic demands are set into these routes.

```

else {
    if (protection) {
        List<Link> workingpath = save.getSeqLinksRealPath();
        System.out.println("Protection-Transparent");
        for(Link t:workingpath) {
            if(c.getSeqLinksRealPath().contains(t)) {
                jump=true;
                break;
            }
        }

        if(jump==false) {
            ProtectionSegment segment=netPlan.addProtectionSegment(c.getSeqLinksRealPath(),
                                                                    d.getOfferedTraffic(), null);

            save.addProtectionSegment(segment);
            odd=true;
            break;
        }

        if(jump==true && counter == droutes.size()) {
            ProtectionSegment segment=netPlan.addProtectionSegment(c.getSeqLinksRealPath(),
                                                                    d.getOfferedTraffic(), null);

            save.addProtectionSegment(segment);
            odd=true;
            throw new Net2PlanException ("Number of routes is not enough");
        }
    }
}
}
}
}
}

```

Figura 6.17: Creation of routes and aggregation of traffic for the transparent with 1+1 protection transport mode. The protection segments are added to all the primary paths that were chosen by the shortest path type method.

```

ArrayList<Long> tNodeIds = netPlan.getNodeIds();
Node in;
Node out;
Set<Route> groomRoute;
Set<ProtectionSegment> protectRoutes;
Route compare=null;
ProtectionSegment compare1=null;
List<Link> path;
int nw=0;

for (long tNodeId : tNodeIds) {
    in = netPlan.getNodeFromId(tNodeId);
    for (long tNodeId1 : tNodeIds) {

        if(tNodeId==tNodeId1)continue;

        out = netPlan.getNodeFromId(tNodeId1);
        double totaltraffic=0;

        groomRoute=netPlan.getNodePairRoutes(in,out,false,lowerLayer);
        protectRoutes=netPlan.getNodePairProtectionSegments(in,out,false,lowerLayer);

        for(Route d:groomRoute)
        {
            totaltraffic = totaltraffic + d.getCarriedTraffic();
            compare=d;
        }

        path=compare.getSeqLinksRealPath();
    }
}

```

Figura 6.18: Creation of routes and aggregation of traffic for the transparent with 1+1 protection transport mode. The traffic demands are set in the candidate primary path routes found earlier and also compared with the backup path routes. The traffic demands are also set into these protection path routes.

```

//Protection Segments
totaltraffic=0;

for(ProtectionSegment protect:protectRoutes) {
    totaltraffic = totaltraffic + protect.getReservedCapacityForProtection();
    compare1 = protect;
}

if (protection) {
    path=compare1.getSeqLinks();
}

```

Figura 6.19: Creation of routes and aggregation of traffic for the transparent with 1+1 protection transport mode. The traffic demands are set in the candidate primary path routes found earlier and also compared with the backup path routes. The traffic demands are also set in these protection path routes.

Function	Definition
netPlan.getDemands(lowerLayer)	Returns the array of demands for the lower layer.
d.getRoutes()	Returns all the routes associated to the demand "d".
c.setCarriedTraffic()	Sets the route carried traffic and the occupied capacity in the links, setting it up to be the same in all links.
d.getOfferedTraffic()	Returns the offered traffic of the demand "d".
save.getSeqLinksRealPath()	Returns the links of routes ordered sequentially.
save.addProtectionSegment(segment)	Add "segment" as a protection path in the route "save".
netPlan.getNodeIds()	Returns the array of the nodes' indexes.
netPlan.getNodeFromId(tNodeId)	Returns the node with the index "tNodeId".
netPlan.getNodePairRoutes(in,out,false,lowerLayer)	Returns the routes at "lowerLayer" from nodes "in" and "out".
netPlan.getNodePairProtectionSegments(in,out,false,lowerLayer)	Returns the protection segments at "lowerLayer" from nodes "in" and "out".
protect.getReservedCapacityForProtection()	Returns the link capacity reserved for protection segments.

Tabela 6.124: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

The final step of the routing and grooming algorithms is to calculate the number of wavelengths per link for the whole network. This is the last and an important step because with the number of wavelengths per link in the network, it is possible to calculate other network components. In the transparent transport mode, as in the figure below shows, the algorithm starts with going through all the nodes which have different index between them (end nodes) and in all the links that crosses between these pairs of nodes is reserved a link capacity based on the previous traffic aggregation. The total carried traffic in the link including protection and non-protection segments will be divided by the wavelength capacity and it is now possible to obtain the number of wavelengths per link.

```

for (Link link:path)
{
    String nw = link.getAttribute("nw");
    nw=0;

    if(nw!=null)
    {
        nw = Integer.parseInt(nw);
        nw = (int) (nw+Math.ceil(totaltraffic/wavelengthCapacity));
        link.setAttribute("nw",String.valueOf(nw));
    }else {
        nw = (int) Math.ceil(totaltraffic/wavelengthCapacity);
        link.setAttribute("nw",String.valueOf(nw));
    }
}

```

Figura 6.20: Calculation of the number of wavelengths per link for the transparent transport mode. The link capacity is reserved based on the previous traffic aggregation.

View/edit network state Algorithm execution View reports

Algorithm: C:\Users\Asus\Documents\algorithms\bin\grooming.class Load

grooming

Description: Algorithm that creates routes and protection paths based on the shortestPath (hops or km) making sure they are bidirectional and according to the logical topology. Link capacity is based on the number of wavelengths necessary with a user defined wavelength traffic capacity.

Parameters

Parameter	Value	Description
numberofroutes	10	Total number of routes p...
protection	yes	1+1 protection (yes/no).
shortestPathType	hops	Each demand is routed ac...
wavelengthCapacity	100	Capacity per wavelength.

Figura 6.21: Load of the grooming algorithm for the transparent with 1+1 protection transport mode. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 6.8.4 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details.



Figura 6.22: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

It is already known all the necessary formulas to obtain the CAPEX value for the reference network 4.1. 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 6.23: 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 6.24: 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 6.25: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 6.26: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 6.27: ODU2 logical topology defined by the ODU2 traffic matrix.

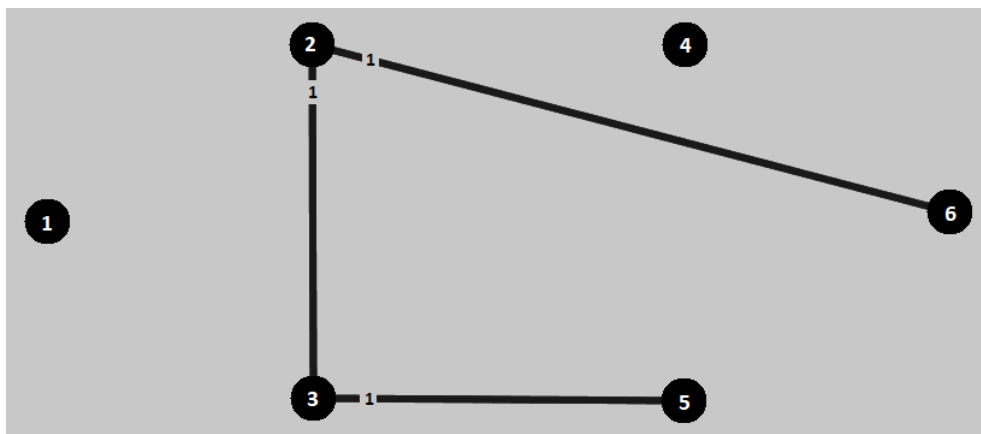


Figura 6.28: ODU3 logical topology defined by the ODU3 traffic matrix.

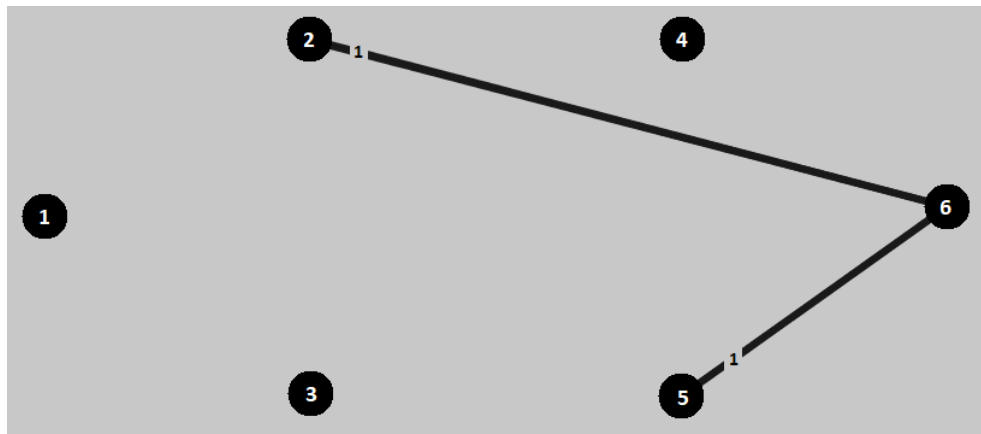


Figura 6.29: ODU4 logical topology defined by the ODU4 traffic matrix.

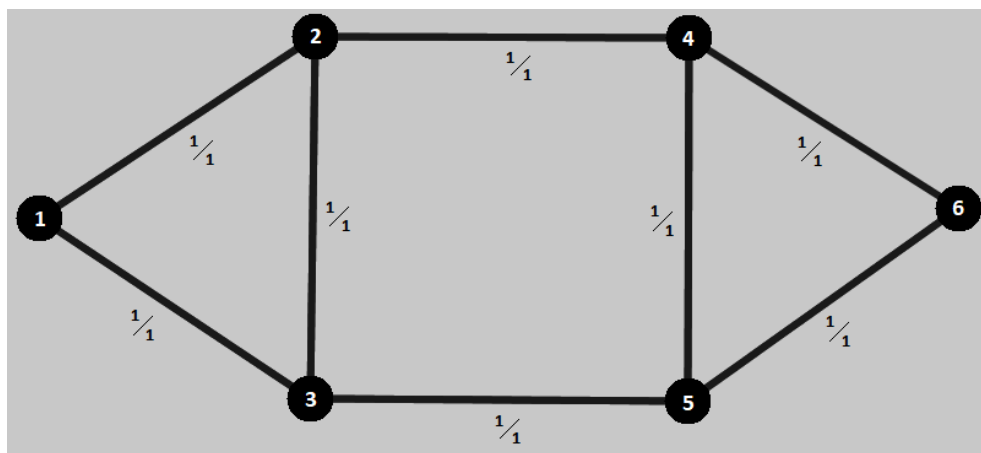


Figura 6.30: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 6.125. In table 5.108 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 €	4 007 590 €
		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						72 527 590 €

Tabela 6.125: 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 6.31: 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 6.32: 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 6.33: ODU0 logical topology defined by the ODU0 traffic matrix.

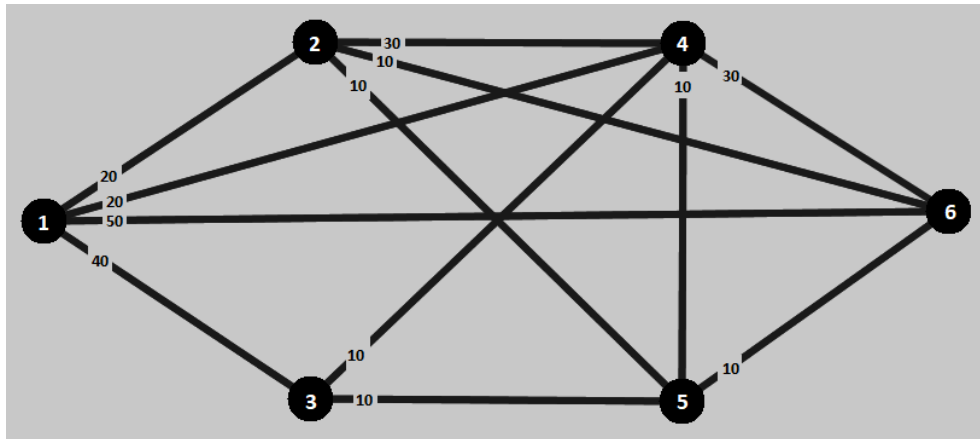


Figura 6.34: ODU1 logical topology defined by the ODU1 traffic matrix.

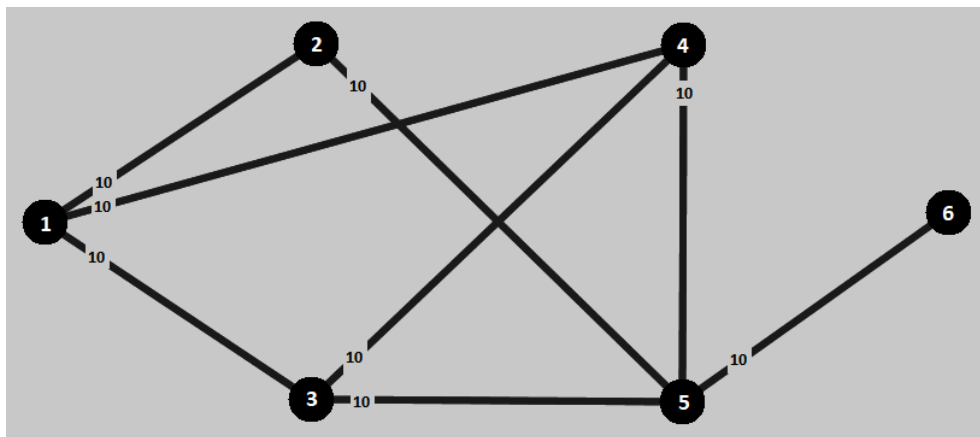


Figura 6.35: ODU2 logical topology defined by the ODU2 traffic matrix.

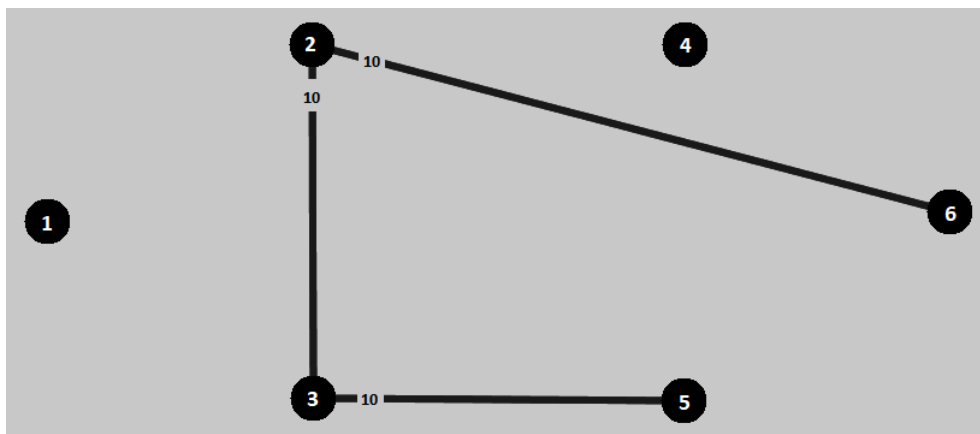


Figura 6.36: ODU3 logical topology defined by the ODU3 traffic matrix.

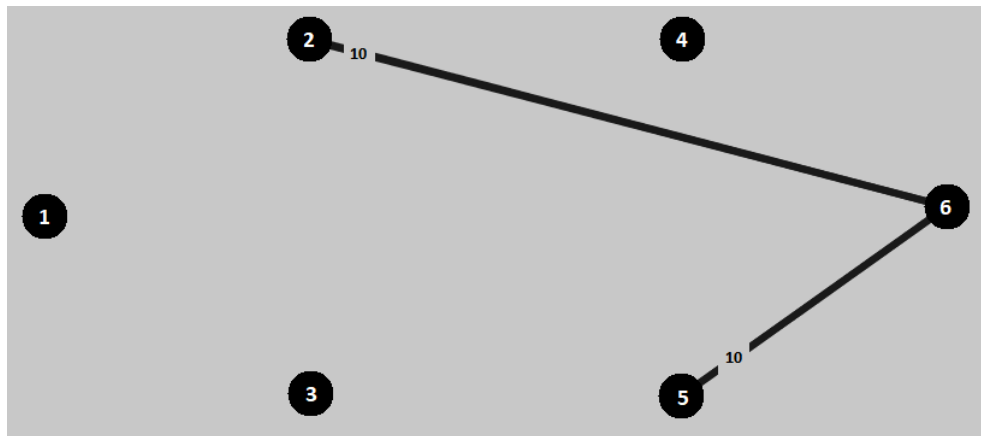


Figura 6.37: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 6.38: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 6.126. In table 5.108 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 €	226 520 000 €
	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 €	15 890 900 €
		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	142	100 000 €/port	14 200 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	452	2 500 €/port	1 130 000 €	
		Add Ports	142	2 500 €/port	355 000 €	
Total Network Cost						242 410 900 €

Tabela 6.126: 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.

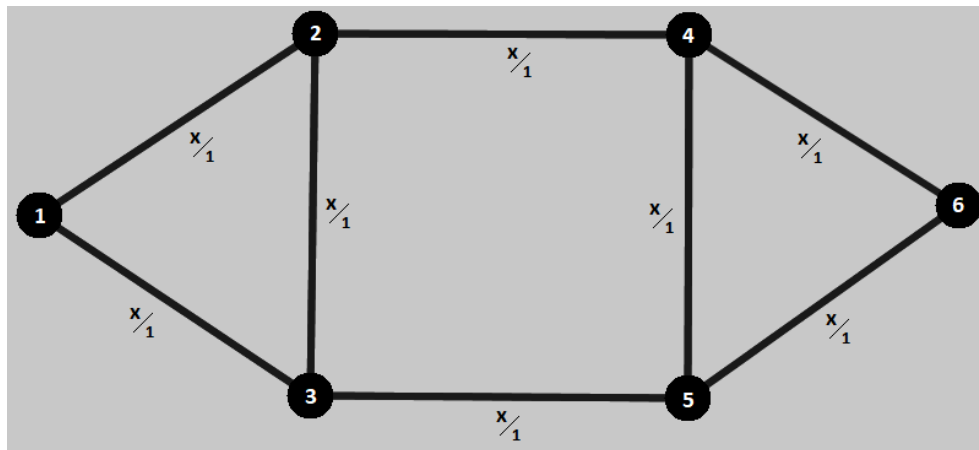


Figura 6.39: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 6.40: 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 6.41: ODU0 logical topology defined by the ODU0 traffic matrix.

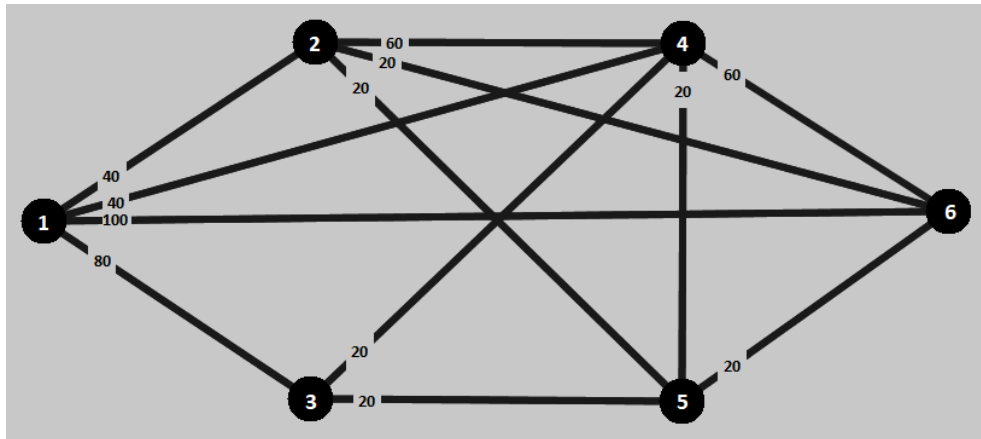


Figura 6.42: ODU1 logical topology defined by the ODU1 traffic matrix.

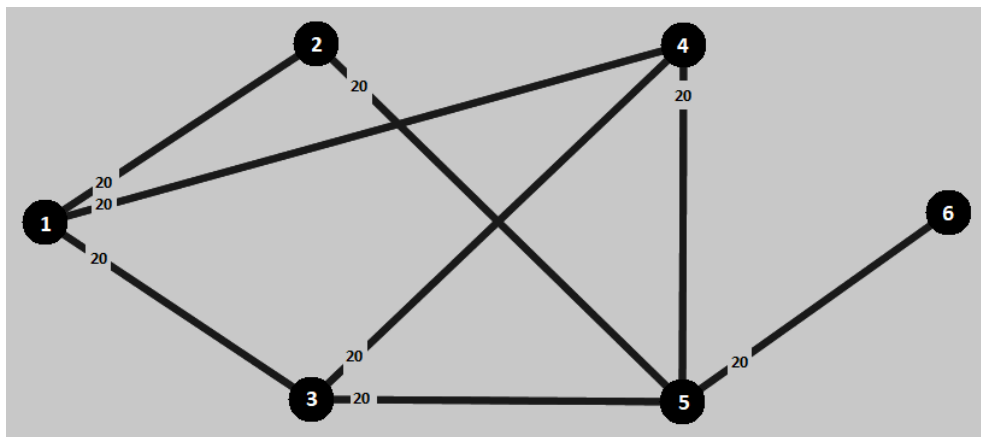


Figura 6.43: ODU2 logical topology defined by the ODU2 traffic matrix.

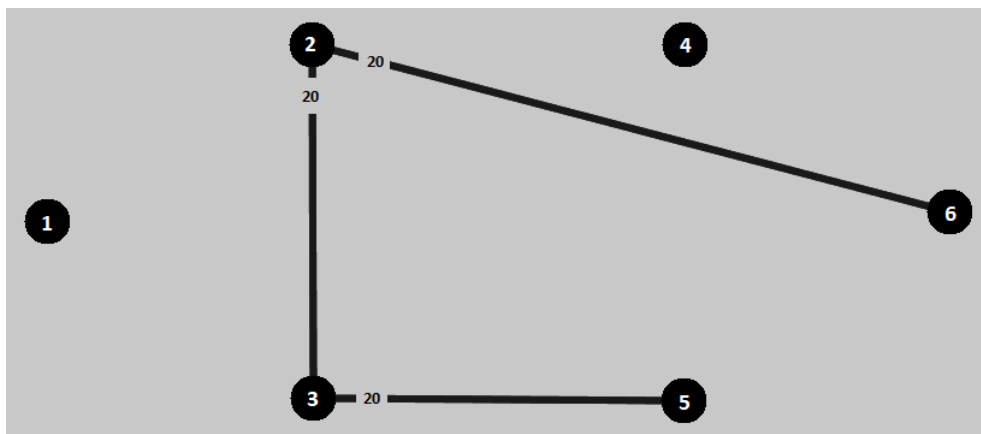


Figura 6.44: ODU3 logical topology defined by the ODU3 traffic matrix.

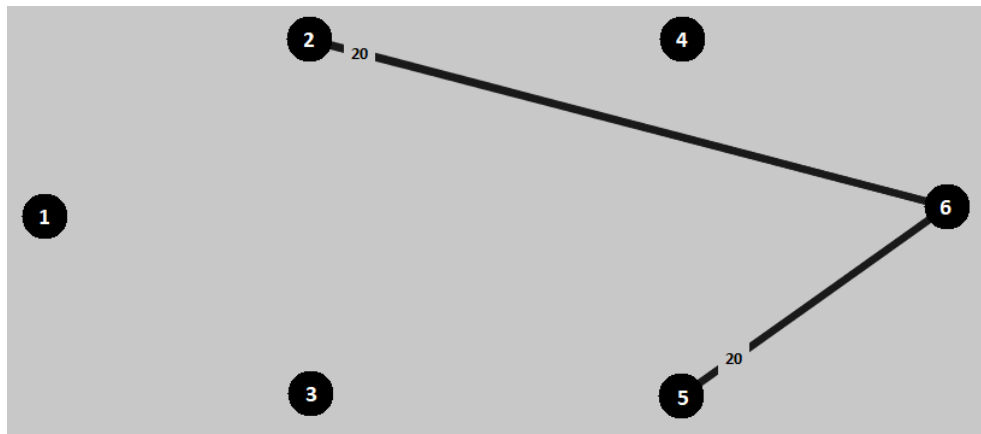


Figura 6.45: ODU4 logical topology defined by the ODU4 traffic matrix.

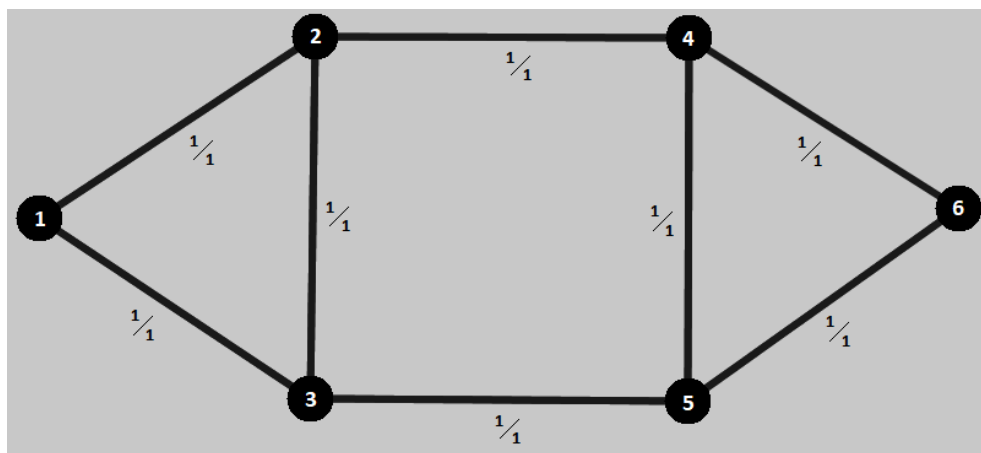


Figura 6.46: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 6.127. In table 5.108 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 €	424 520 000 €
	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 €	29 821 800 €
		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	268	100 000 €/port	26 800 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	848	2 500 €/port	2 120 000 €	
		Add Ports	268	2 500 €/port	670 000 €	
Total Network Cost						454 341 800 €

Tabela 6.127: Table with detailed description of CAPEX of Vasco's 2016 results.

Conclusions

Once we have obtained the results for all scenarios for the 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	30 317 590 €	99 700 900 €	186 006 800 €
CAPEX/Gbit/s without survivability	60 635 €/Gbit/s	19 940 €/Gbit/s	18 600 €/Gbit/s
Traffic (Gbit/s)	500	5 000	10 000
Bidirectional Links used	8	8	8
Number of Add ports	34	142	268
Number of Line ports	136	452	848
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	136	452	848
Link Cost	68 520 000 €	226 520 000 €	454 520 000 €
Node Cost	4 007 590 €	15 890 900 €	29 821 800 €
CAPEX	72 527 590 €	242 410 900 €	454 341 800 €
CAPEX/Gbit/s	145 055 €/Gbit/s	48 482 €/Gbit/s	45 434 €/Gbit/s

Tabela 6.128: 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 transport mode the CAPEX cost for all the three traffic is more than the double;

This happens because in the transparent with 1+1 protection transport mode 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.

6.8.5 Translucent without Survivability

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

The translucent networks (optical-bypass) consist of intermediate optical network architectures between opaque and transparent networks. In the translucent transport mode (multi-hop approach) an OEO conversion is performed when the optical signal falls below a pre-defined threshold. This threshold is called the maximum optical reach and it is the maximum distance that an optical signal can traverse in the optical domain. Then it is needed an wavelength regenerator in order to regenerate the optical signal and maintain the quality level in the transmission (QoT) of the signals. This allows the traversing of the optical signal in the optical domain as much as it can go through the path, from source to destination.

For cost savings, the translucent networks aims at using the minimum number of regenerators and wavelengths of the network, being the most advantageous transport mode in the optical backbone networks.

We also 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 minimization of the network CAPEX is made through the equation 5.1 where in this case for the cost of nodes we have in consideration the electric cost 5.4 and the optical cost 5.5.

In this case the value of $P_{exc,c,n}$ is obtained by equation 6.4 for short-reach and by the equation 6.5 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 6.6.

The equation 6.4 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

$$P_{exc,c,n} = \sum_{d=1}^N D_{nd,c} \quad (6.4)$$

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 6.5 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

$$P_{exc,-1,n} = \sum_{j=1}^N \lambda_{nj} \quad (6.5)$$

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

The equation 6.6 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

$$P_{oxc,n} = \sum_{j=1}^N f_{nj}^{od} + \sum_{j=1}^N \lambda_{nj} \quad (6.6)$$

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.

To implement this heuristic approach there are used algorithms made in Java in a programming software called Eclipse and they are tested in an open-source network program called Net2Plan. In the next pages it will be described all the steps performed to obtain the final results in the translucent transport mode without survivability. In the figure below 6.47 it is shown a fluxogram with the description of this transport mode approach.

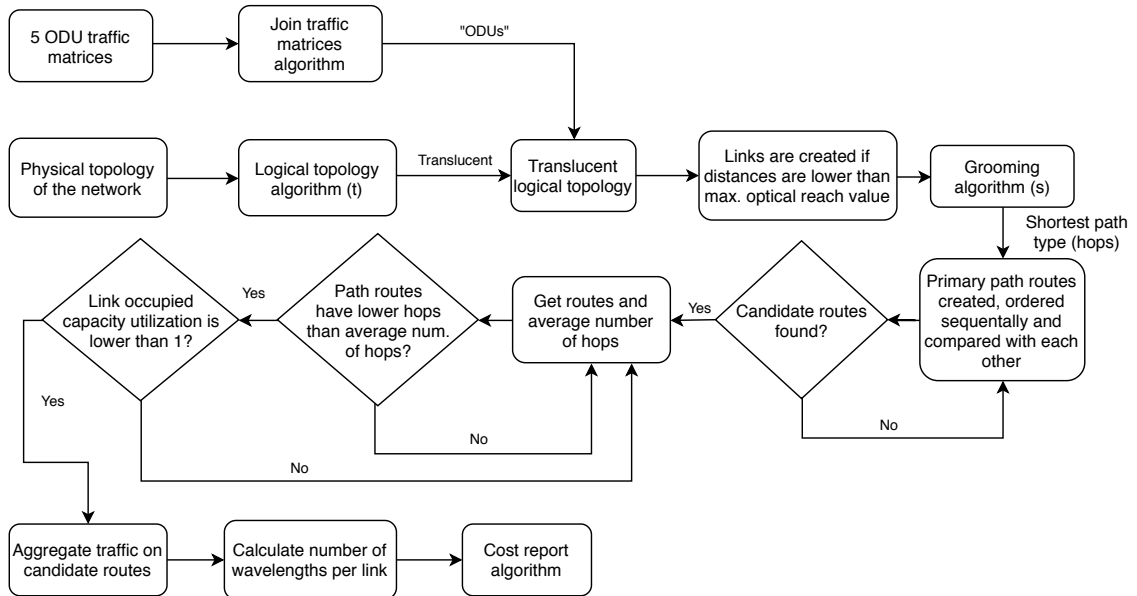


Figura 6.47: Fluxogram with the steps performed in the translucent without survivability transport mode approach.

Creation and join the traffic matrices

The first step is to create the traffic matrices based on the reference network 4.1. In order to create the 5 traffic matrices in Net2Plan it is necessary the length of all the links and the total traffic used in this network, so later it is needed to define in Net2Plan the length in all end nodes and the total traffic depends on the value of traffic used (low traffic - 0.5 Tbit/s, medium traffic - 5 Tbit/s and high traffic - 10 Tbit/s). As you can see in the figure below, it is defined the path of the 5 ODUs and they will be aggregated in just one single ODU, making it possible to join all the demands in just one file and load it later into the network. This final resulting ODU joins the multiple traffic demands from all the traffic matrices previously created and, of course, the traffic demands will depend on the values used on the creation of the matrices (low, medium and high traffic).

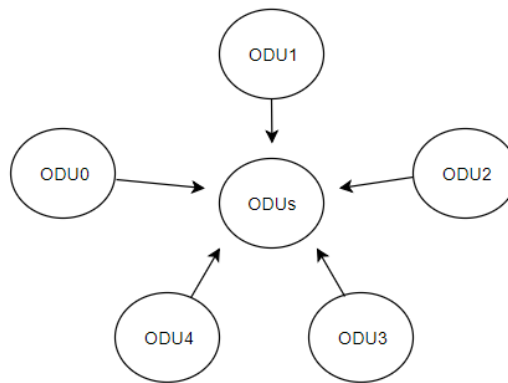


Figura 6.48: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.

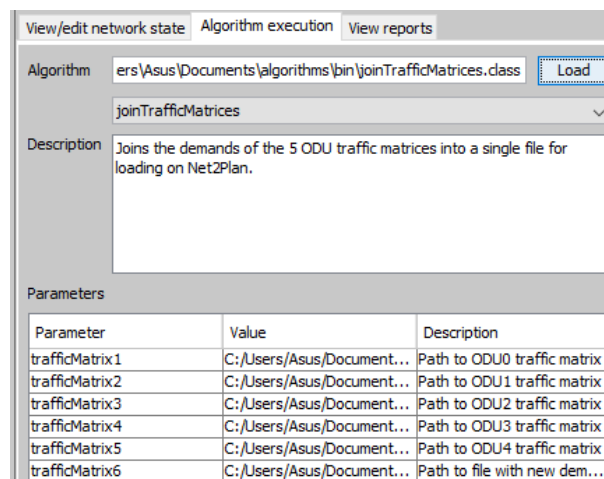


Figura 6.49: Load of the join traffic matrices algorithm for the translucent transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

The next step is to create the allowed physical topology of the network in Net2Plan. This network consists in 6 nodes and 8 bidirectional links. It is now also possible to define the length in all links. In the figure below it is shown the allowed physical topology in this transport mode.

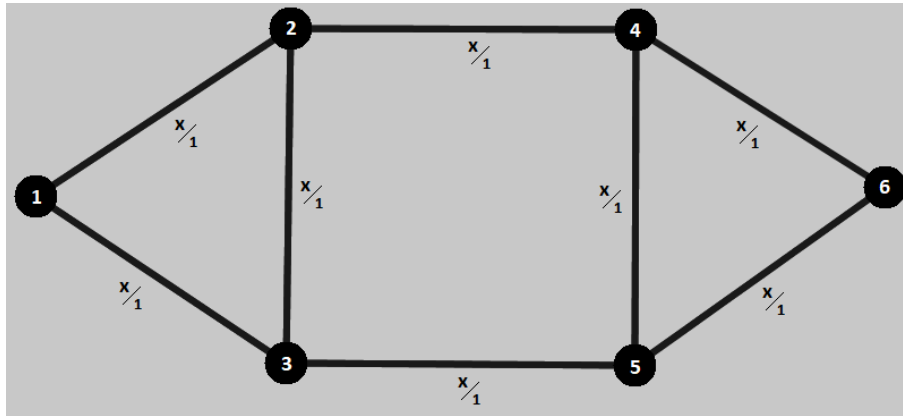


Figura 6.50: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. In the translucent transport mode each node connects to other node if the shortest path distance between them is lower than the maximum optical reach value (in km) that an optical signal can traverse in an optical channel. If the maximum optical reach is higher than the shortest path of a link, then it is not created a logical link of that specific physical link. On the contrary, there are created direct links between all node pairs in the network that follow this rule. These additions of links between end 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 translucent transport mode. The allowed physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 6.8.5 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the translucent transport mode without survivability.

```

if (netPlan.isSingleLayer() && logicalTopology.equalsIgnoreCase("Translucent")) {

    int maximumOpticalReach = Integer.parseInt(algorithmParameters.get("maximumOpticalReach"));
    maxOpticalReach = maximumOpticalReach;

    sendToFile("opticalReach.txt");

    this.lowerLayer = netPlan.getNetworkLayerDefault();
    lowerLayer.setName("Physical Topology");
    this.upperLayer = netPlan.addLayer("Logical Topology Translucent", "Upper layer of the design", "ODU", "ODU", null);
    upperLayer.setDescription("Translucent Logical Topology" + " - Maximum Optical Reach= " + maximumOpticalReach + " km");
    netPlan.removeAllLinks(upperLayer);

    for (Node i : netPlan.getNodes()) {
        for (Node j : netPlan.getNodes()) {
            if (i.getIndex() != j.getIndex()) {
                if (netPlan.getNodePairEuclideanDistance(i, j) <= maximumOpticalReach) {
                    netPlan.addLink(i, j, 0, netPlan.getNodePairEuclideanDistance(i, j), 200000, null, upperLayer);
                }
            }
        }
    }
}

```

Figura 6.51: Java code of the logical topology approach for the translucent transport mode. The logical layer is created by adding direct links between all end nodes if their shortest path between them is lower than the maximum optical reach value. The new layer is now the translucent logical topology of the network.

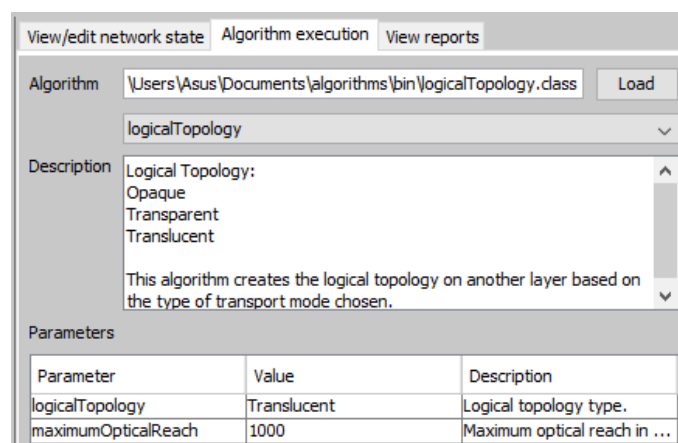


Figura 6.52: Load of the logical topology algorithm for the translucent transport mode on Net2Plan. It is assumed that the maximum optical reach value is 1000 km, so all direct links between node pairs with different index are created in all optical channels.

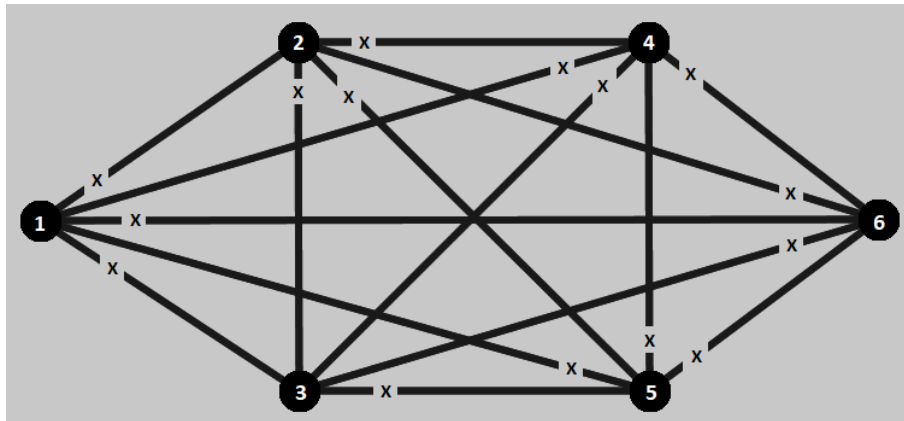


Figura 6.53: Allowed optical topology. It is assumed that each connections between demands supports up to 100 lightpaths. In the translucent transport mode there are several possible logical topologies for a specific network. It depends, for example, on the maximum optical reach value that represents the maximum distance that an optical signal can traverse a link without the need of regenerate.

Creation of routes and aggregation of traffic

After a network topology is created, it is now time to set the routing and then grooming algorithms. In the translucent without survivability transport mode the objective function is to minimize the lightpaths of the network and to find a route for every lightpath demand without considering the wavelength assignment. In this heuristic approach the goal is to minimize the lightpaths blocked and going through the carried lightpaths search for the ones that minimizes the average number of physical hops. Some of the links in the network will suffer from excessive traffic and some other links will occupy only a small part of the bandwidth. In order to do more efficiently, the link's utilizations are almost 1 so there is less non occupied capacity. Firstly, the candidate routes are found by the Dijkstra algorithm for each pair of nodes and calculates the minimum distance for each source and destination nodes and compares with each other. Then, the wavelength assignments are carried out for every lightpaths that have the minimum average of hops for each route and if the path distance is lower than the maximum optical reach value (in this report the maximum optical reach value used is 1000 km). The carried lightpaths resulted previously are sequentially processed.

```

case "Logical Topology Translucent":

    int hops = 0;
    Set<Route> nRoutes = new HashSet<Route>();

    for (Demand d : netPlan.getDemands(lowerLayer)) {

        nRoutes = d.getRoutes();
        for (Route c : nRoutes) {
            hops += c.getNumberOfHops();
        }
    }
    int n = hops/netPlan.getNumberOfRoutes(lowerLayer);

    for (Demand d : netPlan.getDemands(lowerLayer)) {
        boolean odd = true;
        int counter = 0;

        Set<Route> dRoutes = d.getRoutes();

        for (Route c : dRoutes) {
            counter++;
            boolean jump = false;

            if (odd) {
                if (c.getNumberOfHops() < (n-1) && c.getLengthInKm() <= maxOpticalReach) {
                    c.setCarriedTraffic(d.getOfferedTraffic(), d.getOfferedTraffic());
                    save = c;
                    System.out.println("Roots");
                }
                else if (c.getNumberOfHops() > (n-1) && c.getLengthInKm() <= maxOpticalReach) {
                    save = c;
                    System.out.println("Roots");
                }
            }
        }
    }

```

Figura 6.54: Creation of routes and aggregation of traffic for the translucent without survivability transport mode. The candidate routes are searched by the shortest path type method and the average minimum number of physical hops of the routes. The offered traffic demands are set into these routes.

```

for (long tNodeId : tNodeIdsTransl) {
    inTransl = netPlan.getNodeFromId(tNodeId);
    for (long tNodeId1 : tNodeIdsTransl) {

        if (tNodeId == tNodeId1)
            continue;

        outTransl = netPlan.getNodeFromId(tNodeId1);
        double totaltraffic = 0;

        groomRouteTransl = netPlan.getNodePairRoutes(inTransl, outTransl, false, lowerLayer);
        protectRoutesTransl = netPlan.getNodePairProtectionSegments(inTransl, outTransl, false, lowerLayer);

        for (Route c : groomRouteTransl) {
            if(c.getCarriedTraffic() <= c.getOccupiedCapacity()){
                compareTransl = c;
            }
        }

        pathTransl = compareTransl.getSeqLinksRealPath();

        for(Route c : groomRouteTransl){
            for (Link link : pathTransl){
                if(link.getUtilizationNotIncludingProtectionSegments() < 1){
                    totaltraffic = totaltraffic + c.getCarriedTraffic();
                    compareTransl2 = c;
                }
                else
                    compareTransl = c;
            }
        }

        pathTransl2 = compareTransl2.getSeqLinksRealPath();
    }
}

```

Figura 6.55: Creation of routes and aggregation of traffic for the translucent without survivability transport mode. Minimizing the blocked traffic, the traffic demands are set into the candidate primary path routes found earlier.

Function	Definition
netPlan.getDemands(lowerLayer)	Returns the array of demands for the lower layer.
d.getRoutes()	Returns all the routes associated to the demand "d".
c.getNumberOfHops()	Returns the route number of traversed links.
c.getLengthInKm()	Returns the route length in km, summing the traversed link lengths, as many times as the link is traversed.
c.setCarriedTraffic()	Sets the route carried traffic and the occupied capacity in the links, setting it up to be the same in all links.
d.getOfferedTraffic()	Returns the offered traffic of the demand "d".
netPlan.getNodeIds()	Returns the array of the nodes' indexes.
netPlan.getNodeFromId(tNodeId)	Returns the node with the index "tNodeId".
netPlan.getNodePairRoutes(in,out,false,lowerLayer)	Returns the routes at "lowerLayer" from nodes "in" and "out".
c.getCarriedTraffic()	Returns the route carried traffic at that moment.
c.getOccupiedCapacity()	Returns the route occupied capacity at that moment.

Tabela 6.129: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

The final step of the routing and grooming algorithms is to calculate the number of wavelengths per link for the whole network. This is the last and an important step because with the number of wavelengths per link in the network, it is possible to calculate other network components. In the translucent transport mode, as in the figure below shows, the algorithm starts with going through all the nodes which have different index between them (end nodes) and if the path distance between them is lower than the maximum optical reach value and in all the links that crosses between these pairs of nodes is reserved a link capacity based on the previous traffic aggregation on routes. The total carried traffic in the link including protection and non-protection segments will be divided by the wavelength capacity and it is now possible to obtain the number of wavelengths per link.

```
for (Link link:path)
{
    String nw = link.getAttribute("nw");
    nw=0;

    if(nw!=null)
    {
        nw = Integer.parseInt(nw);
        nw = (int) (nw+Math.ceil(totaltraffic/wavelengthCapacity));
        link.setAttribute("nw",String.valueOf(nw));
    }else {
        nw = (int) Math.ceil(totaltraffic/wavelengthCapacity);
        link.setAttribute("nw",String.valueOf(nw));
    }
}
```

Figura 6.56: Calculation of the number of wavelengths per link for the translucent transport mode. The link capacity is reserved based on the previous traffic aggregation.

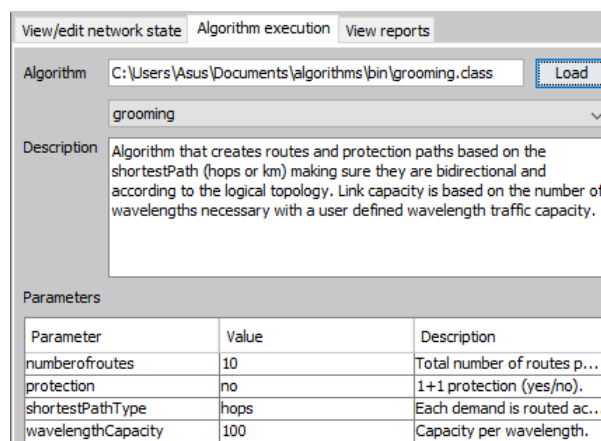


Figura 6.57: Load of the grooming algorithm. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 6.8.5 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details.



Figura 6.58: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

It is already known all the necessary formulas to obtain the CAPEX value for the reference network 4.1. 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 Pedro's heuristics. 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.

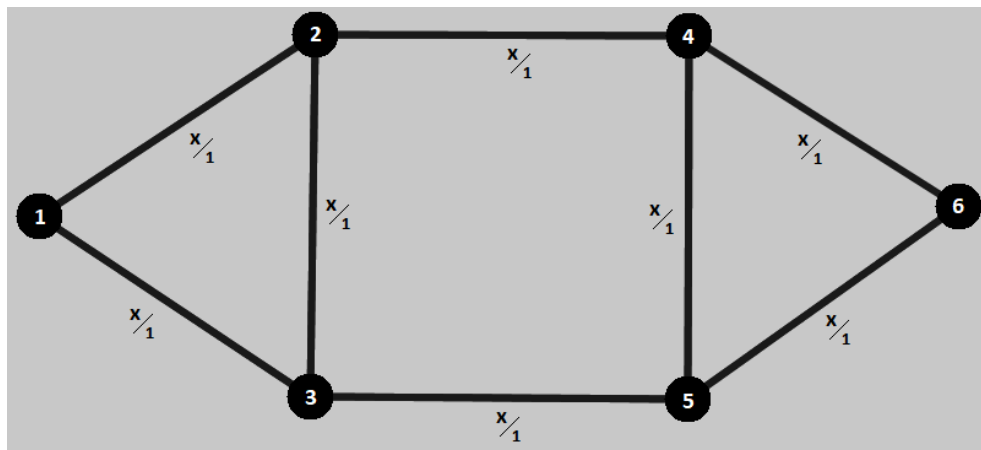


Figura 6.59: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 6.60: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 6.61: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 6.62: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 6.63: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 6.64: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 6.65: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 6.66: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 Pedro's heuristics can be consulted in the following table 6.130.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	9 520 000 €
	100 Gbits/s Transceivers		18	5 000 €/Gbit/s	9 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	2 072 590 €
		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	18	100 000 €/port	1 800 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	18	2 500 €/port	45 000 €	
		Add Ports	18	2 500 €/port	45 000 €	
Total Network Cost						11 592 590 €

Tabela 6.130: Table with detailed description of CAPEX.

All the values calculated in the previous table were obtained through the equations 5.2 and 5.3 referred to in section 5.1, but for a more detailed analysis we created table 6.131 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	$\sum_{n=1}^N \sum_{j=1}^N N_{exc,n} \lambda_{od} \gamma_{e1,-1}$
OXC	$\sum_{n=1}^N N_{oxc,n} \gamma_{o0}$
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 6.131: Table with description of calculation

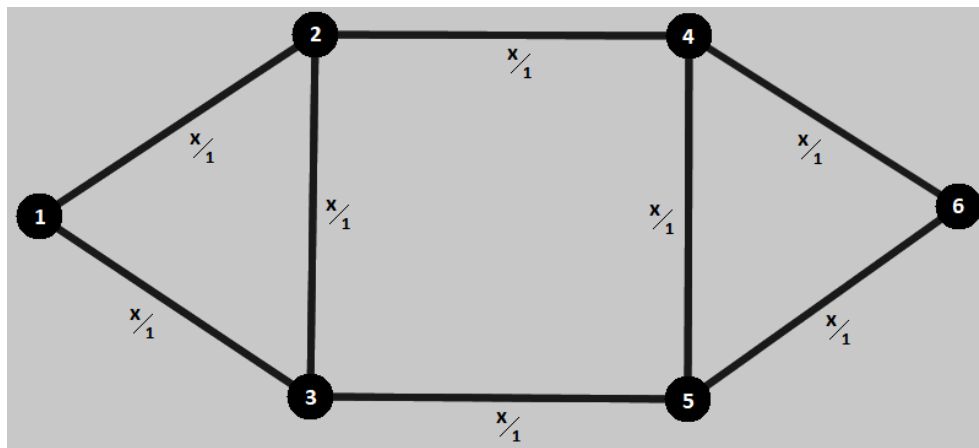


Figura 6.67: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional



Figura 6.68: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 6.69: ODU0 logical topology defined by the ODU0 traffic matrix.

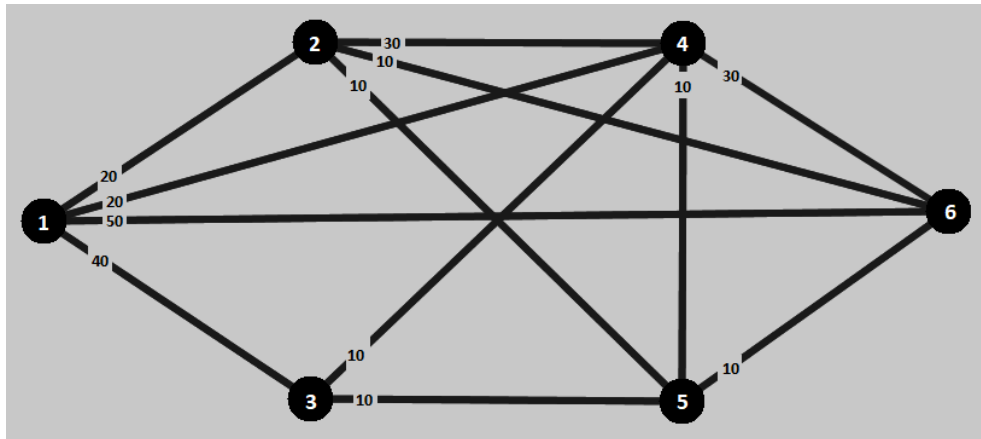


Figura 6.70: ODU1 logical topology defined by the ODU1 traffic matrix.

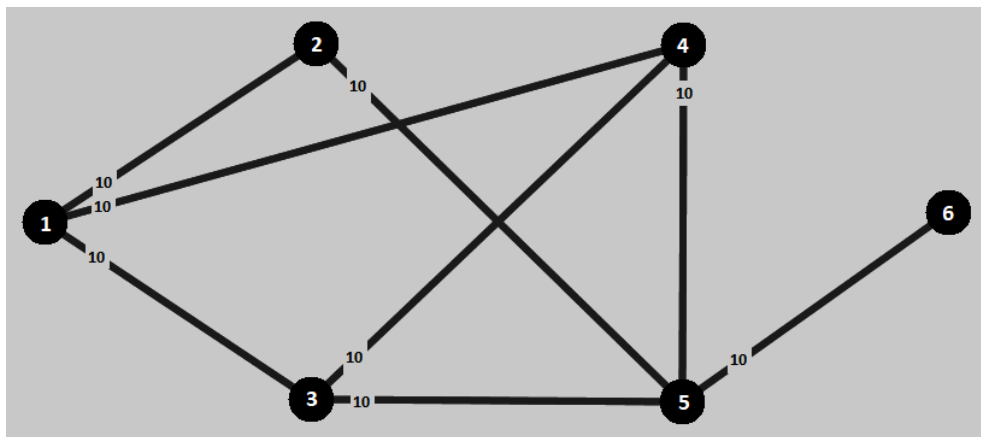


Figura 6.71: ODU2 logical topology defined by the ODU2 traffic matrix.

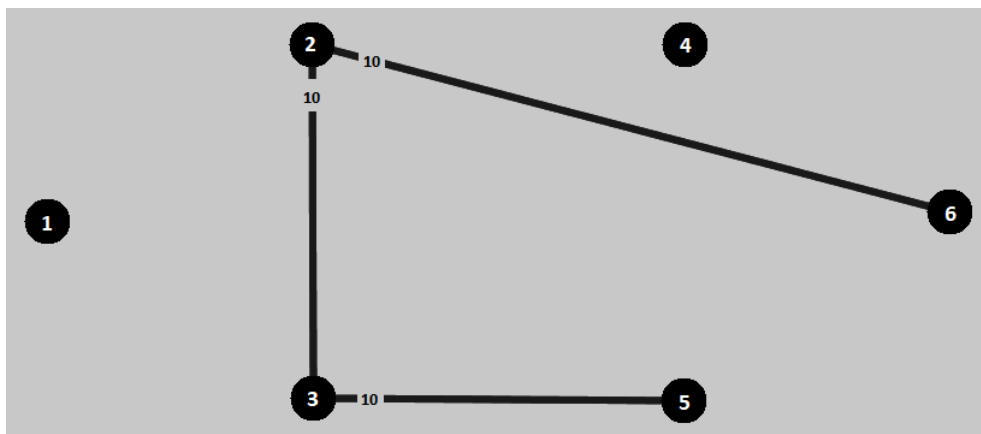


Figura 6.72: ODU3 logical topology defined by the ODU3 traffic matrix.

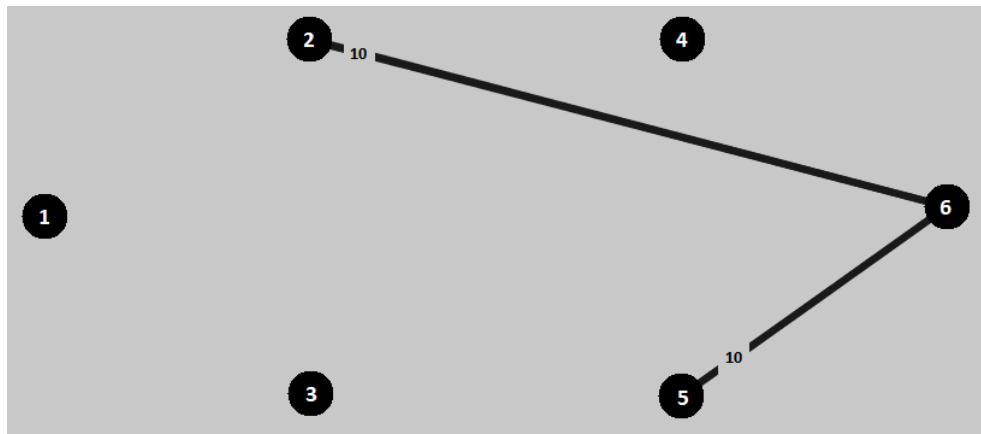


Figura 6.73: ODU4 logical topology defined by the ODU4 traffic matrix.

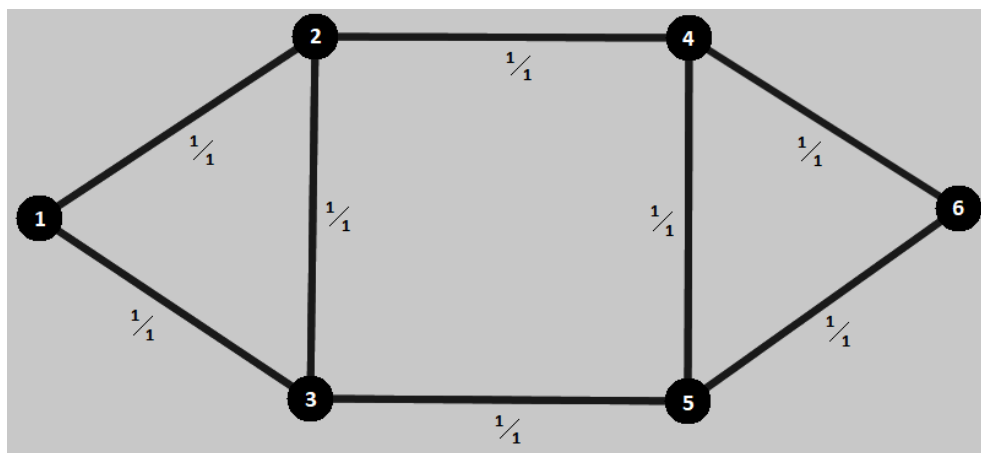


Figura 6.74: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 Pedro's heuristics can be consulted in the following table 6.132. In table 6.131 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 €	40 520 000 €
	100 Gbits/s Transceivers		80	5 000 €/Gbit/s	40 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	8 605 900 €
		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	80	100 000 €/port	8 000 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	80	2 500 €/port	200 000 €	
		Add Ports	80	2 500 €/port	200 000 €	
Total Network Cost						49 125 900 €

Tabela 6.132: 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 topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.

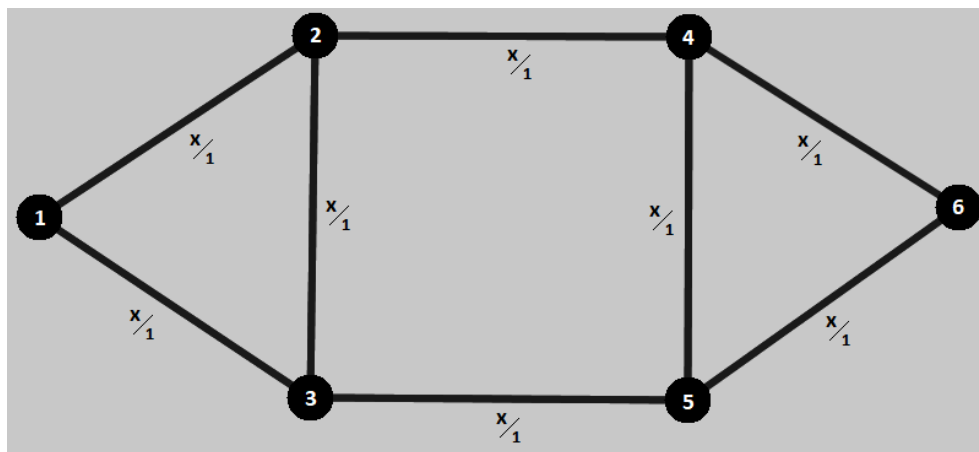


Figura 6.75: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 6.76: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 6.77: ODU0 logical topology defined by the ODU0 traffic matrix.

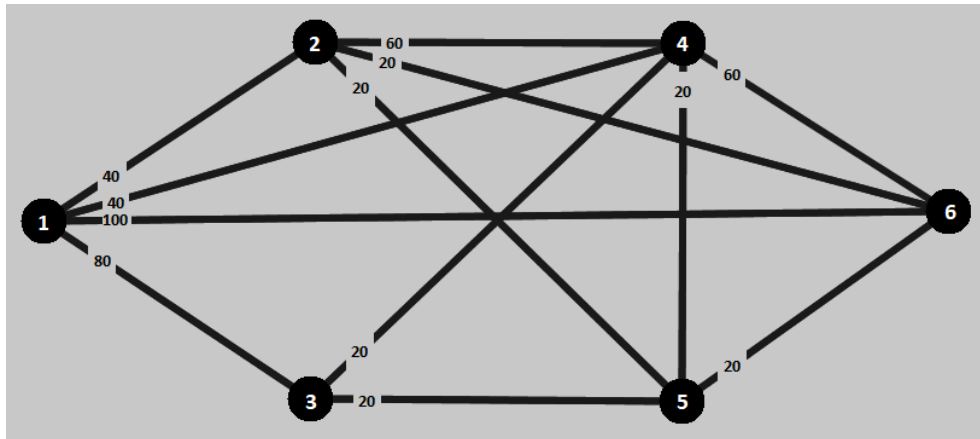


Figura 6.78: ODU1 logical topology defined by the ODU1 traffic matrix.

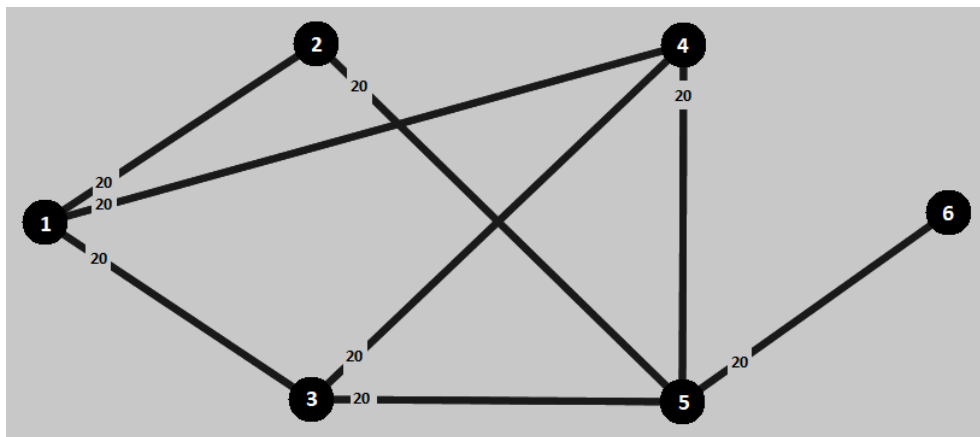


Figura 6.79: ODU2 logical topology defined by the ODU2 traffic matrix.

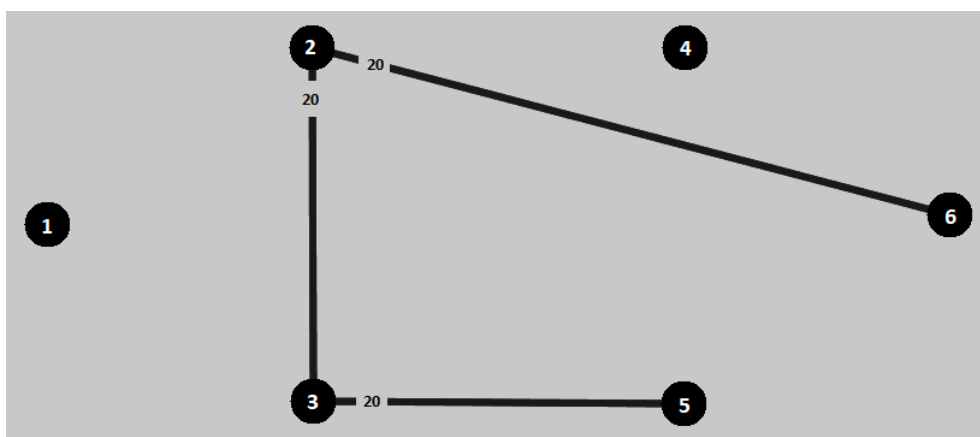


Figura 6.80: ODU3 logical topology defined by the ODU3 traffic matrix.

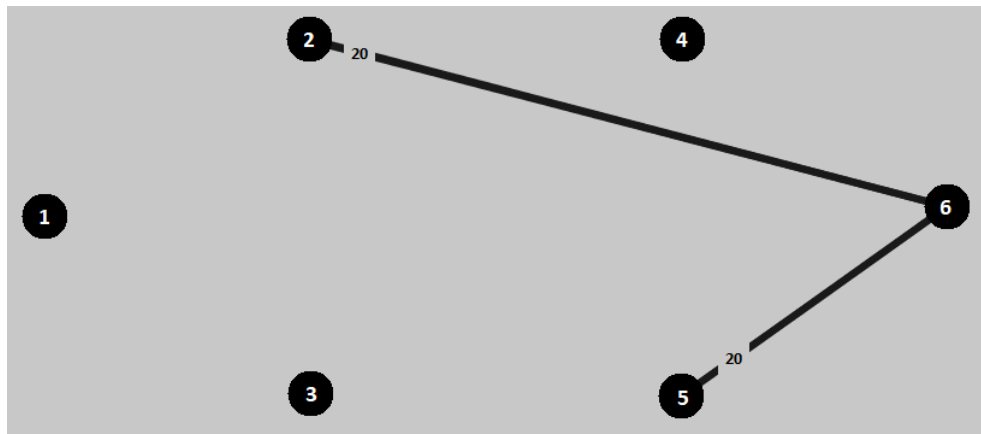


Figura 6.81: ODU4 logical topology defined by the ODU4 traffic matrix.

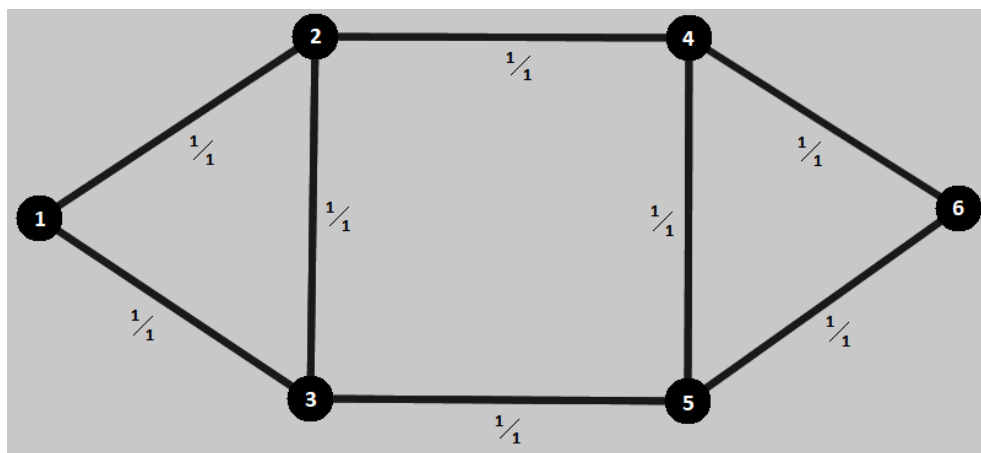


Figura 6.82: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 Pedro's heuristics can be consulted in the following table 6.133. In table 6.131 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 €	77 520 000 €
	100 Gbits/s Transceivers		154	5 000 €/Gbit/s	61 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	16 401 800 €
		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	154	100 000 €/port	15 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	154	2 500 €/port	385 000 €	
		Add Ports	154	2 500 €/port	385 000 €	
Total Network Cost						93 921 800 €

Tabela 6.133: 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 6.134 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	18	80	154
Number of Line ports	18	80	154
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	18	80	154
Link Cost	9 520 000 €	40 520 000 €	77 520 000 €
Node Cost	2 072 590 €	8 605 900 €	16 401 800 €
CAPEX	11 592 590 €	49 125 900 €	93 921 800 €
CAPEX/Gbit/s	23 185 €/Gbit/s	9 825 €/Gbit/s	9 392 €/Gbit/s

Tabela 6.134: 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. The difference between the low traffic and medium/high traffics is significantly high;

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 maximum optical reach value in optical channels.

It is assumed that the maximum optical reach value is 1000 km, so all direct links between node pairs with different index are created in all optical channels;

- Allow multiple transmission system.

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

6.8.6 Translucent with 1+1 Protection

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

The translucent networks in the translucent transport mode with 1+1 protection consist also of intermediate optical network architectures between opaque and transparent networks like this transport mode without survivability. In this, there will be created backup paths in order to prevent a network failure and loose all traffic data. The methodology is the same but in this case if, for any reason, there is a link or a path that do not work, then the traffic data can traverse to the same destination path in different links that were created for this purpose. These new created paths are longer than the primary ones and the network CAPEX will be significantly higher. The OEO conversions are also made when the optical signal falls and the maximum optical reach value is used to regenerate the same optical signal.

For cost savings, the translucent networks aims at using the minimum number of regenerators and wavelengths of the network, being the most advantageous transport mode in the optical backbone networks.

We also 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 minimization of the network CAPEX is made through the equation 5.1 where in this case for the cost of nodes we have in consideration the electric cost 5.4 and the optical cost 5.5.

In this case the value of $P_{exc,c,n}$ is obtained by equation 6.7 for short-reach and by the equation 6.8 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 6.9.

The 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

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

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

As previously mentioned, the 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 add ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^N \lambda_{nj} \quad (6.8)$$

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

The equation 6.9 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

$$P_{oxc,n} = \sum_{j=1}^N f_{nj}^{od} + \sum_{j=1}^N \lambda_{nj} \quad (6.9)$$

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.

To implement this heuristic approach there are used algorithms made in Java in a programming software called Eclipse and they are tested in an open-source network program called Net2Plan. In the Net2Plan guide section ?? there is an explanation on how to use and test them in this network planner.

In the next pages it will be described all the steps performed to obtain the final results in the translucent transport mode with 1+1 protection. In the figure below 6.83 it is shown a fluxogram with the description of this transport mode approach.

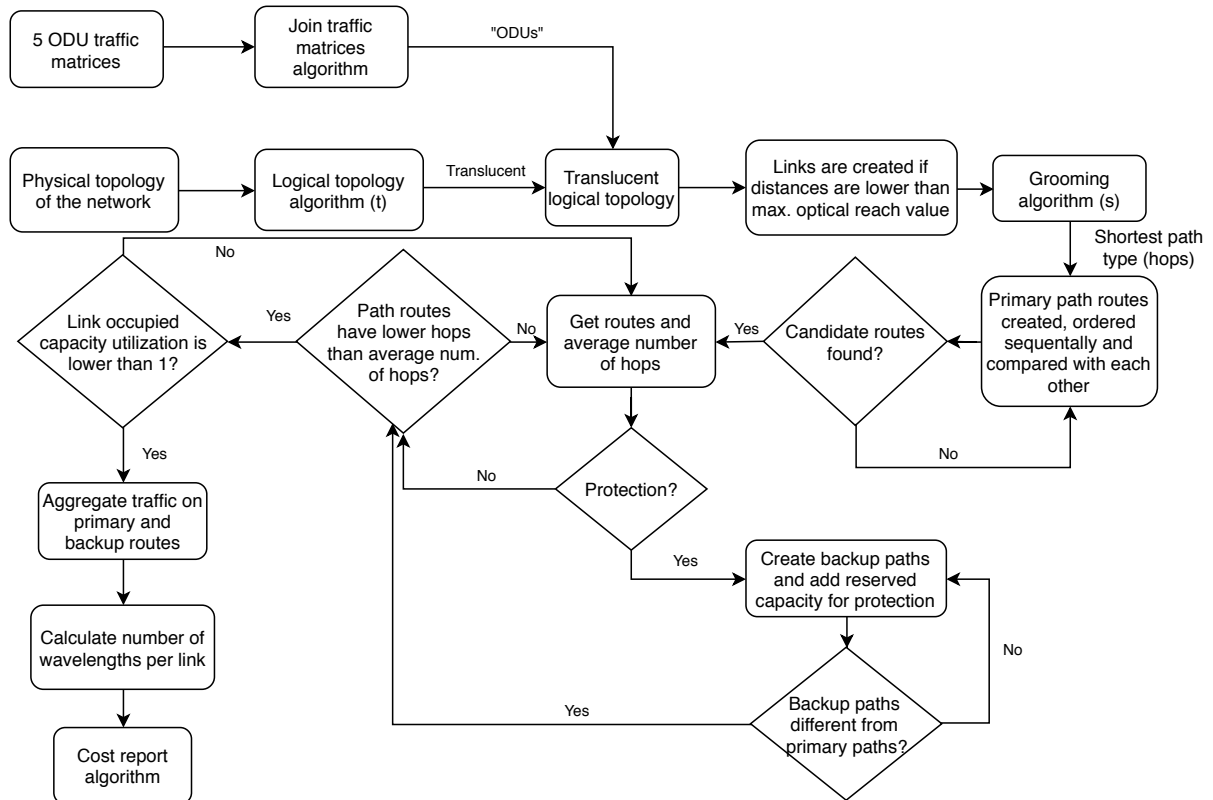


Figura 6.83: Fluxogram with the steps performed in the translucent with 1+1 protection transport mode approach.

Creation and join the traffic matrices

The first step is to create the traffic matrices based on the reference network 4.1. In order to create the 5 traffic matrices in Net2Plan it is necessary the length of all the links and the total traffic used in this network, so later it is needed to define in Net2Plan the length in all end nodes and the total traffic depends on the value of traffic used (low traffic - 0.5 Tbit/s, medium traffic - 5 Tbit/s and high traffic - 10 Tbit/s). As you can see in the figure below, it is defined the path of the 5 ODUs and they will be aggregated in just one single ODU, making it possible to join all the demands in just one file and load it later into the network. This final resulting ODU joins the multiple traffic demands from all the traffic matrices previously created and, of course, the traffic demands will depend on the values used on the creation of the matrices (low, medium and high traffic).

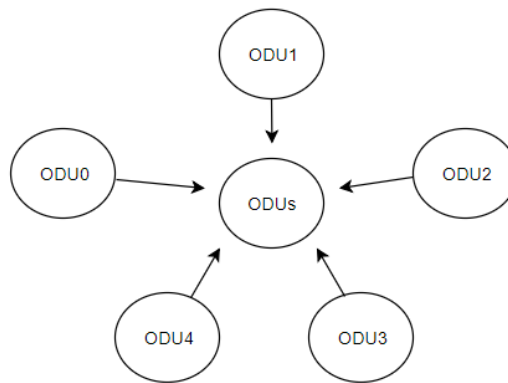


Figura 6.84: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.

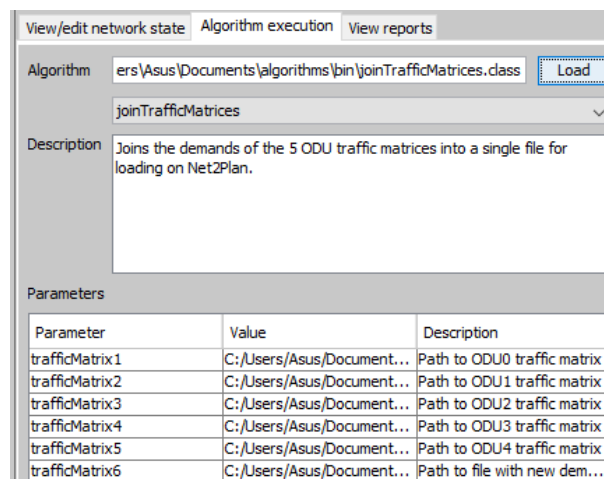


Figura 6.85: Load of the join traffic matrices algorithm for the translucent transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

The next step is to create the allowed physical topology of the network in Net2Plan. This network consists in 6 nodes and 8 bidirectional links. It is now also possible to define the length in all links. In the figure below it is shown the allowed physical topology in this transport mode.



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.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. In the translucent transport mode each node connects to other node if the shortest path distance between them is lower than the maximum optical reach value (in km) that an optical signal can traverse in an optical channel. If the maximum optical reach is higher than the shortest path of a link, then it is not created a logical link of that specific physical link. On the contrary, there are created direct links between all node pairs in the network that follow this rule. These additions of links between end 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 translucent transport mode. The allowed physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 6.8.6 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the translucent transport mode with 1+1 protection.

```

if (netPlan.isSingleLayer() && logicalTopology.equalsIgnoreCase("Translucent")) {

    int maximumOpticalReach = Integer.parseInt(algorithmParameters.get("maximumOpticalReach"));
    maxOpticalReach = maximumOpticalReach;

    sendToFile("opticalReach.txt");

    this.lowerLayer = netPlan.getNetworkLayerDefault();
    lowerLayer.setName("Physical Topology");
    this.upperLayer = netPlan.addLayer("Logical Topology Translucent", "Upper layer of the design", "ODU", "ODU", null);
    upperLayer.setDescription("Translucent Logical Topology" + " - Maximum Optical Reach= " + maximumOpticalReach + " km");
    netPlan.removeAllLinks(upperLayer);

    for (Node i : netPlan.getNodes()) {
        for (Node j : netPlan.getNodes()) {
            if (i.getIndex() != j.getIndex()) {
                if (netPlan.getNodePairEuclideanDistance(i, j) <= maximumOpticalReach) {
                    netPlan.addLink(i, j, 0, netPlan.getNodePairEuclideanDistance(i, j), 200000, null, upperLayer);
                }
            }
        }
    }
}

```

Figura 6.87: Java code of the logical topology approach for the translucent transport mode. The logical layer is created by adding direct links between all end nodes if their shortest path between them is lower than the maximum optical reach value. The new layer is now the translucent logical topology of the network.

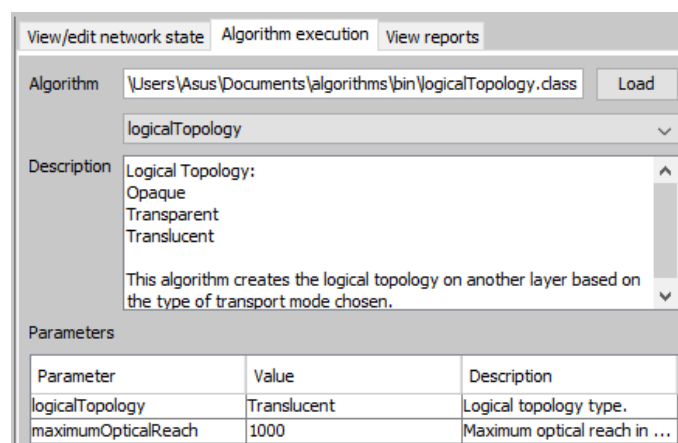


Figura 6.88: Load of the logical topology algorithm for the translucent transport mode on Net2Plan. It is assumed that the maximum optical reach value is 1000 km, so all direct links between node pairs with different index are created in all optical channels.

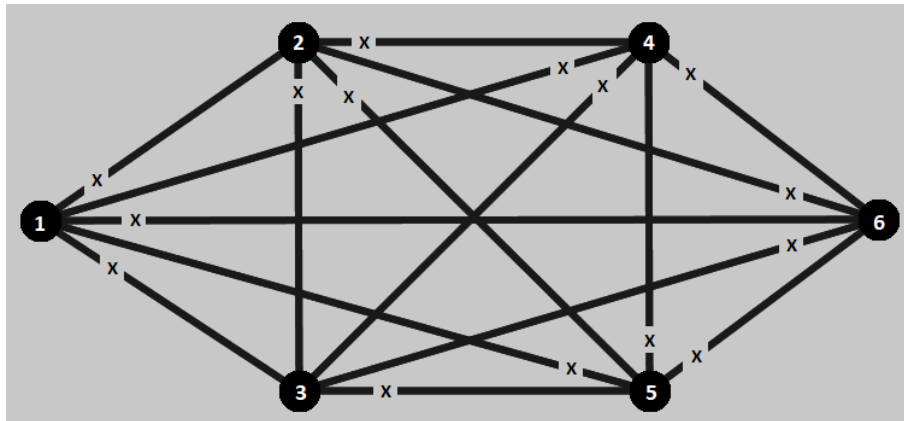


Figura 6.89: Allowed optical topology. It is assumed that each connections between demands supports up to 100 lightpaths. In the translucent transport mode there are several possible logical topologies for a specific network. It depends, for example, on the maximum optical reach value that represents the maximum distance that an optical signal can traverse a link without the need of regenerate.

Creation of routes and aggregation of traffic

After a network topology is created, it is now time to set the routing and then grooming algorithms. In the translucent with 1+1 protection transport mode the objective function is to minimize the lightpaths of the network and to find a route for every lightpath demand without considering the wavelength assignment. In this heuristic approach the goal is to minimize the lightpaths blocked and going through the carried lightpaths search for the ones that minimizes the average number of physical hops. Some of the links in the network will suffer from excessive traffic and some other links will occupy only a small part of the bandwidth. In order to do more efficiently, the link's utilizations are almost 1 so there is less non occupied capacity. Firstly, the candidate routes are found by the Dijkstra algorithm for each pair of nodes and calculates the minimum distance for each source and destination nodes and compares with each other. Then, the wavelength assignments are carried out for every lightpaths that have the minimum average of hops for each route and if the path distance is lower than the maximum optical reach value (in this report the maximum optical reach value used is 1000 km). The algorithm will compare the previous candidate routes that will be saved to a list with the new ones that will be created. If the new routes are different from the previously created ones, if they are the next shortest path routes and if they have the same restrictions as in the translucent without survivability transport mode, then the algorithm will add these routes to the network and they will be the protection segments (backup paths) of the network. The carried lightpaths resulted previously are sequentially processed and the offered traffic demands will be also set into these protection path routes. The routes are saved to a "Set" of routes and in each link of end nodes it is set the traffic demands into these routes that will integrate the whole network. 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.

```

case "Logical Topology Translucent":

    try {
        readFile();
    } catch (IOException e) {
        e.printStackTrace();
    }

    int hops = 0;
    Set<Route> nRoutes = new HashSet<Route>();

    for (Demand d : netPlan.getDemands(lowerLayer)) {

        nRoutes = d.getRoutes();
        for (Route c : nRoutes) {
            hops += c.getNumberOfHops();
        }
    }
    int n = hops/netPlan.getNumberOfRoutes(lowerLayer);

    for (Demand d : netPlan.getDemands(lowerLayer)) {
        boolean odd = true;
        int counter = 0;

        Set<Route> droutes = d.getRoutes();
        System.out.println(droutes.size());

        for (Route c : droutes) {
            counter++;
            boolean jump = false;

```

Figura 6.90: Creation of routes and aggregation of traffic for the translucent with 1+1 protection transport mode. The candidate routes are searched by the shortest path type method and the average minimum number of physical hops of the routes.

```

else {
    if (protection) {
        List<Link> workingpath = save.getSeqLinksRealPath();

        System.out.println("Protection-Translucent");
        for (Link t : workingpath) {
            if (c.getSeqLinksRealPath().contains(t)) {
                jump = true;
                break;
            }
        }

        if (jump == false) {
            if (c.getNumberOfHops() <= (n-1) && c.getLengthInKm() <= maxOpticalReach) {
                ProtectionSegment segment=netPlan.addProtectionSegment(c.getSeqLinksRealPath(),d.getOfferedTraffic(),null);
                save.addProtectionSegment(segment);
            }
            odd = true;
            break;
        }

        if (jump == true && counter == droutes.size()) {
            ProtectionSegment segment=netPlan.addProtectionSegment(c.getSeqLinksRealPath(),d.getOfferedTraffic(),null);
            save.addProtectionSegment(segment);
            odd = true;
            throw new Net2PlanException("Number of routes is not enough");
        }
    }
}

```

Figura 6.91: Creation of routes and aggregation of traffic for the translucent with 1+1 protection transport mode. The protection segments are added to all the primary paths that were chosen by the shortest path type method.

```

netPlan.removeAllRoutesUnused(1);

ArrayList<Long> tNodeIdsTransl = netPlan.getNodeIds();
Node inTransl;
Node outTransl;
Set<Route> groomRouteTransl;
Set<ProtectionSegment> protectRoutesTransl;
Route compareTransl = null;
Route compareTransl2 = null;
ProtectionSegment compare1Transl = null;
List<Link> pathTransl;
List<Link> pathTransl2;
int nWTransl = 0;

for (long tNodeId : tNodeIdsTransl) {
    inTransl = netPlan.getNodeFromId(tNodeId);
    for (long tNodeId1 : tNodeIdsTransl) {

        if (tNodeId == tNodeId1)
            continue;

        outTransl = netPlan.getNodeFromId(tNodeId1);
        double totaltraffic = 0;

        groomRouteTransl = netPlan.getNodePairRoutes(inTransl, outTransl, false, lowerLayer);
        protectRoutesTransl = netPlan.getNodePairProtectionSegments(inTransl, outTransl, false, lowerLayer);
    }
}

```

Figura 6.92: Creation of routes and aggregation of traffic for the translucent with 1+1 protection transport mode. The traffic demands are set into the candidate primary path routes found earlier and also compared with the backup path routes.


```

// Protection Segments
totaltraffic = 0;

for (ProtectionSegment protect : protectRoutesTransl) {
    if(protect.getCarriedTraffic() <= protect.getCapacity()){
        totaltraffic = totaltraffic + protect.getReservedCapacityForProtection();
        compare1Transl = protect;
    }
}

if (protection) {
    pathTransl = compare1Transl.getSeqLinks();
}

```

Figura 6.93: Creation of routes and aggregation of traffic for the translucent with 1+1 protection transport mode. Minimizing the blocked traffic, the traffic demands are also set into the protection path routes and the wavelength assignment is carried out.

Function	Definition
netPlan.getDemands(lowerLayer)	Returns the array of demands for the lower layer.
d.getRoutes()	Returns all the routes associated to the demand "d".
c.getNumberOfHops()	Returns the route number of traversed links.
c.getLengthInKm()	Returns the route length in km, summing the traversed link lengths, as many times as the link is traversed.
c.setCarriedTraffic()	Sets the route carried traffic and the occupied capacity in the links, setting it up to be the same in all links.
d.getOfferedTraffic()	Returns the offered traffic of the demand "d".
save.getSeqLinksRealPath()	Returns the links of routes ordered sequentially.
save.addProtectionSegment(segment)	Add "segment" as a protection path in the route "save".
netPlan.getNodeIds()	Returns the array of the nodes' indexes.
netPlan.getNodeFromId(tNodeId)	Returns the node with the index "tNodeId".
netPlan.getNodePairRoutes (in,out,false,lowerLayer)	Returns the routes at "lowerLayer" from nodes "in" and "out".
netPlan.getNodePairProtectionSegments (in,out,false,lowerLayer)	Returns the protection segments at "lowerLayer" from nodes "in" and "out".
c.getCarriedTraffic()	Returns the route carried traffic at that moment.
protect.getCapacity()	Returns the link capacity.

Tabela 6.135: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

The final step of the routing and grooming algorithms is to calculate the number of wavelengths per link for the whole network. This is the last and an important step because with the number of wavelengths per link in the network, it is possible to calculate other network components. In the translucent transport mode, as in the figure below shows, the algorithm starts with going through all the nodes which have different index between them (end nodes) and if the path distance between them is lower than the maximum optical reach value and in all the links that crosses between these pairs of nodes is reserved a link capacity based on the previous traffic aggregation on routes. The total carried traffic in the link including protection and non-protection segments will be divided by the wavelength capacity and it is now possible to obtain the number of wavelengths per link.

```
for (Link link : pathTransl) {
    String nw = link.getAttribute("nw");
    if (nw != null) {
        nwTransl = Integer.parseInt(nw);
        nwTransl = (int) (nwTransl + Math.ceil(totaltraffic / wavelengthCapacity));
        link.setAttribute("nw", String.valueOf(nwTransl));
    } else {
        nwTransl = (int) Math.ceil(totaltraffic / wavelengthCapacity);
        link.setAttribute("nw", String.valueOf(nwTransl));
    }
}
```

Figura 6.94: Calculation of the number of wavelengths per link for the translucent transport mode. The link capacity is reserved based on the previous traffic aggregation.

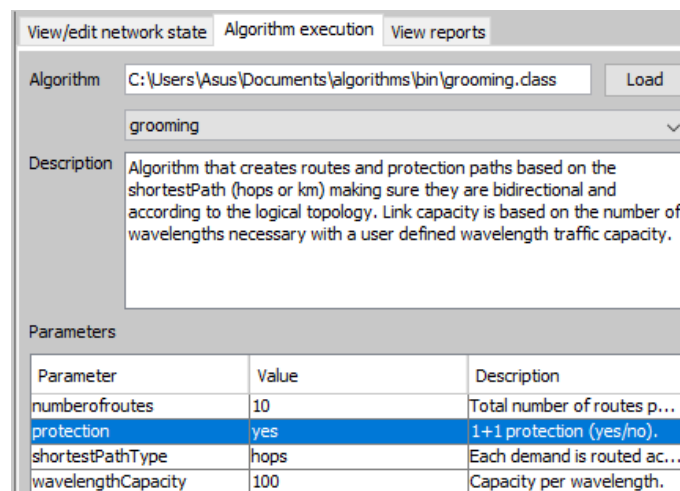


Figura 6.95: Load of the grooming algorithm for the translucent with 1+1 protection transport mode. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 6.8.6 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details.



Figura 6.96: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

It is already known all the necessary formulas to obtain the CAPEX value for the reference network 4.1. 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 Pedro's heuristics. 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 6.97: 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 6.98: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 6.99: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 6.100: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 6.101: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 6.102: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 6.103: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 6.104: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 Pedro's heuristics can be consulted in the following table 6.136. In table 6.131 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 €	2 142 590 €
		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	18	100 000 €/port	1 800 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	46	2 500 €/port	115 000 €	
		Add Ports	18	2 500 €/port	45 000 €	
Total Network Cost						25 662 590 €

Tabela 6.136: Table with detailed description of CAPEX.

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.

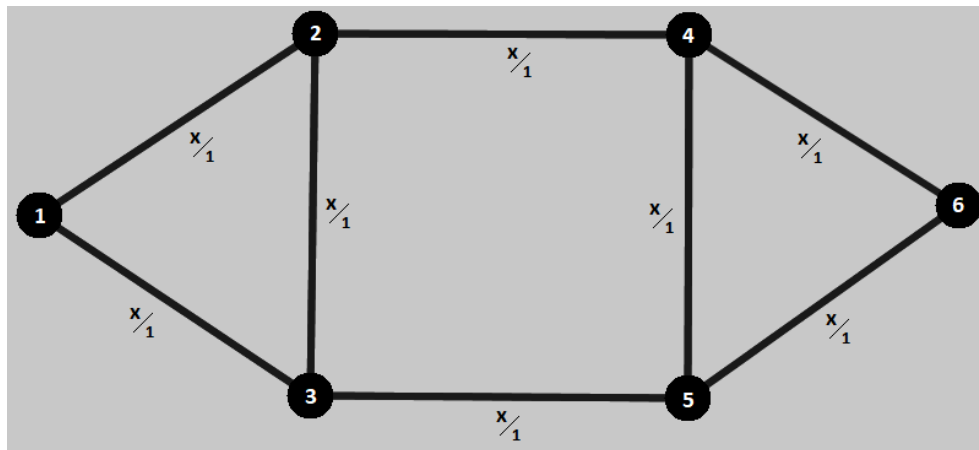


Figura 6.105: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 6.106: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

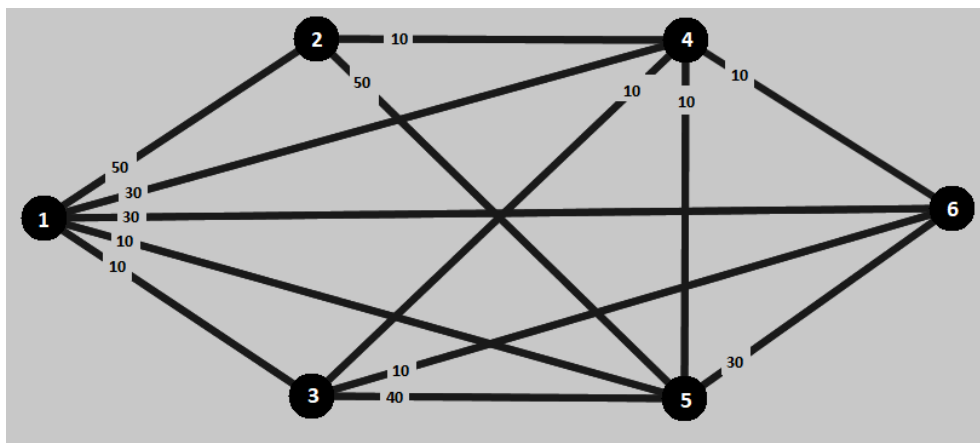


Figura 6.107: ODU0 logical topology defined by the ODU0 traffic matrix.

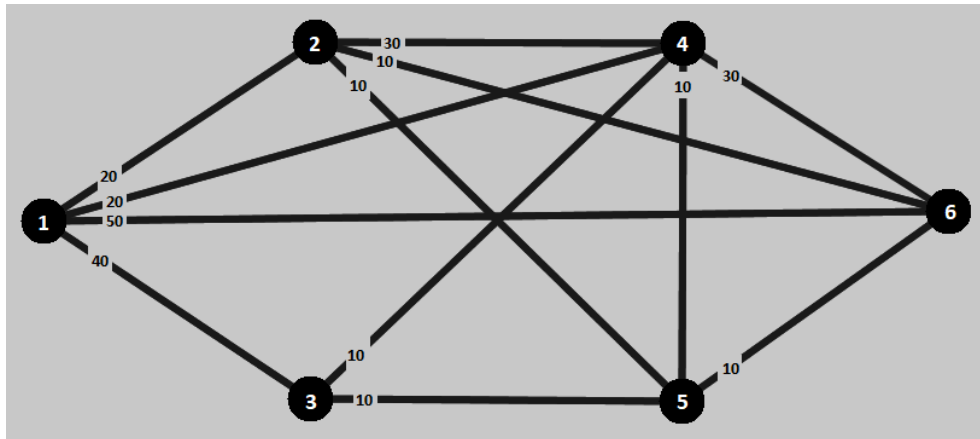


Figura 6.108: ODU1 logical topology defined by the ODU1 traffic matrix.

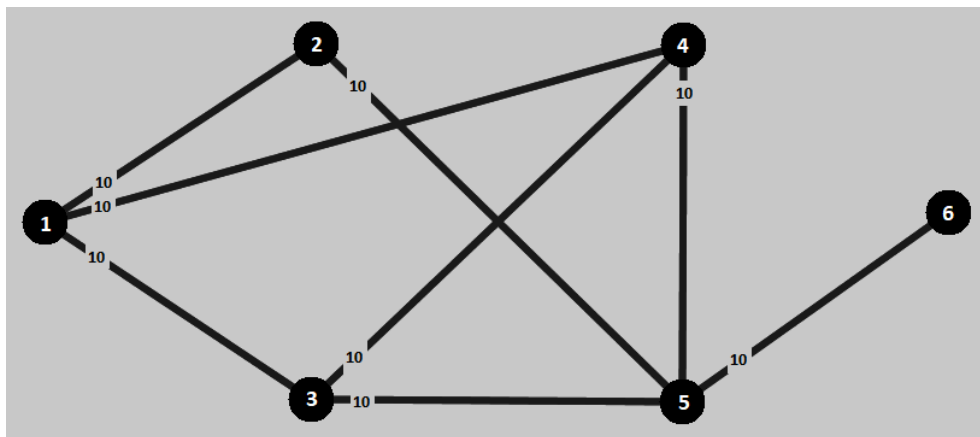


Figura 6.109: ODU2 logical topology defined by the ODU2 traffic matrix.

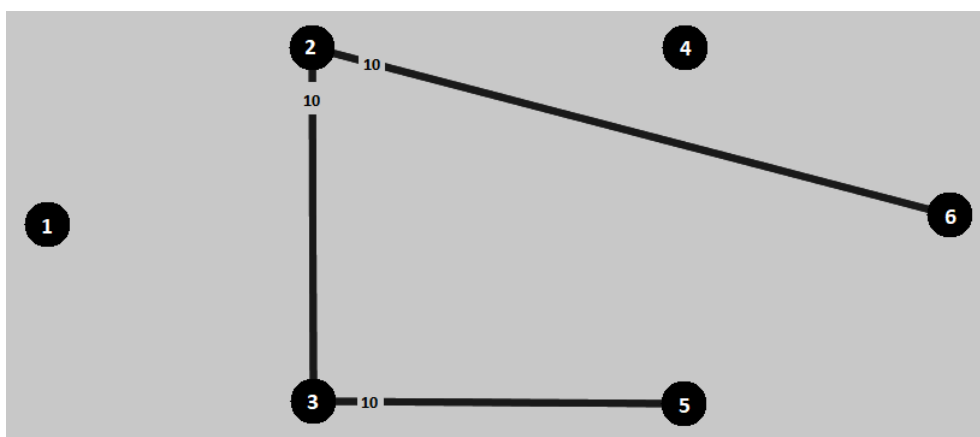


Figura 6.110: ODU3 logical topology defined by the ODU3 traffic matrix.

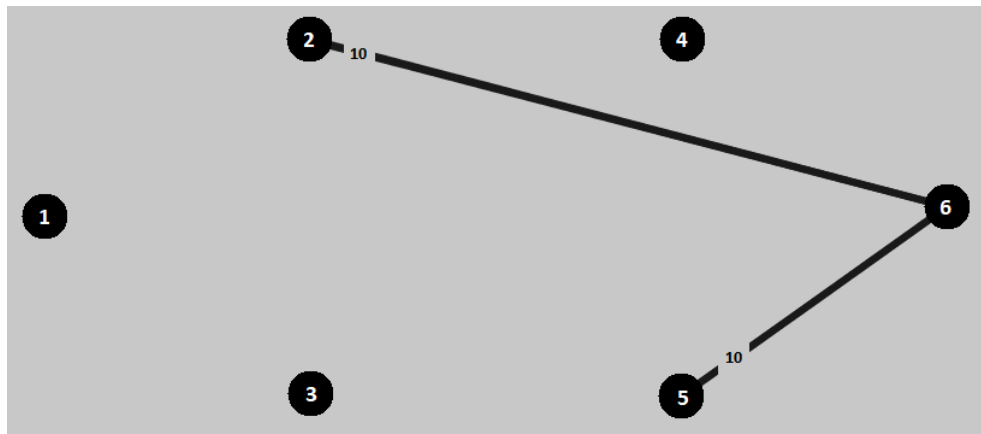


Figura 6.111: ODU4 logical topology defined by the ODU4 traffic matrix.

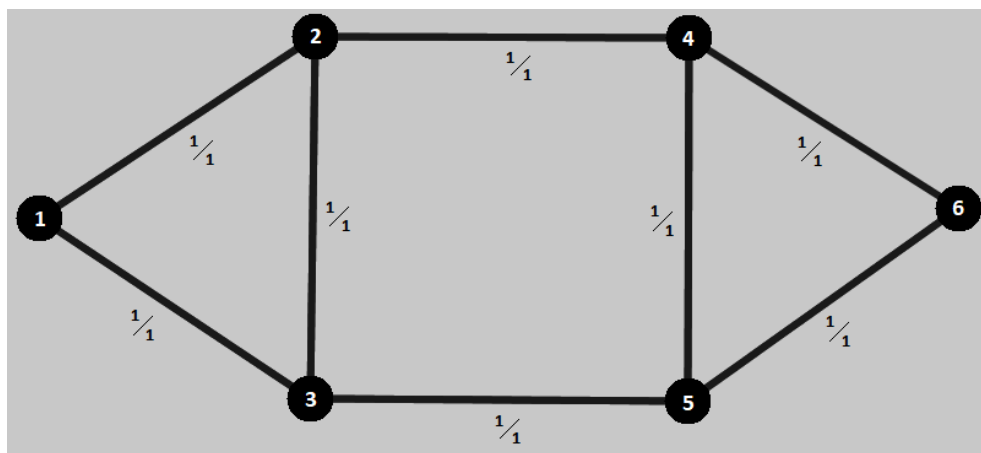


Figura 6.112: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 Pedro's heuristics can be consulted in the following table 6.137. In table 6.131 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 €	78 520 000 €
	100 Gbits/s Transceivers		156	5 000 €/Gbit/s	78 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	8 795 900 €
		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	80	100 000 €/port	8 000 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	156	2 500 €/port	390 000 €	
		Add Ports	80	2 500 €/port	200 000 €	
Total Network Cost						87 315 900 €

Tabela 6.137: 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 topologies, the second are the logical topology for all ODUs and finally the resulting physical topology.



Figura 6.113: 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 6.114: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

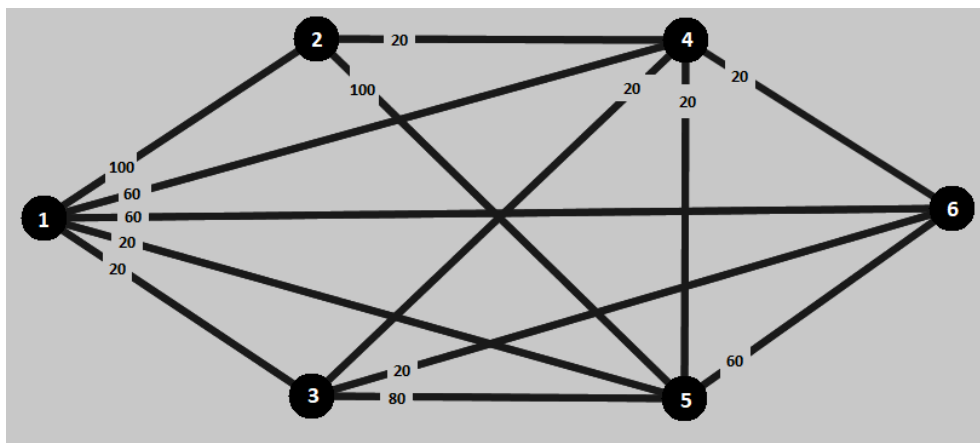


Figura 6.115: ODU0 logical topology defined by the ODU0 traffic matrix.

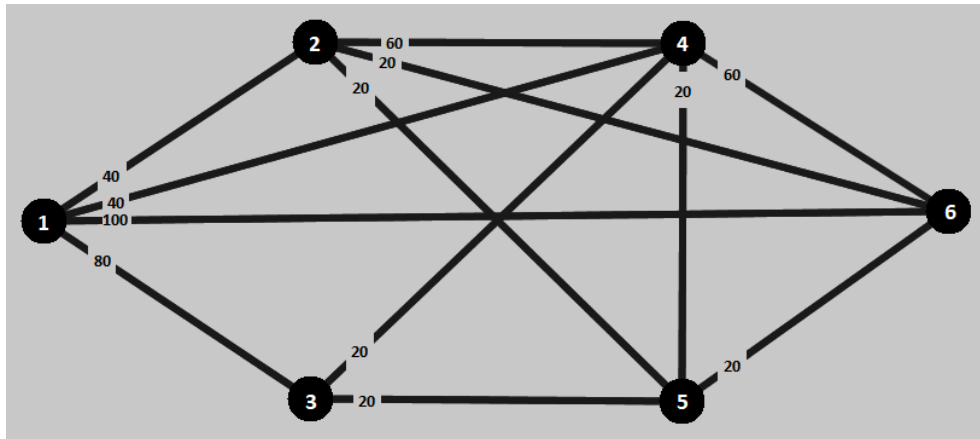


Figura 6.116: ODU1 logical topology defined by the ODU1 traffic matrix.

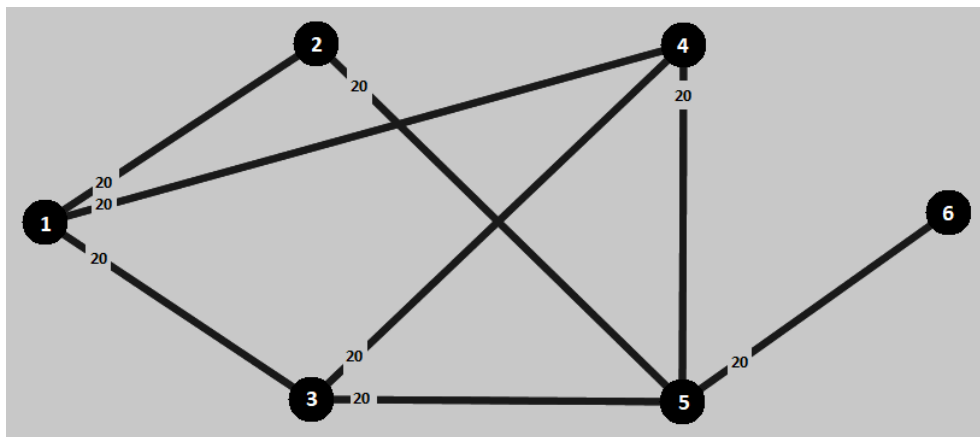


Figura 6.117: ODU2 logical topology defined by the ODU2 traffic matrix.

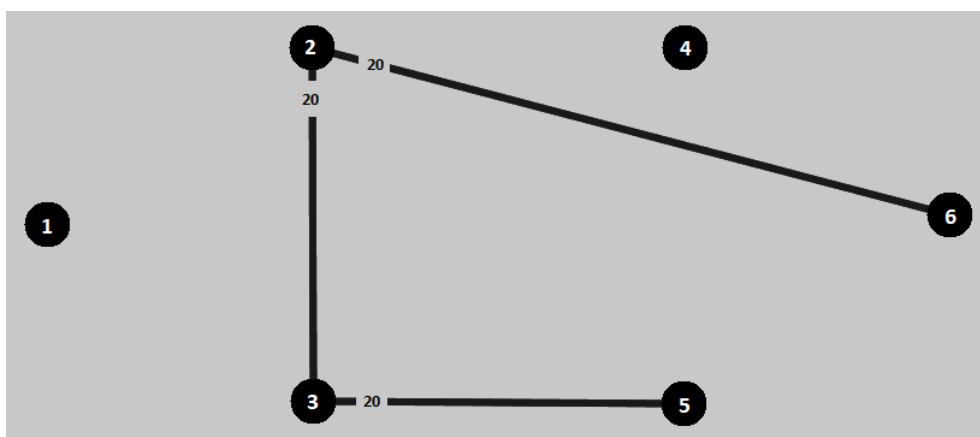


Figura 6.118: ODU3 logical topology defined by the ODU3 traffic matrix.

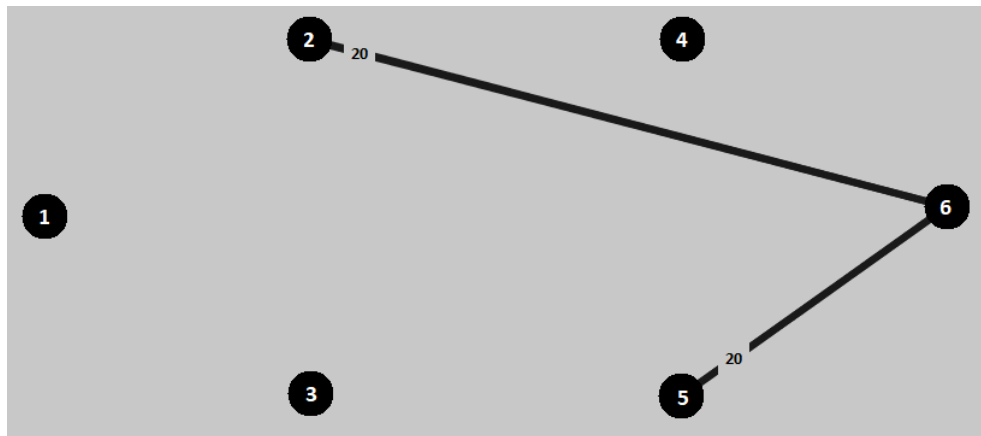


Figura 6.119: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 6.120: Physical topology after dimensioning.

Following all the steps mentioned in the ??, 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 Pedro's heuristics can be consulted in the following table 6.133. In table 6.131 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 €	147 520 000 €
	100 Gbits/s Transceivers		294	5 000 €/Gbit/s	147 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	16 751 800 €
		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	154	100 000 €/port	15 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	294	2 500 €/port	735 000 €	
		Add Ports	154	2 500 €/port	385 000 €	
Total Network Cost						164 271 800 €

Tabela 6.138: Table with detailed description of CAPEX.

Conclusions

Once we have obtained the results for all scenarios for the translucent without survivability and translucent 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 6.139 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	11 592 590 €	49 125 900 €	93 921 800 €
CAPEX/Gbit/s without survivability	23 185 €/Gbit/s	9 825 €/Gbit/s	9 392 €/Gbit/s
Traffic (Gbit/s)	500	5 000	10 000
Bidirectional Links used	8	8	8
Number of Add ports	18	80	154
Number of Line ports	46	156	294
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	46	156	294
Link Cost	23 520 000 €	78 520 000 €	147 520 000 €
Node Cost	2 142 590 €	8 795 900 €	16 751 800 €
CAPEX	25 662 590 €	87 315 900 €	164 271 800 €
CAPEX/Gbit/s	51 325 €/Gbit/s	17 463 €/Gbit/s	16 427 €/Gbit/s

Tabela 6.139: Table with different value of CAPEX for this case.

Looking at the previous table we can make some comparisons between the translucent 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. The difference between the low traffic and medium/high traffics is significantly high;

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 translucent without survivability and translucent with 1+1 protection scenarios:

- We can see that in the translucent with 1+1 protection transport mode the CAPEX cost for all the three traffic is more than the double;

This happens because in the translucent with 1+1 protection transport mode 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 maximum optical reach value in optical channels.

It is assumed that the maximum optical reach value is 1000 km, so all direct links between node pairs with different index are created in all optical channels;

- Allow multiple transmission system.

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

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 CAPEX cost in monetary units, C_C is given by the equation 7.1

$$C_C = C_L + C_N \quad (7.1)$$

where C_L is the Link cost and C_N is the Node cost.

For this calculation first let's focus on the cost of the links. Where to calculate the cost of the Links, C_L , we will use the equation 7.2

$$C_L = (2L\gamma_0^{OLT}) + (2L\gamma_1^{OLT}\tau < w >) + (2N^R c^R) \quad (7.2)$$

where

- $\gamma_0^{OLT} \rightarrow$ OLT cost in euros
- $L \rightarrow$ Number of bidirectional links
- $\gamma_1^{OLT} \rightarrow$ Transponder cost in euros
- $< w > \rightarrow$ Average number of optical channels
- $\tau \rightarrow$ Traffic per port
- $N^R \rightarrow$ Total number of optical amplifiers
- $c^R \rightarrow$ Unidirectional 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 average number of optical channels.

Through the equation 7.3 we can calculate the number of optical amplifiers, N^R , as

$$N^R = \sum_{l=1}^L \left(\left\lceil \frac{len_l}{span} \right\rceil - 1 \right) \quad (7.3)$$

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

Through the equation 7.4 we can calculate the average number of optical channels, $\langle w \rangle$, as

$$\langle w \rangle = \left(\frac{[D \times \langle h \rangle]}{L} \right) (1 + \langle k \rangle) \quad (7.4)$$

where D is the number of unidirectional demands, L is the number of unidirectional Links and $\langle k \rangle$ is the survivability coefficient.

The number of unidirectional demands can be calculated as

$$D = \left(\frac{1}{2} \right) (1 + \xi) \left(\frac{T_1}{\tau} \right) \quad (7.5)$$

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

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, C_N , is given by the sum of these two parts thus obtaining the equation 7.6

$$C_N = C_{EXC} + C_{OXC} \quad (7.6)$$

To know the electric cost, C_{exc} , of the nodes that is given by equation 7.7

$$C_{exc} = N \times (\gamma_{e0} + (\gamma_{e1} \tau \langle P_{exc} \rangle)) + \gamma_{e1} P_{TRIB} \quad (7.7)$$

where:

- $N \rightarrow$ Number of nodes
- $\gamma_{e0} \rightarrow$ EXC cost in euros
- $\gamma_{e1} \rightarrow$ EXC port cost in euros
- $\tau \rightarrow$ Traffic per port
- $\langle P_{exc} \rangle \rightarrow$ Average number of ports of the electrical switch

- P_{TRIB} → Total number of tributary ports

In relation to the optical part, C_{exc} , to know the optical cost of the nodes that is given by equation 7.8

$$C_{exc} = N \times (\gamma_{o0} + (\gamma_{o1} < P_{exc} >)) \quad (7.8)$$

where:

- N → Number of nodes
- γ_{o0} → OXC cost in euros
- γ_{o1} → OXC port cost in euros
- $< P_{exc} >$ → Average number of ports of the optical switch

We have to take into account that the calculated value for the variables $< P_{exc} >$ and $< P_{exc} >$ will depend on the mode of transport used (opaque, transparent or translucent) and the variable P_{TRIB} will depend on the scenario 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	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 Line Ports	γ_{e1}	100 000 €/port
EXC Tributary Ports	γ_{e2}	20 €/port
OXC Port	γ_{o1}	2 500 €/port

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:

- $C_{oxc} = 0$
- $\xi = 1$
- $\langle k \rangle = 0$

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 grooming 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 two variables. The tributary ports, P_{TRIB} , can be calculated through the ODU's matrices referred to in section 4.2 and the average number of ports the electrical switch, $\langle P_{exc} \rangle$, that can be calculated as

$$\langle P_{exc} \rangle = \langle d \rangle \langle h \rangle (1 + \langle k \rangle) \quad (7.9)$$

where $\langle d \rangle$ is the average number of demands, $\langle h \rangle$ is the average number of hops and $\langle k \rangle$ is the survivability coefficient. The number of ports of the electrical switch, in this case, is equal to the number of line ports since we already know the number of tributary ports.

The variable $\langle d \rangle$ is calculated through the equation 7.10

$$\langle d \rangle = \frac{D}{N} \quad (7.10)$$

Result description

We already have all the necessary formulas to obtain the CAPEX value for the reference network 4.1. 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:

$$D = \frac{1}{2} * (1 + 1) * \left(\frac{1000}{100}\right) \quad D = 10$$

Replacing in equation 7.4:

$$\langle w \rangle = \left(\frac{10 * 1.533}{16}\right) * (1 + 0) \quad \langle w \rangle = 1$$

Using equation 7.3:

$$N^R = \left(\frac{460}{100} - 1\right) + \left(\frac{640}{100} - 1\right) + \left(\frac{75}{100} - 1\right) + \left(\frac{684}{100} - 1\right) + \left(\frac{890}{100} - 1\right) + \left(\frac{103}{100} - 1\right) + \left(\frac{761}{100} - 1\right) + \left(\frac{361}{100} - 1\right)$$

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 1) + (2 * 35 * 4\,000)$$

$$C_L = 8\,520\,000 \text{ €}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$\langle d \rangle = \frac{10}{6} \quad \langle d \rangle = 1.6667$$

Replacing in equation 7.9:

$$\langle P_{exc} \rangle = 1.6667 * 1.533 * (1 + 0) \quad \langle P_{exc} \rangle = 2.5550$$

Finally, replacing all in equation 7.7 the Node Cost is:

$$C_N = C_{exc} = 6 * (10\,000 + (1\,000 * 100 * 2.5550)) + (20 * 136)$$

$$C_N = 1\,595\,720 \text{ €}$$

The CAPEX is:

$$CAPEX = 8\,520\,000 + 1\,595\,720$$

$$CAPEX = 10\,115\,720 \text{ €}$$

Medium Traffic Scenario

In this scenario we have to take into account the traffic calculated in 4.2.2.

Using equation 7.5:

$$D = \frac{1}{2} * (1 + 1) * \left(\frac{10000}{100} \right) \quad D = 100$$

replacing in equation 7.4:

$$\langle w \rangle = \left(\frac{100 * 1.533}{16} \right) * (1 + 0) \quad \langle w \rangle = 9.625$$

Using equation 7.3:

$$N^R = \left(\frac{460}{100} - 1 \right) + \left(\frac{640}{100} - 1 \right) + \left(\frac{75}{100} - 1 \right) + \left(\frac{684}{100} - 1 \right) + \left(\frac{890}{100} - 1 \right) + \left(\frac{103}{100} - 1 \right) + \left(\frac{761}{100} - 1 \right) + \left(\frac{361}{100} - 1 \right)$$

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 9.625) + (2 * 35 * 4\,000)$$

$$C_L = 77\,520\,000 \text{ €}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$\langle d \rangle = \frac{100}{6} \quad \langle d \rangle = 16.6667$$

Replacing in equation 7.9:

$$\langle P_{exc} \rangle = 16.6667 * 1.533 * (1 + 0) \quad \langle P_{exc} \rangle = 25.5501$$

Finally, replacing all in equation 7.7 the Node Cost is:

$$C_N = C_{exc} = 6 * (10\,000 + (1\,000 * 100 * 25.5501)) + (20 * 1\,360)$$

$$C_N = 15\,417\,260 \text{ €}$$

The CAPEX is:

$$CAPEX = 77\,520\,000 + 15\,417\,260$$

$$CAPEX = 92\,937\,260 \text{ €}$$

High Traffic Scenario

In this scenario we have to take into account the traffic calculated in 4.2.3.

Using equation 7.5:

$$D = \frac{1}{2} * (1 + 1) * \left(\frac{20000}{100} \right) \quad D = 200$$

replacing in equation 7.4:

$$\langle w \rangle = \left(\frac{200 * 1.533}{16} \right) * (1 + 0) \quad \langle w \rangle = 19.1875$$

Using equation 7.3:

$$N^R = \left(\frac{460}{100} - 1 \right) + \left(\frac{640}{100} - 1 \right) + \left(\frac{75}{100} - 1 \right) + \left(\frac{684}{100} - 1 \right) + \left(\frac{890}{100} - 1 \right) + \left(\frac{103}{100} - 1 \right) + \left(\frac{761}{100} - 1 \right) + \left(\frac{361}{100} - 1 \right)$$

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 19.1875) + (2 * 35 * 4\,000)$$

$$C_L = 154\,020\,000 \text{ €}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$\langle d \rangle = \frac{200}{6} \quad \langle d \rangle = 33.3333$$

Replacing in equation 7.9:

$$\langle P_{exc} \rangle = 33.3333 * 1.533 * (1 + 0) \quad \langle P_{exc} \rangle = 51.0999$$

Finally, replacing all in equation 7.7 the Node Cost is:

$$C_N = C_{exc} = 6 * (10\,000 + (1\,000 * 100 * 51.0999)) + (20 * 2\,720)$$

$$C_N = 30\,774\,340 \text{ €}$$

The CAPEX is:

$$CAPEX = 154\,020\,000 + 30\,774\,340$$

$$CAPEX = 184\,794\,340 \text{ €}$$

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:

- $C_{oxc} = 0$
- $\xi = 1$
- $\langle k \rangle = \langle kp \rangle$

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 grooming coefficient has value 1 and finally in the last particularity we are assuming that the survivability coefficient is $\langle kp \rangle$ because it is with 1+1 protection where

$$\langle kp \rangle = \frac{\langle h' \rangle}{\langle h \rangle} = \frac{2.467}{1.533} = 1.609 \quad (7.11)$$

Finally looking at the equation 7.7 we can see that we already have practically all the values with the exception of two variables. The tributary ports, P_{TRIB} , can be calculated through the ODU's matrices referred to in section 4.2 and the average number of ports the electrical switch, $\langle P_{exc} \rangle$, that can be calculated as

$$\langle P_{exc} \rangle = \langle d \rangle \langle h \rangle (1 + \langle k \rangle) \quad (7.12)$$

where $\langle d \rangle$ is the average number of demands, $\langle h \rangle$ is the average number of hops and $\langle k \rangle$ is the survivability coefficient. The number of ports of the electrical switch, in this case, is equal to the number of line ports since we already know the number of tributary ports.

Result description

We already have all the necessary formulas to obtain the CAPEX value for the reference network 4.1. 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:

$$D = \frac{1}{2} * (1 + 1) * \left(\frac{1000}{100} \right) \quad D = 10$$

Replacing in equation 7.4:

$$\langle w \rangle = \left(\frac{10 * 1.533}{16} \right) * (1 + 1.609) \quad \langle w \rangle = 2.609$$

Using equation 7.3:

$$N^R = \left(\frac{460}{100} - 1 \right) + \left(\frac{640}{100} - 1 \right) + \left(\frac{75}{100} - 1 \right) + \left(\frac{684}{100} - 1 \right) + \left(\frac{890}{100} - 1 \right) + \left(\frac{103}{100} - 1 \right) + \left(\frac{761}{100} - 1 \right) + \left(\frac{361}{100} - 1 \right)$$

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 2.609) + (2 * 35 * 4\,000)$$

$$C_L = 21\,392\,000 \text{ €}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$\langle d \rangle = \frac{10}{6} \quad \langle d \rangle = 1.6667$$

Replacing in equation 7.12:

$$\langle P_{exc} \rangle = 1.6667 * 1.533 * (1 + 1.609) \quad \langle P_{exc} \rangle = 6.6661$$

Finally, replacing all in equation 7.7 the Node Cost is:

$$C_N = C_{exc} = 6 * (10\,000 + (1\,000 * 100 * 6.6661)) + (20 * 136)$$

$$C_N = 4\,062\,380 \text{ €}$$

The CAPEX is:

$$CAPEX = 21\,392\,000 + 4\,062\,380$$

$$CAPEX = 25\,454\,380 \text{ €}$$

Medium Traffic Scenario

In this scenario we have to take into account the traffic calculated in 4.2.2.

Using equation 7.5:

$$D = \frac{1}{2} * (1 + 1) * \left(\frac{10000}{100} \right) \quad D = 100$$

Replacing in equation 7.4:

$$\langle w \rangle = \left(\frac{100 * 1.533}{16} \right) * (1 + 1.609) \quad \langle w \rangle = 25.11$$

Using equation 7.3:

$$N^R = \left(\frac{460}{100} - 1 \right) + \left(\frac{640}{100} - 1 \right) + \left(\frac{75}{100} - 1 \right) + \left(\frac{684}{100} - 1 \right) + \left(\frac{890}{100} - 1 \right) + \left(\frac{103}{100} - 1 \right) + \left(\frac{761}{100} - 1 \right) + \left(\frac{361}{100} - 1 \right)$$

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 25.11) + (2 * 35 * 4\,000)$$

$$C_L = 201\,400\,000 \text{ €}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$\langle d \rangle = \frac{100}{6} \quad \langle d \rangle = 16.6667$$

Replacing in equation 7.12:

$$\langle P_{exc} \rangle = 16.6667 * 1.533 * (1 + 1.609) \quad \langle P_{exc} \rangle = 66.6601$$

Finally, replacing all in equation 7.7 the Node Cost is:

$$C_N = C_{exc} = 6 * (10\,000 + (1\,000 * 100 * 66.6601)) + (20 * 1\,360)$$

$$C_N = 40\,083\,260 \text{ €}$$

The CAPEX is:

$$CAPEX = 201\,400\,000 + 40\,083\,260$$

$$CAPEX = 241\,483\,260 \text{ €}$$

High Traffic Scenario

In this scenario we have to take into account the traffic calculated in 4.2.3.

Using equation 7.5:

$$D = \frac{1}{2} * (1 + 1) * \left(\frac{20000}{100} \right) \quad D = 200$$

Replacing in equation 7.4:

$$\langle w \rangle = \left(\frac{200 * 1.533}{16} \right) * (1 + 1.609) \quad \langle w \rangle = 50.060$$

Using equation 7.3:

$$N^R = \left(\frac{460}{100} - 1 \right) + \left(\frac{640}{100} - 1 \right) + \left(\frac{75}{100} - 1 \right) + \left(\frac{684}{100} - 1 \right) + \left(\frac{890}{100} - 1 \right) + \left(\frac{103}{100} - 1 \right) + \left(\frac{761}{100} - 1 \right) + \left(\frac{361}{100} - 1 \right)$$

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 50.060) + (2 * 35 * 4\,000)$$

$$C_L = 401\,001\,500 \text{ €}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$\langle d \rangle = \frac{200}{6} \quad \langle d \rangle = 33.3333$$

Replacing in equation 7.12:

$$\langle P_{exc} \rangle = 33.3333 * 1.533 * (1 + 1.609) \quad \langle P_{exc} \rangle = 133.3198$$

Finally, replacing all in equation 7.7 the Node Cost is:

$$C_N = C_{exc} = 6 * (10\,000 + (1\,000 * 100 * 133.3198)) + (20 * 2\,720)$$

$$C_N = 80\,106\,280 \text{ €}$$

The CAPEX is:

$$CAPEX = 401\,001\,500 + 80\,106\,280$$

$$CAPEX = 481\,107\,780 \text{ €}$$

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:

- $\xi = 1.25$
- $\langle k \rangle = 0$

The first particularity exists because we are assuming that the grooming coefficient has value 1.25 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 three variables. The tributary ports, P_{TRIB} , can be calculated through the ODU's matrices referred to in section 4.2, the average number of ports the electrical switch, $\langle P_{exc} \rangle$, that can be calculated as

$$\langle P_{exc} \rangle = \langle d \rangle \quad (7.13)$$

and the average number of ports the optical switch, $\langle P_{oxc} \rangle$, can be calculated as

$$\langle P_{oxc} \rangle = \langle d \rangle [1 + (1 + \langle k \rangle) \langle h \rangle] \quad (7.14)$$

where $\langle d \rangle$ is the average number of demands, $\langle k \rangle$ is the survivability coefficient and $\langle h \rangle$ is the average number of hops. The number of ports of the electrical switch, in this case, is equal to the number of add ports since we already know the number of tributary ports. The number of ports of the optical switch, in this case, is equal to the sum of the line ports with the add ports.

Result description

We already have all the necessary formulas to obtain the CAPEX value for the reference network 4.1. 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:

$$D = \frac{1}{2} * (1 + 1.25) * \left(\frac{1000}{100}\right) \quad D = 11.25$$

Replacing in equation 7.4:

$$\langle w \rangle = \left(\frac{11.25 * 1.533}{16}\right) * (1 + 0) \quad \langle w \rangle = 1.125$$

Using equation 7.3:

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 1.125) + (2 * 35 * 4\,000)$$

$$C_L = 9\,520\,000 \text{ €}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$\langle d \rangle = \frac{11.25}{6} \quad \langle d \rangle = 1.875$$

Replacing in equation 7.13 and 7.14:

$$\langle P_{exc} \rangle = 1.875$$

$$\langle P_{oxc} \rangle = 1.875 * [1 + (1 + 0) * 1.533] \quad \langle P_{oxc} \rangle = 4.7494$$

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

$$C_N = (6 * (10000 + (1000 * 100 * 1.875))) + (20 * 136) + (6 * (20000 + (2500 * 4.7494)))$$

$$C_N = 1\,187\,720 + 120\,072 = 1\,307\,792 \text{ €}$$

The CAPEX is:

$$CAPEX = 9\,520\,000 + 1\,307\,792$$

$$CAPEX = 10\,827\,792 \text{ €}$$

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.2.

Using equation 7.5:

$$D = \frac{1}{2} * (1 + 1.25) * \left(\frac{10000}{100} \right) \quad D = 112.5$$

Replacing in equation 7.4:

$$\langle w \rangle = \left(\frac{112.5 * 1.533}{16} \right) * (1 + 0) \quad \langle w \rangle = 10.8125$$

Using equation 7.3:

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 10.8125) + (2 * 35 * 4\,000)$$

$$C_L = 87\,020\,000 \text{ €}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$\langle d \rangle = \frac{112.5}{6} \quad \langle d \rangle = 18.75$$

Replacing in equation 7.13 and 7.14:

$$\langle P_{exc} \rangle = 18.75$$

$$\langle P_{oxc} \rangle = 18.75 * [1 + (1 + 0) * 1.533] \quad \langle P_{oxc} \rangle = 47.4938$$

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

$$C_N = (6 * (10000 + (1000 * 100 * 18.75))) + (20 * 1360) + (6 * (20000 + (2500 * 47.4938)))$$

$$C_N = 11\,337\,200 + 832\,407 = 12\,169\,607 \text{ €}$$

The CAPEX is:

$$CAPEX = 87\,020\,000 + 12\,169\,607$$

$$CAPEX = 99\,189\,607 \text{ €}$$

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.3.

Using equation 7.5:

$$D = \frac{1}{2} * (1 + 1.25) * \left(\frac{20000}{100} \right) \quad D = 225$$

Replacing in equation 7.4:

$$\langle w \rangle = \left(\frac{225 * 1.533}{16} \right) * (1 + 0) \quad \langle w \rangle = 21.5625$$

Using equation 7.3:

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 21.5625) + (2 * 35 * 4\,000)$$

$$C_L = 173\,020\,000 \text{ €}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$\langle d \rangle = \frac{225}{6} \quad \langle d \rangle = 37.5$$

Replacing in equation 7.13 and 7.14:

$$\langle P_{exc} \rangle = 37.5$$

$$\langle P_{oxc} \rangle = 37.5 * [1 + (1 + 0) * 1.533] \quad \langle P_{oxc} \rangle = 94.9875$$

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

$$C_N = (6 * (10000 + (1000 * 100 * 37.5))) + (20 * 2720) + (6 * (20000 + (2500 * 94.9875)))$$

$$C_N = 22\,614\,400 + 1\,544\,813 = 24\,159\,213 \text{ €}$$

The CAPEX is:

$$CAPEX = 173\,020\,000 + 24\,159\,213$$

$$CAPEX = 197\,179\,213 \text{ €}$$

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:

- $\xi = 1.25$
- $\langle k \rangle = \langle kp \rangle$

The first particularity exists because we are assuming that the grooming coefficient has value 1.25 and finally in the last particularity we are assuming that the survivability coefficient is $\langle kp \rangle$ 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 three variables. The tributary ports, P_{TRIB} , can be calculated through the ODU's matrices referred to in section 4.2, the average number of ports the electrical switch, $\langle P_{exc} \rangle$, that can be calculated as

$$\langle P_{exc} \rangle = \langle d \rangle \quad (7.15)$$

and the average number of ports the optical switch, $\langle P_{oxc} \rangle$, can be calculated as

$$\langle P_{oxc} \rangle = \langle d \rangle [1 + (1 + \langle k \rangle) \langle h \rangle] \quad (7.16)$$

where $\langle d \rangle$ is the average number of demands, $\langle k \rangle$ is the survivability coefficient and $\langle h \rangle$ is the average number of hops. The number of ports of the electrical switch, in this case, is equal to the number of add ports since we already know the number of tributary ports. The number of ports of the optical switch, in this case, is equal to the sum of the line ports with the add ports.

Result description

We already have all the necessary formulas to obtain the CAPEX value for the reference network 4.1. 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:

$$D = \frac{1}{2} * (1 + 1.25) * \left(\frac{1000}{100}\right) \quad D = 11.25$$

Replacing in equation 7.4:

$$\langle w \rangle = \left(\frac{11.25 * 1.533}{16}\right) * (1 + 1.609) \quad \langle w \rangle = 2.9351$$

Using equation 7.3:

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 2.9351) + (2 * 35 * 4\,000)$$

$$C_L = 24\,000\,800 \text{ €}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$\langle d \rangle = \frac{11.25}{6} \quad \langle d \rangle = 1.875$$

Replacing in equation 7.13 and 7.14:

$$\langle P_{exc} \rangle = 1.875$$

$$\langle P_{oxc} \rangle = 1.875 * [1 + (1 + 1.609) * 1.533] \quad \langle P_{oxc} \rangle = 9.3742$$

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

$$C_N = (6 * (10000 + (1000 * 100 * 1.875))) + (20 * 136) + (6 * (20000 + (2500 * 9.3742)))$$

$$C_N = 1\,187\,720 + 260\,613 = 1\,448\,333 \text{ €}$$

The CAPEX is:

$$CAPEX = 24\,000\,800 + 1\,448\,333$$

$$CAPEX = 25\,449\,133 \text{ €}$$

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.2.

Using equation 7.5:

$$D = \frac{1}{2} * (1 + 1.25) * \left(\frac{10000}{100} \right) \quad D = 112.5$$

Replacing in equation 7.4:

$$< w > = \left(\frac{112.5 * 1.533}{16} \right) * (1 + 1.609) \quad < w > = 28.2098$$

Using equation 7.3:

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 28.2098) + (2 * 35 * 4\,000)$$

$$C_L = \mathbf{226\,198\,400\,€}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$< d > = \frac{112.5}{6} \quad < d > = 18.75$$

Replacing in equation 7.13 and 7.14:

$$< P_{exc} > = 18.75$$

$$< P_{oxc} > = 18.75 * [1 + (1 + 1.609) * 1.533] \quad < P_{oxc} > = 93.7424$$

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

$$C_N = (6 * (10000 + (1000 * 100 * 18.75))) + (20 * 1360) + (6 * (20000 + (2500 * 93.7424)))$$

$$C_N = 11\,337\,200 + 1\,526\,136 = \mathbf{12\,863\,336\,€}$$

The CAPEX is:

$$CAPEX = 226\,198\,400 + 12\,863\,336$$

$$CAPEX = \mathbf{239\,061\,736\,€}$$

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 4.2.3.

Using equation 7.5:

$$D = \frac{1}{2} * (1 + 1.25) * \left(\frac{20000}{100} \right) \quad D = 225$$

Replacing in equation 7.4:

$$< w > = \left(\frac{225 * 1.533}{16} \right) * (1 + 1.609) \quad < w > = 56.2566$$

Using equation 7.3:

$$N^R = 35$$

Finally, replacing all in equation 7.2 the Link Cost is:

$$C_L = (2 * 8 * 15\,000) + (2 * 8 * 5\,000 * 100 * 56.2566) + (2 * 35 * 4\,000)$$

$$C_L = 450\,572\,800 \text{ €}$$

In relation to the cost of the nodes we first use the equation 7.10:

$$< d > = \frac{225}{6} \quad < d > = 37.5$$

Replacing in equation 7.13 and 7.14:

$$< P_{exc} > = 37.5$$

$$< P_{oxc} > = 37.5 * [1 + (1 + 1.609) * 1.533] \quad < P_{oxc} > = 187.4849$$

Finally, replacing all in equation 7.7 and 7.8 the Node Cost is:

$$C_N = (6 * (10000 + (1000 * 100 * 37.5))) + (20 * 2720) + (6 * (20000 + (2500 * 187.4849)))$$

$$C_N = 22\,614\,400 + 2\,932\,273 = 25\,546\,673 \text{ €}$$

The CAPEX is:

$$CAPEX = 450\,572\,800 + 25\,546\,673$$

$$CAPEX = 476\,119\,473 \text{ €}$$

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.

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, the table 8.1 was created with all the scenarios used and their values obtained.

		Analytical	ILP	Heuristic
Low Traffic	Link Cost	8 520 000 €	9 404 000 €	12 020 000 €
	Node Cost	1 595 720 €	1 862 590 €	2 362 590 €
	CAPEX	10 115 720 €	11 266 590 €	14 382 590 €
Medium Traffic	Link Cost	77 520 000 €	75 520 000 €	77 020 000 €
	Node Cost	15 417 260 €	15 085 900 €	15 385 900 €
	CAPEX	92 937 260 €	90 605 900 €	92 405 900 €
High Traffic	Link Cost	154 020 000 €	148 520 000 €	149 020 000 €
	Node Cost	30 774 340 €	29 711 800 €	29 814 200 €
	CAPEX	184 794 340 €	178 231 800 €	178 834 200 €

Tabela 8.1: Opaque without survivability: Table with different value of CAPEX for all scenarios.

As expected, in all three scenarios, the result obtained through the ILP model is always better (lower) than the value obtained through heuristics. This happens because with the ILP model we always get the optimal solution while with the heuristics we get an approximation of this solution. We can conclude that the greater the traffic, the lower the difference between the ILP and the heuristics because the traffic increase also increases the variables for the heuristic algorithms. Compared with the analytical value, this comparison can not be done literally because the analytical model works with mean values, so this result may be lower or higher than that obtained in the ILP model. It is possible to conclude that this value always has a margin of error of less than 10% for low scenario and less than 5% for the other two scenarios. We can conclude that after obtaining the analytical value if applied the margin of error previously mentioned we know that in this interval is the optimal cost.

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, the table 8.2 was created with all the scenarios used and their values obtained.

		Analytical	ILP	Heuristic
Low Traffic	Link Cost	21 392 000 €	22 520 000 €	23 520 000 €
	Node Cost	4 062 380 €	4 462 590 €	4 662 590 €
	CAPEX	25 454 380 €	26 982 590 €	28 182 590 €
Medium Traffic	Link Cost	201 400 000 €	199 520 000 €	199 520 000 €
	Node Cost	40 083 260 €	39 885 900 €	39 885 900 €
	CAPEX	241 483 260 €	239 405 900 €	239 405 900 €
High Traffic	Link Cost	401 001 500 €	397 520 000 €	397 520 000 €
	Node Cost	80 106 280 €	79 511 800 €	79 514 200 €
	CAPEX	481 107 780 €	477 031 800 €	477 034 200 €

Tabela 8.2: Opaque with 1+1 protection: Table with different value of CAPEX for all scenarios.

Again, as expected, in all three scenarios, the result obtained by the ILP model is always better (smaller) than the value obtained through the heuristic. As the ILP model always gets the optimal solution, another scenario could not happen. As it is possible to see for average traffic values, the heuristics can reach the optimum value, thus concluding that the higher the traffic, the smaller the difference between the ILP and the heuristics. Compared to the analytical value, as this model works with mean values the comparison is made taking into account its margin of error. It can be concluded that this value always has a margin of error of less than 5% for the low scenario and less than 1% for the other two scenarios. We can conclude that after obtaining the analytical value, if we apply the margin of error mentioned above, we know that in this interval is the optimal cost.

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, the table 8.3 was created with all the scenarios used and their values obtained.

		Analytical	ILP	Heuristic
Low Traffic	Link Cost	9 520 000 €	26 520 000 €	26 520 000 €
	Node Cost	1 307 792 €	3 797 590 €	3 797 590 €
	CAPEX	10 827 792 €	30 317 590 €	30 317 590 €
Medium Traffic	Link Cost	87 020 000 €	84 520 000 €	84 520 000 €
	Node Cost	12 169 607 €	12 310 900 €	15 180 900 €
	CAPEX	99 189 607 €	96 830 900 €	99 700 900 €
High Traffic	Link Cost	173 020 000 €	157 520 000 €	157 520 000 €
	Node Cost	24 159 213 €	22 951 800 €	28 486 800 €
	CAPEX	197 179 213 €	180 471 800 €	186 006 800 €

Tabela 8.3: Transparent without survivability: Table with different value of CAPEX for all scenarios.

Comparing the ILP model with the analytical model for this transport mode without survivability we noticed that for the low scenario there is a very high margin of error, approximately 64%, this error is high due to the grooming coefficient. For the analytic model this value is initially defined and is fixed for any scenario but in the case of the ILP model this does not happen. In the ILP model, the coefficient varies and in the low scenario case due to the existence of little traffic the coefficient is much higher than the analytical one. For the remaining scenarios it is possible to conclude that there is a much lower margin of error (below 10%). In comparison with the heuristic model, once again as expected, the result obtained by the ILP model is always better than the value obtained through the heuristic. In the case of low scenario the heuristic can achieve the optimum cost. In this mode of transport, the smaller the amount of traffic, the heuristic is closer to the ILP model.

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, the table 8.4 was created with all the scenarios used and their values obtained.

		Analytical	ILP	Heuristic
Low Traffic	Link Cost	24 000 800 €	68 520 000 €	68 520 000 €
	Node Cost	1 448 333 €	3 947 590 €	4 007 590 €
	CAPEX	25 449 133 €	72 467 590 €	72 527 590 €
Medium Traffic	Link Cost	226 198 400 €	226 520 000 €	226 520 000 €
	Node Cost	12 863 336 €	13 020 900 €	15 890 900 €
	CAPEX	239 061 736 €	239 540 900 €* 	242 410 900 €
High Traffic	Link Cost	450 572 800 €	424 520 000 €	424 520 000 €
	Node Cost	25 546 673 €	24 286 800 €	29 821 800 €
	CAPEX	476 119 473 €	448 806 800 €* 	454 341 800 €

Tabela 8.4: Transparent with 1+1 protection: Table with different value of CAPEX for all scenarios.

Comparing the ILP model with the analytical model for this transport mode with 1 + 1 protection there is a very high margin of error (approximately 64%) for the low scenario. This error happens again for the same reason as above. In this ILP model the coefficient of grooming varies and in this case this value is once again much higher than the analytic one. For the other two scenarios, as previously mentioned, due to its complexity the model was only executed during two weeks. After these two weeks is presented the best result found so far, which may be the optimal cost or not. Still in relation to the analytical mode, for the remaining scenarios, it is possible to conclude that it has a much lower margin of error (below 10%). Equating to the heuristic model it is possible to observe that the result obtained by the ILP model is always better (smaller) than the value obtained through the heuristic. For the medium and high scenarios, although it is not possible to guarantee that the indicated value is optimal, it is possible to affirm that it is quite close since, as previously mentioned, it maintains a margin lower than 10% (compared to the analytic) and obtained a lower value in relation to heuristic.

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.

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, the table 8.5 was created with all the scenarios used and their values obtained.

		ILP	Heuristic
Low Traffic	Link Cost	6 294 000 €	9 520 000 €
	Node Cost	1 237 590 €	2 072 590 €
	CAPEX	7 531 590 €	11 592 590 €
Medium Traffic	Link Cost	36 482 000 €	40 520 000 €
	Node Cost	6 945 900 €	8 605 900 €
	CAPEX	43 427 900 €	49 125 900 €
High Traffic	Link Cost	72 482 000 €	77 520 000 €
	Node Cost	13 506 800 €	16 401 800 €
	CAPEX	85 988 800 €	93 921 800 €

Tabela 8.5: Translucent without survivability: Table with different value of CAPEX for all scenarios.

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.

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, the table 8.6 was created with all the scenarios used and their values obtained.

		ILP	Heuristic
Low Traffic	Link Cost	10 490 000 €	27 520 000 €
	Node Cost	2 077 590 €	2 162 590 €
	CAPEX	12 567 590 €	29 682 590 €
Medium Traffic	Link Cost	82 520 000 €	90 520 000 €
	Node Cost	14 145 900 €	8 855 900 €
	CAPEX	96 665 900 €	99 375 900 €
High Traffic	Link Cost	xxxxxxx €	169 520 000 €
	Node Cost	xxxxxxx €	16 861 800 €
	CAPEX	xxxxxxx €	186 381 800 €

Tabela 8.6: Translucent with 1+1 protection: Table with different value of CAPEX for all scenarios.

