Universidade de Aveiro Departamento de Eletrónica, Telecomunicações e Informática
2018

Tiago Duarte Esteves

Dimensionamento e Optimização em Redes Ópticas de Transporte

Dimensioning and Optimization in Optical Transport Networks

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Dimensioning and Optimization in Optical Transport Networks

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

instituto de
telecomunicações

Aos meus pais, Joaquim e Alice, e a minha esposa Cristina

**"'Apply yourself both now and in the next life.
Without effort, you cannot be prosperous.
Though the land be good,
You cannot have an abundant crop
without cultivation."'**

Plato

o júri / the jury

presidente / president	**Doutor Amaro Fernandes de Sousa** Professor Auxiliar da Universidade de Aveiro
vogais / examiners committee	**Doutor João José de Oliveira Pires** Professor Auxiliar do Instituto Superior Técnico da Universidade de Lisboa
	Doutor Armando Humberto Moreira Nolasco Pinto Professor Associado da Universidade de Aveiro (orientador)

agradecimentos / acknowledgements

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A todos um sincero obrigado!

palavras-chave

CAPEX, topologia fisica, topologia óptica, canais ópticos, modo opaco, modo transparente, modo translucido, modelo analítico, programação linear inteira

resumo

Nesta dissertação é apresentado um estudo de dimensionamento e optimização de redes ópticas de transporte tendo em consideração vários aspectos específicos e determinadas restrições. Primeiramente é definido a topologia física da rede usada para este estudo definindo os seus nós e as suas ligações. Para uma analise mais detalhada e para uma vasta variedade de resultados são tidos em conta três diferentes quantidades de tráfego injetado na rede onde é necessário ter em conta como esse tráfego é agregado e encaminhado na rede. O encaminhamento do tráfego é baseado nas diferentes topologias logicas (Opaco, Transparente e Translucido). Nesta dissertação o principal factor em causa é o CAPEX da rede e para isso são criados modelos de programação linear baseados em restrições e funções objectivo com o propósito de minimizar esse valor garantindo o encaminhamento total do tráfego. Os resultados destes modelos são descritos detalhadamente ao longo da dissertação. Os cálculos analíticos deste processo também são considerados. Com estes resultados e tendo em conta algoritmos de agregação e encaminhamento aplicados a um software livre usado numa dissertação anterior é feita a comparação de resultados. Por fim são apresentadas todas as conclusões.

keywords

CAPEX, physical topology, optical topology, optical channels, opaque mode, transparent mode, translucent mode, analytical model, integer linear programming

abstract

This thesis presents a study of design and optimization of optical transport networks taking into account a number of specific aspects and certain restrictions. First, the physical topology of the network used for this study is defined defining its nodes and their connections. For a more detailed analysis and for a wide variety of results, three different amounts of traffic injected into the network are taken into account where it is necessary to take into account how this traffic is aggregated and routed in the network. Traffic routing is based on different logical topologies (Opaque, Transparent and Translucent). In this dissertation the main factor in question is the CAPEX of the network and for this are created linear programming models based on constraints and objective functions with the purpose of minimizing this value guaranteeing the total routing of traffic. The results of these models are described in detail throughout the dissertation. The analytical calculations of this process are also considered. With these results and taking into account algorithms of aggregation and routing applied to a free software used in a previous dissertation the comparison of results is made. Finally, all the conclusions are presented.

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List of acronyms

CAPEX	capital expenditures
EXC	electrical cross connect
ILP	integer linear programming
LR	long-reach
ODU	optical data unit
OEO	optical-electrical-optical
OLT	optical line terminal
OPEX	operational expenditures
OXC	optical cross connect
SR	short-reach
WDM	wavelength division multiplexing

List of symbols

(i,j)	physical link between the nodes i and j
(o,d)	demand between the nodes o and d
(o,d,c)	demand between the nodes o and d with bit rate c
(p,k)	lightpath between the nodes p and k
γ_0^{OLT}	OLT without transponders cost
γ_1^{OLT}	transponder cost
γ_{e0}	EXC cost
$\gamma_{e1,-1}$	EXC Port for line ports cost
$\gamma_{e1,0}$	EXC Port for ODU0 cost
$\gamma_{e1,1}$	EXC Port for ODU1 cost
$\gamma_{e1,2}$	EXC Port for ODU2 cost
$\gamma_{e1,3}$	EXC Port for ODU3 cost
$\gamma_{e1,4}$	EXC Port for ODU4 cost
γ_{e2}	Tributary Port cost
γ_{o0}	OXC cost in monetary units (e.g. euros, or dollars)
γ_{o1}	OXC Port cost
δ	nodal degree
λ_{od}	the number of 100 Gbit/s optical channels between the nodes o and d
ξ	grooming coefficient
τ	line bit-rate

B	natural number corresponding to the maximum index of short-reach ports
B_c	client signals granularities (1.25, 2.5, 10, 40, 100)
c	index for bit rate of the client signal
c^R	cost of unidirectional optical amplifier
C	set of the client signal
C_C	total network CAPEX in monetary units (e.g. euros, or dollars)
C_{EXC}	electrical part cost
C_L	Link cost in monetary units (e.g. euros, or dollars)
C_N	Node cost in monetary units (e.g. euros, or dollars)
C_{OXC}	optical part cost
$< d >$	average number of demands
d	index for node that is destination of a demand
D	number of unidirectional demands
D_{odc}	client demands between nodes o and d with bit rate c
$D_{nd,c}$	client demands between nodes n and d with bit rate c
f_{ij}^{od}	the number of 100 Gbit/s optical channels between the nodes o and d that uses link (i,j)
fb_{ij}^{od}	binary variable indicating if link between the nodes i and j is used in the path between nodes o and d
fp_{ij}^{od}	the number of 100 Gbit/s optical channels with protection between the nodes o and d that uses link (i,j)
G	Network topology in form of adjacency matrix
G_{ij}	binary indicating if connection between (i, j) in network topology exists
$< h >$	average number of hops for working paths
$< h' >$	average number of hops for backup paths
i	index for start node of a physical link
j	index for end node of a physical link
$< k >$	survivability coefficient
$< kp >$	survivability coefficient in protection case
K_{ij}	maximum number of optical channels supported by each transmission system

$< len >$	average link length
len_{ij}	length of link ij in kilometers
len_l	length of link l
L_{ij}	binary variable indicating if link between the nodes i and j is used
L_u	number of unidirectional Links
Ls_{ij}^{od}	Number of ODU-o low speed signals from node o to node d employing lightpath (i,j)
N	total number of nodes
$N_{exc,n}$	binary variable indicating if node n is used in electrical part
$N_{oxc,n}$	binary variable indicating if node n is used in optical part
N^R	total number of optical amplifiers
N_{ij}^R	number of optical amplifiers in link (i, j)
o	index for node that is origin of a demand
$< P_{exc} >$	average number of ports of the electrical switch
$< P_{oxc} >$	average number of ports of the optical switch
$P_{exc,c,n}$	number of ports of the electrical switch
$P_{oxc,n}$	number of ports of the optical switch
P_{TRIB}	total number of tributary ports
$span$	distance between amplifiers in kilometers
T	total bidirectional traffic
T_1	total unidirectional traffic
T_1^0	unidirectional traffic of the ODU0
T_1^1	unidirectional traffic of the ODU1
T_1^2	unidirectional traffic of the ODU2
T_1^3	unidirectional traffic of the ODU3
T_1^4	unidirectional traffic of the ODU4
$< w >$	average number of optical channels
w_{nj}	number of optical channels that are routed through the link between the nodes n and j
W_{ij}	total number of optical channels that are routed through the link between the nodes i and j

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CHAPTER 1

Introduction

The amount of traffic, in particular IP traffic, has been increasing very substantially. This increase is due to the growing number of Internet-based applications, the increase in the number of devices connected to the Internet, the expansion of optical fiber to customers' homes, increased bandwidth of mobile access technologies, and increased of video traffic. At the same time, with the increase in traffic, operators are under heavy pressure to reduce the cost per bit transported. This implies the introduction of new technologies, which on the one hand increase the capacity of transport of the networks and on the other, reduce the costs of operation (OPEX). This process of technological conversion is operating in a macroeconomic scenario in which operators find it difficult to finance which forces them to have strong investment constraints (CAPEX). The transport networks have been networks predominantly based on circuit switching, either at the level of the optical channels or at the level of the electrical circuits, and the introduction of packet switching undermines this paradigm. In this scenario, particularly considering the increase in packet traffic, packet switching solutions for transport networks and mixed solutions have been presented by the device manufacturers where packet and circuit switching coexists on the same equipment.

1.1 Motivation and objectives

To achieve the main objectives of this dissertation, the following steps must be taken:

1. Define one reference network and three different scenarios for performing tests.
2. Develop ILP models for opaque, transparent and translucent networks without protection and using 1 + 1 protection.
3. Develop ILP models for opaque, transparent and translucent networks with 1 + 1 protection.
4. Get analytical solutions for the two previous points.
5. Compare the analytical results and results based on ILP with the results obtained through heuristics.

1.2 Thesis outline

This thesis is organized in 7 chapters. Chapter 2 consists of a state-of-art review about optical transport networks. In this chapter is also where the reference network used throughout the dissertation as well as the different traffics used is defined. The Chapter 3 begins by determining the CAPEX calculation formula for use in the ILP model and for analytical calculations. The first section refers to ILP models and the other to analytical models. In Chapter 4 are several sections each for a particular mode of transport and certain survivability. In section 4.1 we have opaque without survivability, in section 4.2 opaque with 1+1 protection. Sections 4.3 and 4.4 relate to the transparent and lastly sections 4.5 and 4.6 refer to the translucent. In the referred section it is possible to see the model description, the detailed description of the results and the conclusions of these results. The analytical calculation of all the models referred to in Chapter 4 can be found in Chapter 5. In Chapter 6 the results obtained throughout this dissertation are compared and the chapter is divided into six sections where each corresponds to a certain mode of transport with their respective survivability. The last step is the conclusions 7 and suggestions for future research directions.

CHAPTER 2

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 dissertation. 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 subsections, the first 2.4 to describe the physical topology of the network and a second 2.5 to create the traffic matrix for the three existing traffic models (low, medium and high traffic).

2.1 Network Components

2.1.1 Link architecture

2.1.2 Node architecture

2.2 Network Topologies

2.2.1 Physical topology

2.2.2 Logical topology

2.3 Transport Modes

2.3.1 Opaque transport mode

2.3.2 Transparent transport mode

2.3.3 Translucent transport mode

2.4 Reference Network Topology

The networks are distinguished by different physical topologies. A physical topology is defined by a set of nodes and links, which physically interconnect the nodes, that characterize the network. In this specific case the physical topology ca be seen in figure 2.1 where it is possible to see that the 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.

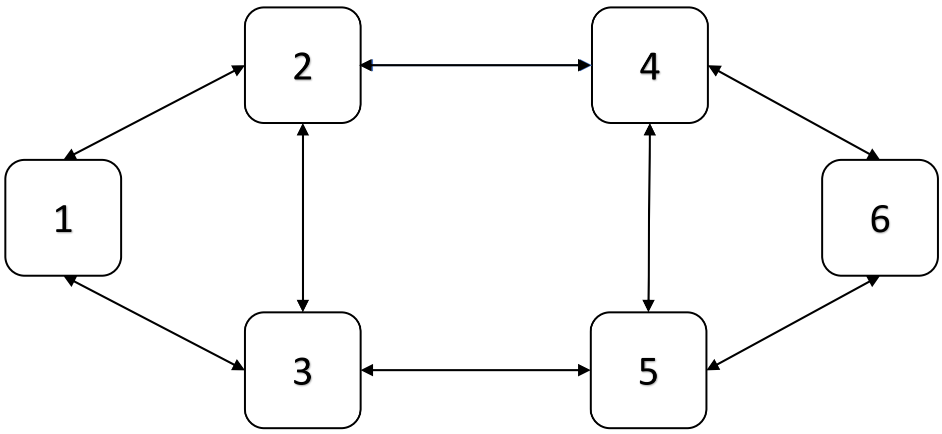

Figure 2.1: Physical topology of the reference network.

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 $node1$ to $node2$ must be the same as $node2$ to $node1$.

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

For this case study has to take into consideration the table 2.1 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
$<\delta>$	Node degree	2.667
<len>	Mean link length (km)	500
<h>	Mean number of hops for working paths	1.533
<h'>	Mean number of hops for backup paths	2.467

Table 2.1: Table of reference network values.

2.5 Network Traffic

For a better interpretation of the later results we will assume three traffic scenarios for this network. Being the first scenario with a low traffic, the second with a medium traffic and a last one with a high traffic. 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 matrices 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.

2.5.1 Low traffic scenario

For this scenario as it is intended low traffic is decided that will have an average of less than 100 Gbits/s per node, preferring a total of traffic of the network of 0.5 Tbits/s. After defining the traffic it is necessary to divide this traffic by the different ODU's thus creating several traffic matrices. The traffic matrices for this scenario are:

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

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

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

Through these ODUs, we can calculate and confirm the total network traffic for the low traffic scenario:

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

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

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

Where the variable T_1^x represents the unidirectional traffic of the ODUx. 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.

Once the traffic matrices are defined we will focus on the logical network topology. In the following figures we can see the logical topopologies of the different ODUs created based on the respective matrices.

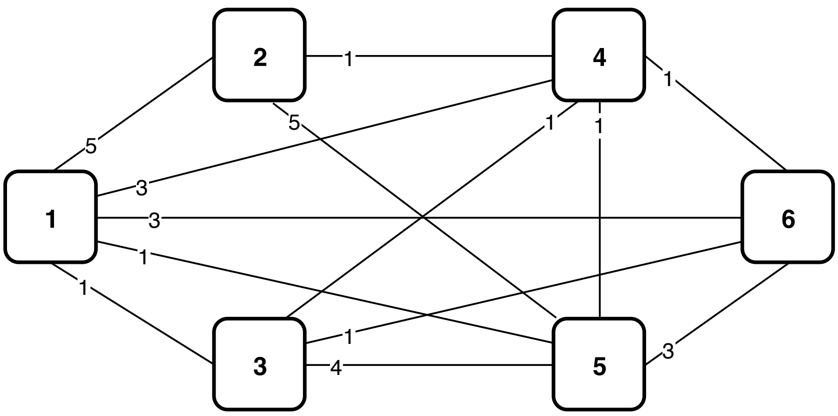

Figure 2.2: ODU0 logical topology defined by the ODU0 traffic matrix in low scenario.

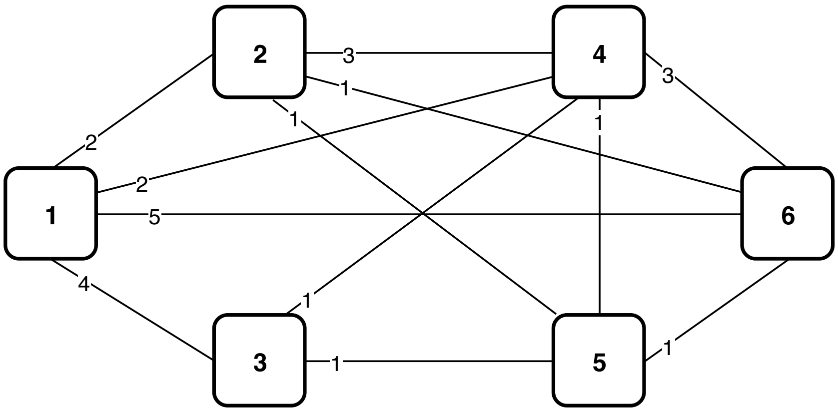

Figure 2.3: ODU1 logical topology defined by the ODU1 traffic matrix in low scenario.

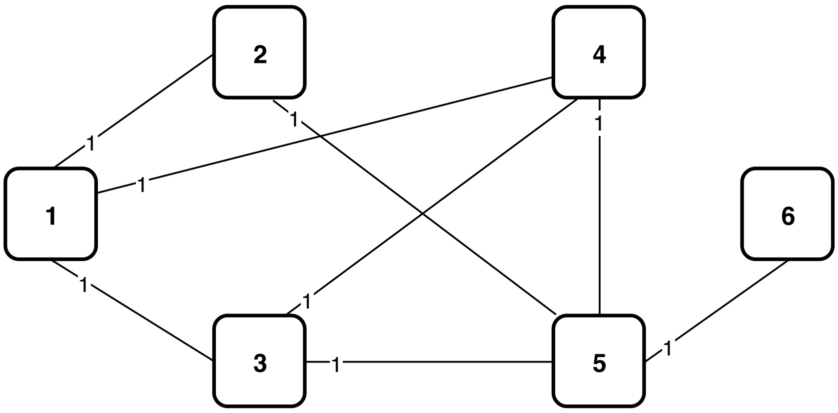

Figure 2.4: ODU2 logical topology defined by the ODU2 traffic matrix in low scenario.

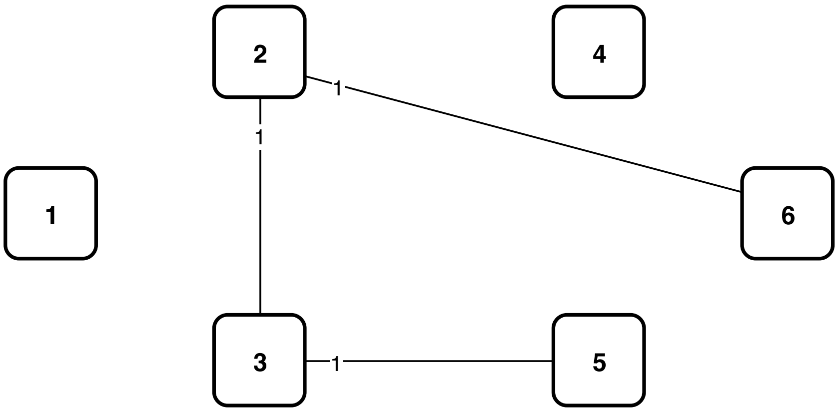

Figure 2.5: ODU3 logical topology defined by the ODU3 traffic matrix in low scenario.

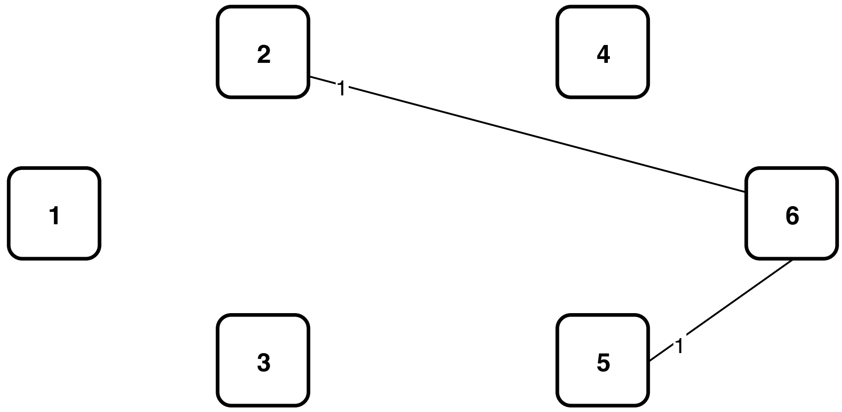

Figure 2.6: ODU4 logical topology defined by the ODU4 traffic matrix in low scenario.

2.5.2 Medium traffic scenario

Now, in this scenario, a significant increase in traffic is already assumed, assuming a medium scenario. For this it is decided that it will have an average of less than 1 Tbits / s per node, prefiguring a total of 5 Tbits / s network traffic. In the next step the division of the traffic defined previously by the different ODUs is made, thus creating several matrices of traffic. The traffic matrices for this scenario are:

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

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

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

Once again, through these ODU's we can calculate and confirm the total network traffic for the medium traffic scenario:

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

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

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

Again, focusing on the logical topology of the network, we can see the different topopologies created based on the respective matrices.

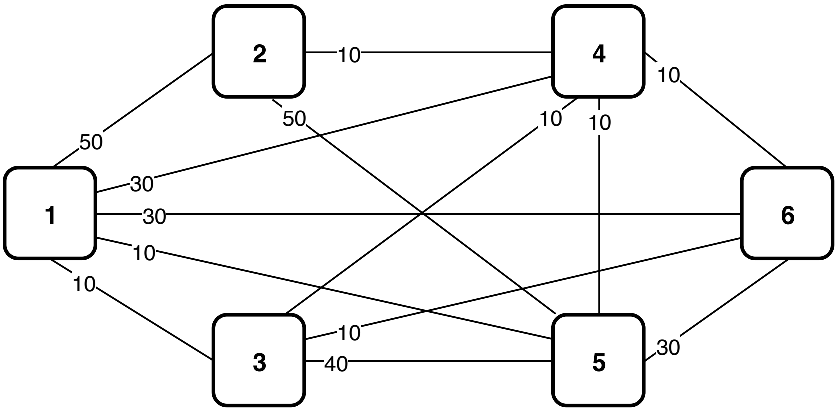

Figure 2.7: ODU0 logical topology defined by the ODU0 traffic matrix in medium scenario.

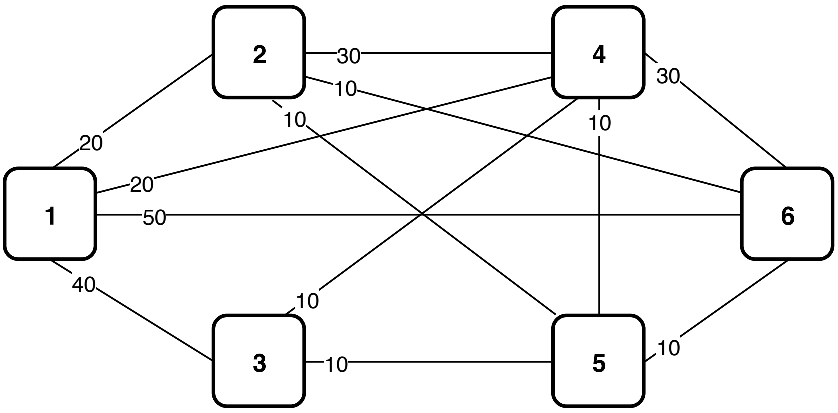

Figure 2.8: ODU1 logical topology defined by the ODU1 traffic matrix in medium scenario.

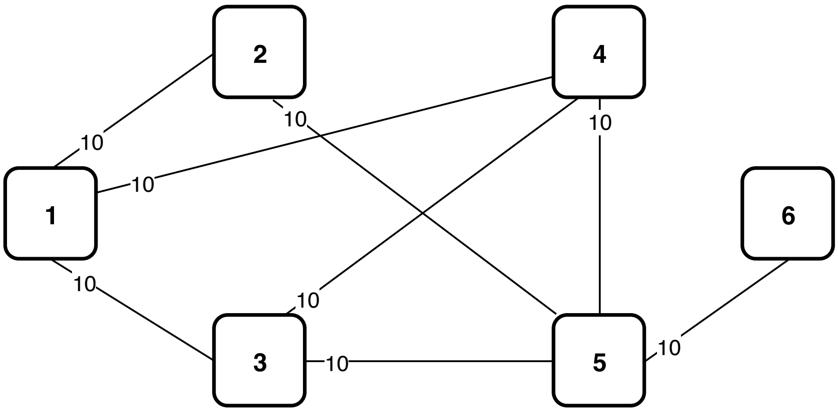

Figure 2.9: ODU2 logical topology defined by the ODU2 traffic matrix in medium scenario.

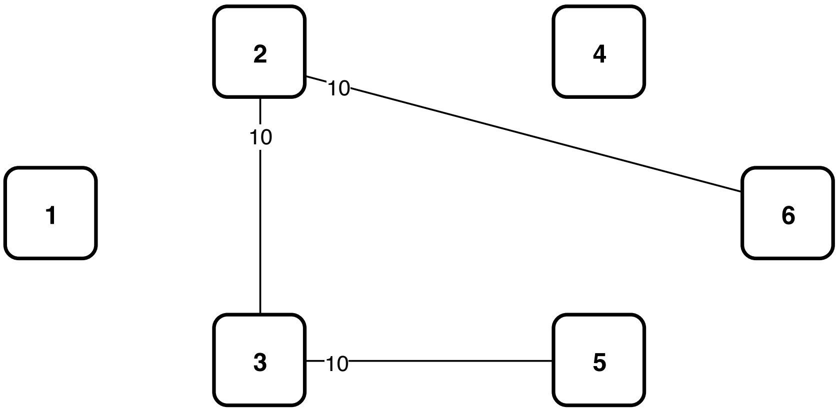

Figure 2.10: ODU3 logical topology defined by the ODU3 traffic matrix in medium scenario.

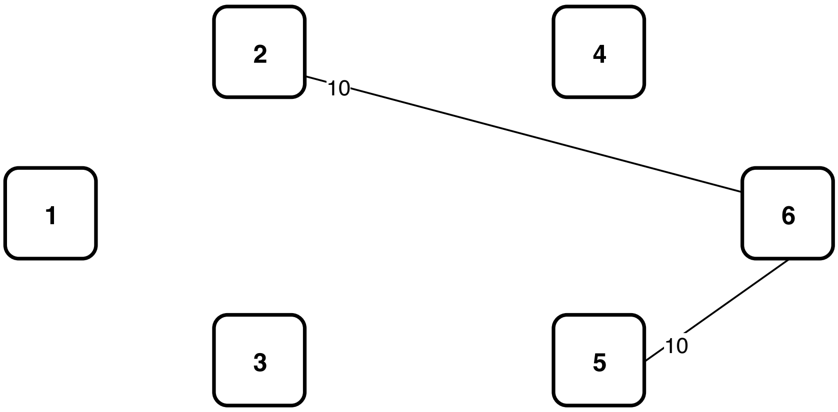

Figure 2.11: ODU4 logical topology defined by the ODU4 traffic matrix in medium scenario.

2.5.3 High traffic scenario

In the latter scenario it is considered to create a new increase of traffic thus leaving the network with a lot of traffic to carry. It is assumed that it will have an average of 2 Tbits/s per node, prefiguring a total of 10 Tbits/s network traffic. In the next step the division of the traffic defined previously by the different ODUs is made, thus creating several matrices of traffic. The traffic matrices for this scenario are:

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

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

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

One more time, through these ODU's we can confirm the total network traffic for the high traffic scenario:

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

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

T_1^4 = 80x100 = 8000 Gbits/s

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

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

In this last scenario we also present the different topologies created based on the respective matrices.

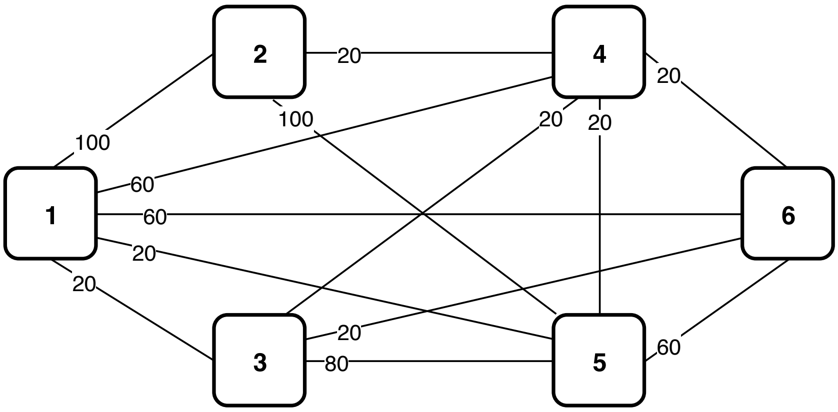

Figure 2.12: Opaque without survivability in high scenario: ODU0 logical topology defined by the ODU0 traffic matrix.

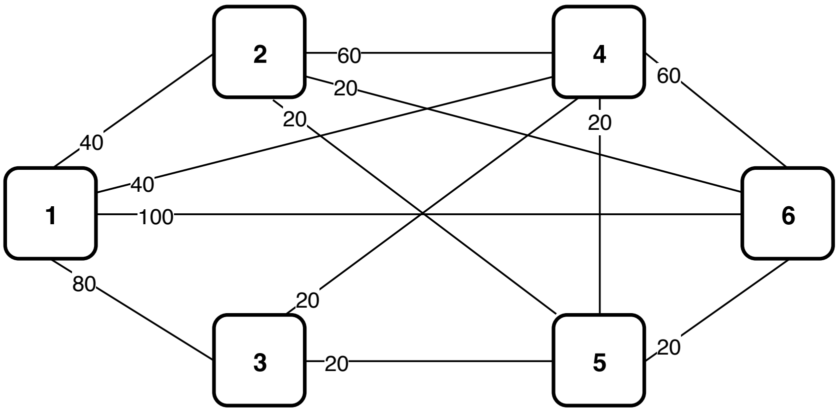

Figure 2.13: ODU1 logical topology defined by the ODU1 traffic matrix in high scenario.

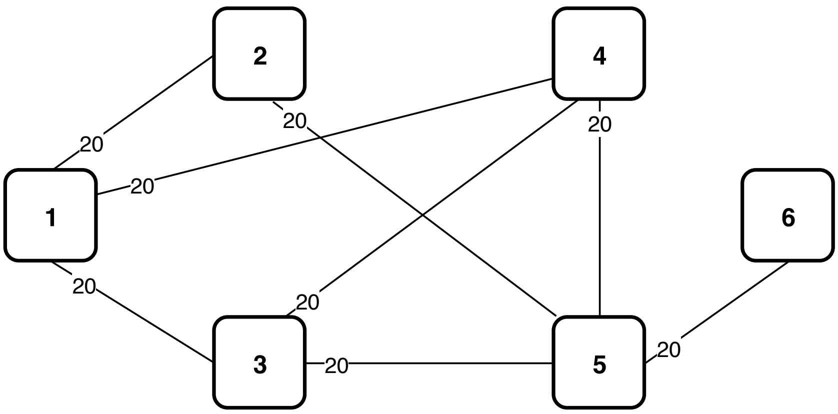

Figure 2.14: ODU2 logical topology defined by the ODU2 traffic matrix in high scenario.

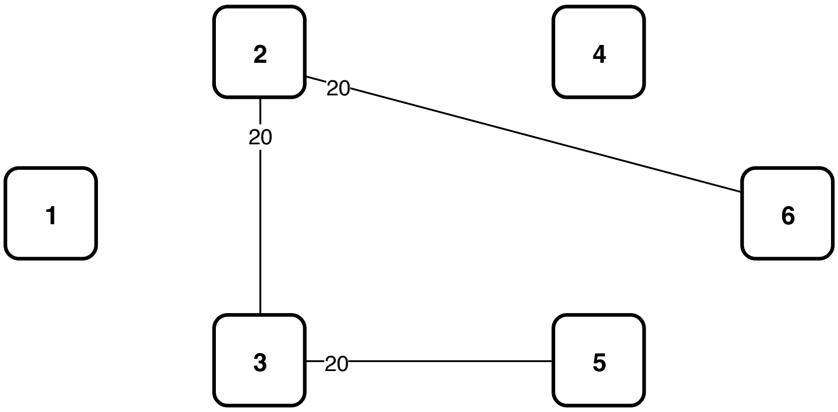

Figure 2.15: ODU3 logical topology defined by the ODU3 traffic matrix in high scenario.

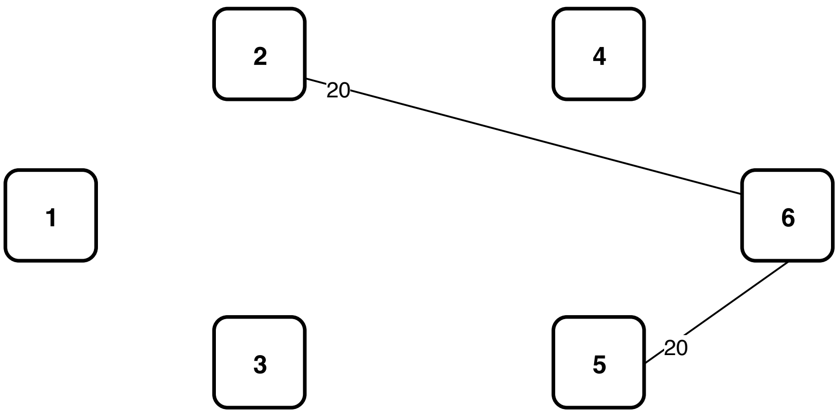

Figure 2.16: ODU4 logical topology defined by the ODU4 traffic matrix in high scenario.

CHAPTER 3

Capital Expenditure

The cost of a telecommunications network can be divided into capital and operational expenditures. The CAPEX is the amount of money needed to set up and install a particular network and the 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. The current chapter is to propose and describe an optimization model to calculate capital expenditures of the network using as a tool ILP models and analytical models. These calculations are made based on the three modes of transport (opaque, transparent and translucent) with 1+1 protection and without survivability. In the section 3.1 it is described how the network CAPEX is calculated using ILP models and in its subsections, the calculations and constraints of the three transport modes mentioned above are identified. In the section3.2 it is described how the network CAPEX is calculated using analytical models and in its subsections, the calculations and constraints of the opaque and transparent modes of transport are identified.

3.1 Using ILP models

As we know the telecommunications networks are made up of links and nodes, so it is possible to define the CAPEX as being the sum of the cost of links and cost of nodes[**?**]. This can be said that the CAPEX cost in monetary units (e.g. euros, or dollars), C_C, is given by the equation 3.1

$$C_C = C_L + C_N \tag{3.1}$$

where C_L is the link cost in monetary units (e.g. euros, or dollars) and C_N is the node cost in monetary units (e.g. euros, or dollars).

For this calculation first let's focus on the cost of the links and for this we have to take into account the figure 3.1 where we can see the design of a link. In this figure we can see that a link consists of two optical line terminals (one at each end), it also has several amplifiers (this number depends on the length of the link) placed at a certain distance (span) and finally it also consists of several optical channels each with a certain wavelength [**?**][**?**].

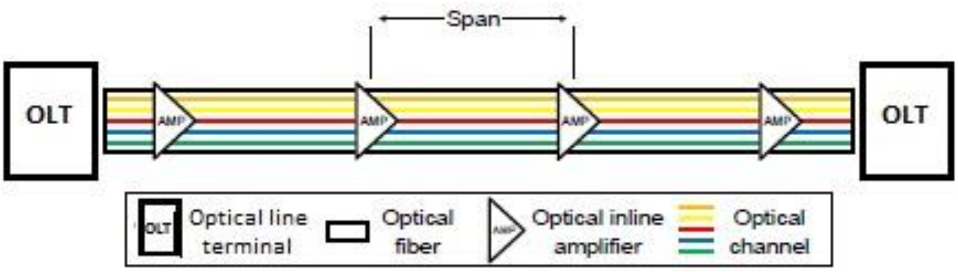

Figure 3.1: Design of a link.

Thus, through the previous image, we can conclude that the link cost in monetary units (e.g. euros, or dollars), C_L, is calculated by the equation 3.2

$$C_L = \sum_{i=1}^{N} \sum_{j=i+1}^{N} L_{ij} \left(2\gamma_0^{OLT} + 2\gamma_1^{OLT} \tau W_{ij} + 2N_{ij}^{R} c^{R} \right) \tag{3.2}$$

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
- $W_{ij} \rightarrow$ Total number of optical channels in link i j
- $N_{ij}^R \rightarrow$ Number of optical amplifiers in link i j
- $c^R \rightarrow$ Optical amplifiers cost in monetary units (e.g. euros, or dollars)

The number of amplifiers for each link can be calculated by equation 3.3

$$N_{ij}^R = \sum_{i=1} \sum_{j=i+1} \left(\left\lceil \frac{len_{ij}}{span} \right\rceil - 1 \right) \tag{3.3}$$

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

The next step is to take into account the cost of the nodes, but for this we must first know how a node is constituted. The nodes have an electrical part, C_{EXC}, and an optical part, C_{OXC}, so we can conclude that the cost of the nodes, C_N, is given by the sum of these two parts [**?**] thus obtaining the equation 3.4.

$$C_N = C_{EXC} + C_{OXC} \tag{3.4}$$

In relation to the electric part we can see the figure 3.2 where it shows its constitution. Through this image, we can conclude in a simple way that the electric cost is the sum of the fixed cost of the electrical connection with the total cost of all the electric ports.
Therefore the electric cost in monetary units (e.g. euros, or dollars), C_{EXC}, is given by equation 3.5

$$C_{EXC} = \sum_{n=1}^{N} N_{exc,n} \left(\gamma_{e0} + \sum_{c=-1}^{B} \gamma_{e1,c} P_{exc,c,n} \right) \tag{3.5}$$

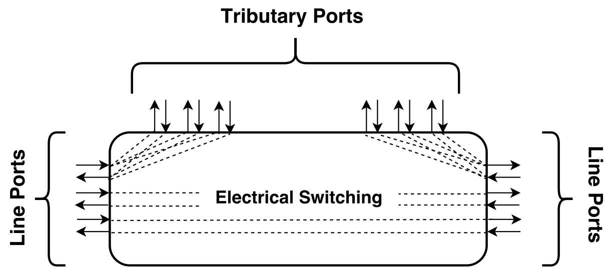

Figure 3.2: Design of a electrical switching.

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)

Table 3.1: Table with index and your corresponding bit rate

Now, in relation to the optical part through the figure 3.3 we can see its constitution.

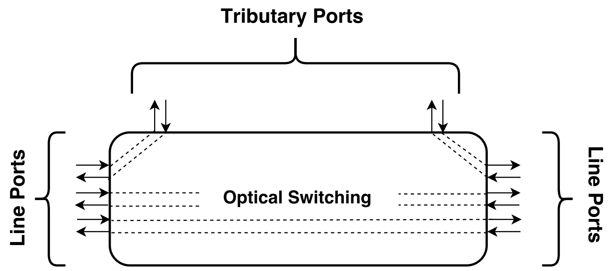

Figure 3.3: Design of a optical switching.

Through the previous image, we can conclude in a simple way that the optical cost is the sum of the fixed cost of the optical connection with the total cost of all the optical ports. Therefore the optical cost in monetary units (e.g. euros, or dollars), C_{OXC}, is given by equation 3.6

$$C_{OXC} = \sum_{n=1}^{N} N_{oxc,n} \Bigg(\gamma_{o0} + \gamma_{o1} P_{oxc,n} \Bigg) \tag{3.6}$$

where

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

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

To obtain the best possible value, it will be necessary to minimize the cost of the capex mentioned above so that we can obtain the objective function 3.7.

$$minimize \quad \Big\{ \quad C_C \quad \Big\} \tag{3.7}$$

Subject to the following restrictions where these restrictions are the flow conservation constraints [**?**].

$$\sum_{j \backslash \{o\}} f_{ij}^{od} = Z \qquad \forall (o,d) : o < d, \forall i : i = o \tag{3.8}$$

This are the usual flow conservation constraints and ensure that, for each (o, d) pair, we route Z units of flow from node o to node d, the source node sends Z units of flow. The variable Z depends of the transport mode and survivability mechanism.

$$\sum_{j \backslash \{o\}} f_{ij}^{od} = \sum_{j \backslash \{d\}} f_{ji}^{od} \qquad \forall (o,d) : o < d, \forall i : i \neq o, d \tag{3.9}$$

This constraint ensure that the remaining nodes, being neither origin or destination, the receive flow have to be send.

$$\sum_{j\setminus\{d\}} f_{ji}^{od} = Z \qquad \forall(o,d) : o < d, \forall i : i = d \quad (3.10)$$

This are the usual flow conservation constraints and ensure that, for each (o, d) pair, we route Z units of flow from node o to node d, the destination node has to receive those Z units of flow. The variable Z depends of the transport mode and survivability mechanism.

Finally, one aspect to be taken into account is the cost of the equipment used in the network. Through the table 3.2 we can see the cost in euros of the equipment.

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

Table 3.2: Table of costs used to calculate CAPEX using ILP models.

3.1.1 Opaque transport mode

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

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

The objective function of following the ILP is a minimization of the CAPEX through the equation 3.1 where in this case for the cost of nodes we only have in consideration the electric cost 3.5 because of the particularity previously mentioned. In this case the value of $P_{exc,c,n}$ is obtained by equation 3.11 for long-reach and by the equation 3.12 for short-reach.

As previously mentioned, equation 3.11 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e. the number of line ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} w_{nj} \tag{3.11}$$

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

As previously mentioned, equation 3.12 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{3.12}$$

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

In this case there is the following particularity:

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

3.1.2 Transparent transport mode

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

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

The objective function of following the ILP is a minimization of the CAPEX through the equation 3.1 where in this case for the cost of nodes we have in consideration electric 3.5 and optical cost 3.6. In this case the value of $P_{exc,c,n}$ is obtained by equation 3.13 for short-reach and by the equation 3.14 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 3.15.

The equation 3.13 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{3.13}$$

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

In this case there is the following particularity:

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

As previously mentioned, the equation 3.14 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n, $P_{exc,-1,n}$, i.e. the number of add ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^{N} \lambda_{nj} \tag{3.14}$$

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

The equation 3.15 refers to the number of ports in optical switch in node n, $P_{oxc,n}$, i.e. the number of line ports and the number of adding ports of node n which can be calculated as

$$P_{oxc,n} = \sum_{j=1}^{N} f_{nj}^{od} + \sum_{j=1}^{N} \lambda_{nj} \tag{3.15}$$

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

3.1.3 Translucent transport mode

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

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

The objective function of following the ILP is a minimization of the CAPEX through the equation 3.1 where in this case for the cost of nodes we have in consideration electric 3.5 and optical cost 3.6. In this case the value of $P_{exc,c,n}$ is obtained by equation 3.16 for short-reach and by the equation 3.17 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 3.18.

The equation 3.16 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n, $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c} \tag{3.16}$$

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 3.17 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

$$P_{exc,-1,n} = \sum_{k=1}^{N} \lambda_{nk} \tag{3.17}$$

where λ_{nk} is the number of optical channels between lightpath n and node k.

The equation 3.18 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

$$P_{oxc,n} = \sum_{j=1}^{N} f_{nj}^{pk} + \sum_{k=1}^{N} \lambda_{nk} \tag{3.18}$$

where f_{nj}^{pk} refers to the number of line ports for all lightpath pairs (p, k) and λ_{nk} refers to the number of add ports.

3.2 Using Analytical models

Again, in this section we will only focus on CAPEX, but this time the calculations are made in an analytical way in order to get a different point of view and expected similar results [?]. This can be said that the CAPEX cost in monetary units, C_C is given by the equation 3.19

$$C_C = C_L + C_N \tag{3.19}$$

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 3.20

$$C_L = \left(2L\gamma_0^{OLT}\right) + \left(2L\gamma_1^{OLT}\tau < w >\right) + \left(2N^R c^R\right) \tag{3.20}$$

where

- $\gamma_0^{OLT} \rightarrow$ OLT cost in euros
- $L \rightarrow$ Number of bidirectional links
- $\gamma_1^{OLT} \rightarrow$ Transponder cost in euros
- $< w > \rightarrow$ Average number of optical channels
- $\tau \rightarrow$ Line bit rate
- $N^R \rightarrow$ Total number of optical amplifiers
- $c^R \rightarrow$ Unidirectional Optical amplifiers cost in euros

Looking at the equation 3.20 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 3.21 we can calculated the number of optical amplifiers, N^R, as

$$N^R = \sum_{l=1}^{L} \left(\left\lceil \frac{len_l}{span} \right\rceil - 1 \right) \tag{3.21}$$

where len_l is the length of link l and $span$ is the distance between amplifiers (assuming 100 km).

Through the equation 3.22 we can calculated the average number of optical channels, $< w >$, as

$$< w >= \left(\frac{\lceil D\times < h > \rceil}{L_u} \right) (1+ < k >) \tag{3.22}$$

where D is the number of unidirectional demands, L_u is the number of unidirectional Links and $< k >$ is the survivability coefficient. The number os unidirectional demands can be calculated as

$$D = \left(\frac{1}{2}\right)(1+\xi)\left(\frac{T_1}{\tau}\right) \tag{3.23}$$

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 3.24

$$C_N = C_{EXC} + C_{OXC} \tag{3.24}$$

To know the electrical cost, C_{exc}, of the nodes that is given by equation 3.25

$$C_{exc} = N \times (\gamma_{e0} + (\gamma_{e1}\tau < P_{exc} >)) + \gamma_{e1} P_{TRIB} \tag{3.25}$$

where:

- $N \rightarrow$ Number of nodes
- $\gamma_{e0} \rightarrow$ EXC cost in euros
- $\gamma_{e1} \rightarrow$ EXC port cost in euros
- $\tau \rightarrow$ Line bit rate
- $< P_{exc} > \rightarrow$ Average number of ports of the electrical switch
- $P_{TRIB} \rightarrow$ Total number of tributary ports

In relation to the optical part, C_{oxc}, to know the optical cost of the nodes that is given by equation 3.26

$$C_{oxc} = N \times (\gamma_{o0} + (\gamma_{o1} < P_{oxc} >)) \tag{3.26}$$

where:

- $N \rightarrow$ Number of nodes
- $\gamma_{o0} \rightarrow$ OXC cost in euros
- $\gamma_{o1} \rightarrow$ OXC port cost in euros
- $< P_{oxc} > \rightarrow$ Average number of ports of the optical switch

We have to take into account that the calculated value for the variables $< P_{exc} >$ and $< P_{oxc} >$ 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 3.3.

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

Table 3.3: Table of costs used to calculate CAPEX using analytical models.

3.2.1 Opaque transport mode

Before carrying out the detailed description we must take into account the following peculiarities of this mode of transport:

- C_{oxc} = 0
- ξ = 1
- $< k >$ = 0 or $< k >$ = $< kp >$ (depending of survivability)

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 when it is without survivability or $< kp >$ when it is with 1+1 protection where

$$< kp >= \frac{< h' >}{< h >} \tag{3.27}$$

Finally looking at the equation 3.25 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 2.5 and the average number of ports the electrical switch,$< P_{exc} >$, that can be calculated as

$$< P_{exc} >=< d >< h > (1+ < k >) \tag{3.28}$$

where $< d >$ is the average number of demands, $< h >$ is the average number of hops and $< k >$ 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 $< d >$ is calculated through the equation 3.29

$$< d >= \frac{D}{N} \tag{3.29}$$

3.2.2 Transparent transport mode

Before carrying out the detailed description we must take into account the following peculiarities of this mode of transport:

- ξ = 1.25
- $< k >$ = 0 or $< k >$ = $< kp >$ (depending of survivability)

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 or $< kp >$ when it is with 1+1 protection where

$$< kp >= \frac{< h' >}{< h >} \tag{3.30}$$

Finally looking at the equation 3.25 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 2.5, the average number of ports the electrical switch,$< P_{exc} >$, that can be calculated as

$$< P_{exc} >=< d > \tag{3.31}$$

and the average number of ports the optical switch,$< P_{oxc} >$, can be calculated as

$$< P_{oxc} >=< d > [1 + (1+ < k >) < h >] \tag{3.32}$$

where $< d >$ is the average number of demands, $< k >$ is the survivability coefficient and $< h >$ 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.

CHAPTER 4

Integer Linear Programming

ILP models are used to design networks that describe real components and their capabilities through a set of linear equations. Despite their quality, the solutions obtained through these models, depending on the number of variables and computational resources, can take days, months or even years [**?**]. The current chapter is to propose and describe an optimization model for calculating the capital expenditures of the network, based on the three modes of transport (opaque, transparent and translucent) without survivability and protection. In the following sections it is proposed in detail the restrictions of the three models previously mentioned, without survivability and with protection as well as a detailed report of the obtained results for each case.

4.1 Opaque without Survivability

4.1.1 Model description

Firstly, in order to be able to apply the ILP model we have to take into account the physical and logical topologies allowed by this mode of transport and the type of survivability. Through the following figures it is possible to see these topologies.

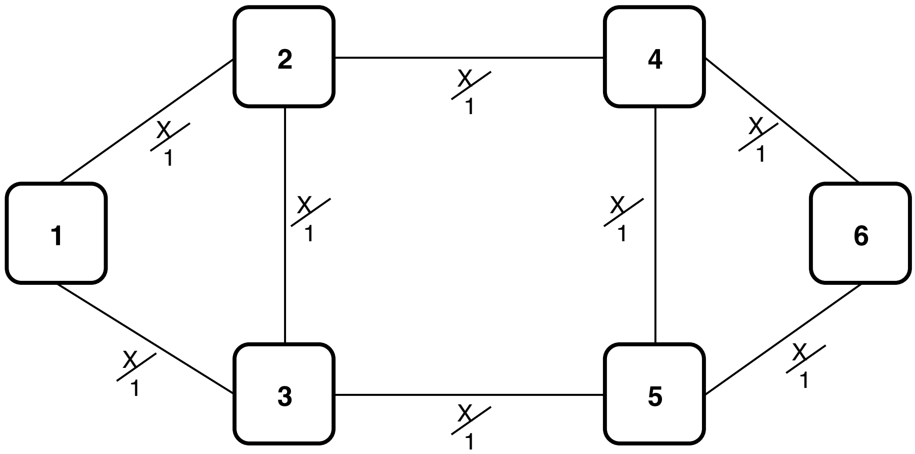

Figure 4.1: Opaque without survivability: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

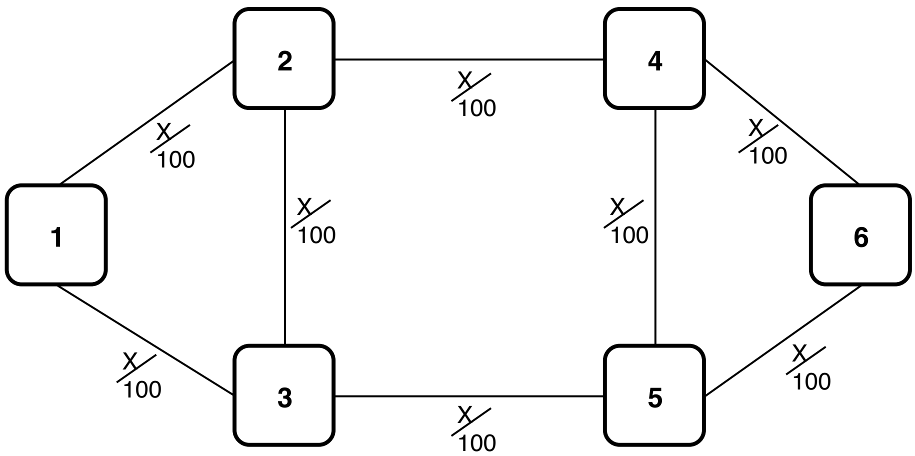

Figure 4.2: Opaque without survivability: Allowed optical topology. The allowed optical topology is defined by the transport mode. It is assumed that each transmission system supports up to 100 optical channels.

Now taking this into account and based on the specific constraints of the opaque mode without survivability it is possible to define the ILP model.

The objective function, to be minimized, is the expression 3.7, i.e.,

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

$subject\ to$

$$\sum_{j\backslash\{o\}} fb_{ij}^{od} = 1 \qquad \forall (o,d) : o < d, \forall i : i = o \qquad (4.1)$$

This constraint is equal to the constraint 3.8 assuming that Z variable has the value of 1.

$$\sum_{j\backslash\{o\}} fb_{ij}^{od} = \sum_{j\backslash\{d\}} f_{ji}^{od} \qquad \forall (o,d) : o < d, \forall i : i \neq o, d \qquad (4.2)$$

This constraint is equal to the constraint 3.9.

$$\sum_{j\backslash\{d\}} fb_{ji}^{od} = 1 \qquad \forall (o,d) : o < d, \forall i : i = d \qquad (4.3)$$

This constraint is equal to the constraint 3.10 assuming that Z variable has the value of 1.

$$\sum_{o=1} \sum_{d=o+1} \left(fb_{ij}^{od} + fb_{ji}^{od} \right) \sum_{c \in C} (B\,(c)\, D_{odc} \leq \tau W_{ij} G_{ij} \qquad \forall (i,j) : i < j \qquad (4.4)$$

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

$$W_{ij} \leq K_{ij} L_{ij} \qquad \forall (i,j) : i < j \qquad (4.5)$$

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

$$fb_{ij}^{od}, fb_{ji}^{od} \in \{0, 1\} \qquad \forall (i,j) : i < j, \forall (o,d) : o < d \qquad (4.6)$$

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

$$W_{ij} \in \mathbb{N} \qquad \forall(i,j) : i < j \tag{4.7}$$

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

4.1.2 Result description

To perform the calculations using the implementation of the models described previously it is necessary to use a mathematical software tool. For this we will use MATLAB which is ideal for dealing with linear programming problems and can call the LPsolve through an external interface. We already have all the necessary to obtain the CAPEX value for the reference network 2.4. As described in the subsection of network traffic 2.5, we have three values of network traffic (low, medium and high traffic) so we have to obtain three different CAPEX. The value of the CAPEX of the network will be calculated based on the costs of the equipment present in the table 3.2.

Low Traffic Scenario:

In this scenario, we have to take into account the traffic calculated in 2.5.1. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.1.

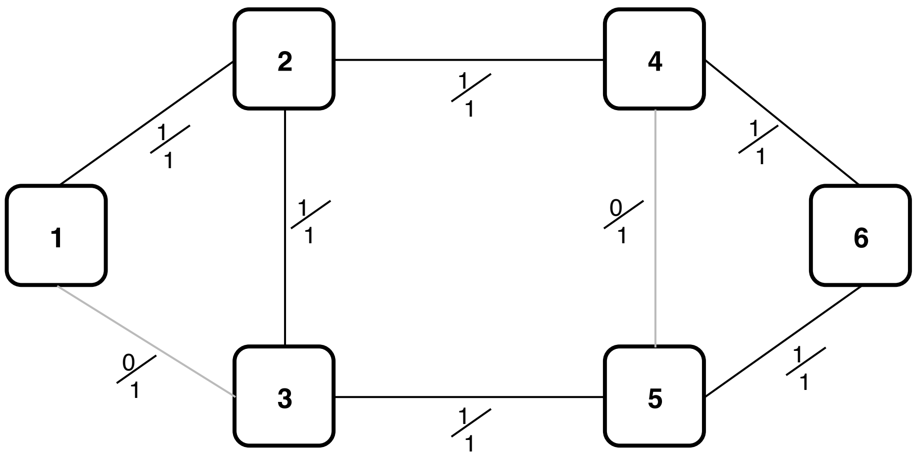

Figure 4.3: Opaque without survivability in low scenario: Physical topology after dimensioning.

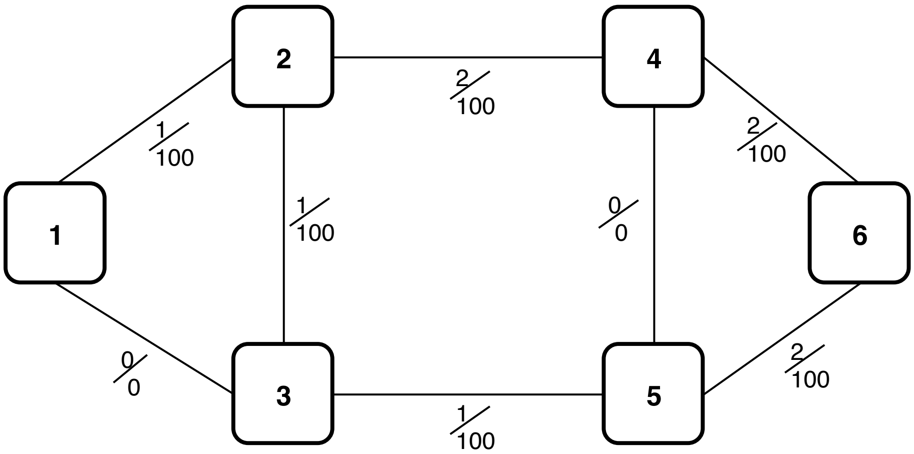

Figure 4.4: Opaque without survivability in low scenario: Optical topology after dimensioning.

In table 4.1 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3. In the case where there are no optical channels we assume that the number of amplifiers is zero.

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

Table 4.1: Table with information regarding links for opaque mode without survivability in low scenario.

In table 4.2 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports calculated using 3.11 and the number of tributary ports calculated using 3.12 for each node.

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

Table 4.2: Table with information regarding nodes for opaque mode without survivability in low scenario.

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

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

Table 4.3: Opaque without survivability in low scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, and can be observed in section 2.5.1.

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

Table 4.4: Opaque without survivability in low scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, and can be observed in section 2.5.1.

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

Table 4.5: Opaque without survivability in low scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, and can be observed in section 2.5.1.

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

Table 4.6: Opaque without survivability in low scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, and can be observed in section 2.5.1.

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

Table 4.7: Opaque without survivability in low scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, and can be observed in section 2.5.1.

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

Table 4.8: Opaque without survivability in low scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, and can be observed in section 2.5.1.

In next step let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 4.9 we can see all the routing obtained for all nodes.

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

Table 4.9: Opaque without survivability in low scenario: Description of demands routing. We are assuming that between a pair of nodes all demands follow the same route.

Finally and most importantly through table 4.10 we can see the CAPEX result for this model. All the values calculated in the next table were obtained through the equations 3.2 and 3.4 referred to in section 3.1.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		12	15 000 €	180 000 €	9 404 000 €
	100 Gbits/s Transceivers		18	5 000 €/Gbit/s	9 000 000 €	
	Amplifiers		56	4 000 €	224 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	1 862 590 €
		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	18	100 000 €/port	1 800 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						11 266 590 €

Table 4.10: Opaque without survivability in low scenario: Detailed description of CAPEX for this scenario.

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.2. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.2.

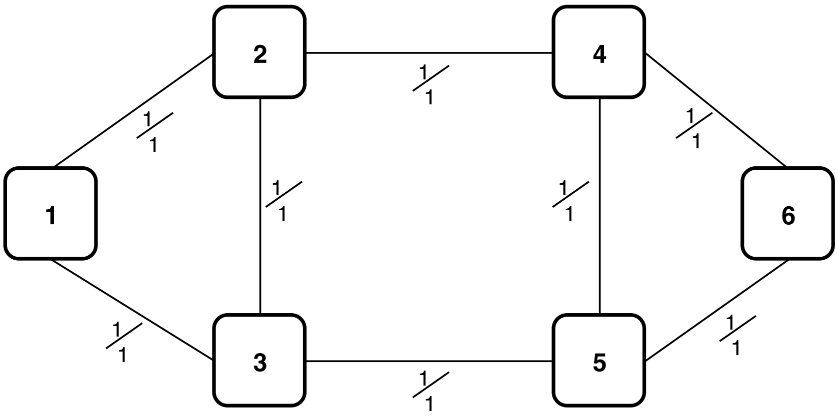

Figure 4.5: Opaque without survivability in medium scenario:Physical topology after dimensioning.

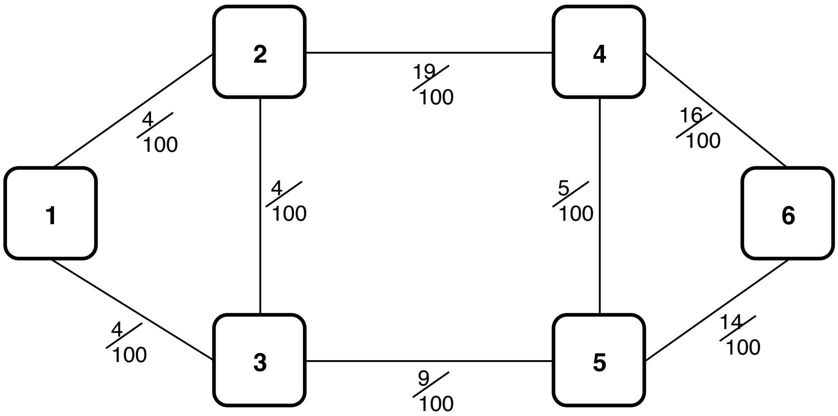

Figure 4.6: Opaque without survivability in medium scenario: Optical topology after dimensioning.

In table 4.11 we can see the number of optical channels calculated using 3.2 and 3.1 and the number of amplifiers for each link calculated using 3.3.

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

Table 4.11: Table with information regarding links for opaque mode without survivability in medium scenario.

In table 4.12 we can see the resulting nodal degree at the physical layer, the number of line ports using 3.11 and the number of tributary ports using 3.12 for each node.

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

Table 4.12: Table with information regarding nodes for opaque mode without survivability in medium scenario.

Once again, through the information obtained previously on the nodes we can now create tables with detailed information about each node.

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

Table 4.13: Opaque without survivability in medium scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.14: Opaque without survivability in medium scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.15: Opaque without survivability in medium scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.16: Opaque without survivability in medium scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.17: Opaque without survivability in medium scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.18: Opaque without survivability in medium scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

In next step let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 4.19 we can see all the routing obtained for all nodes.

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

Table 4.19: Table with description of demands routing. We are assuming that between a pair of nodes all demands follow the same route.

Finally through the table 4.20 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

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

Table 4.20: Opaque without survivability in medium scenario: Detailed description of CAPEX for this scenario.

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.3. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.3.

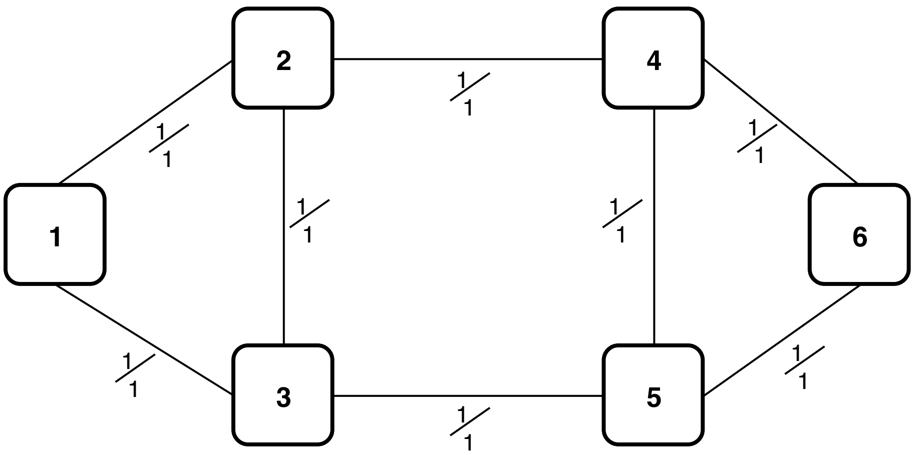

Figure 4.7: Opaque without survivability in high scenario: Physical topology after dimensioning.

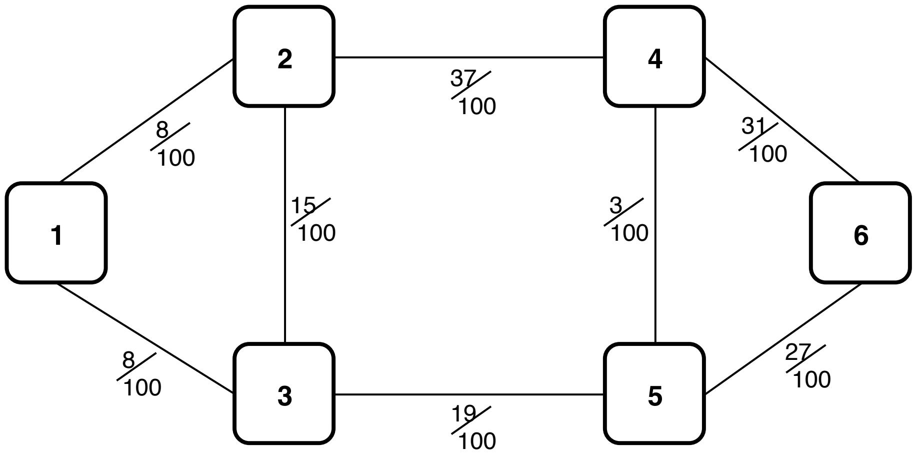

Figure 4.8: Opaque without survivability in high scenario: Optical topology after dimensioning.

In table 4.21 we can see the number of optical channels calculated using 3.2 and 3.1 and the number of amplifiers for each link calculated using 3.21.

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

Table 4.21: Table with information regarding links for opaque mode without survivability in high scenario.

In table 4.22 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports calculated using 3.11 and the number of tributary ports calculated using 3.12 for each node.

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

Table 4.22: Table with information regarding nodes for opaque mode without survivability in high scenario.

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

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

Table 4.23: Opaque without survivability in high scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3 .

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

Table 4.24: Opaque without survivability in high scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

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

Table 4.25: Opaque without survivability in high scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

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

Table 4.26: Opaque without survivability in high scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

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

Table 4.27: Opaque without survivability in high scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

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

Table 4.28: Opaque without survivability in high scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

Next step let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 4.29 we can see all the routing obtained for all nodes.

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

Table 4.29: Opaque without survivability in high scenario: Description of demands routing. We are assuming that between a pair of nodes all demands follow the same route.

Finally and most importantly through table 4.30 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	148 520 000 €
	100 Gbits/s Transceivers		296	5 000 €/Gbit/s	148 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	29 711 800 €
		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 €	
		Line Ports	296	100 000 €/port	29 600 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						178 231 800 €

Table 4.30: Opaque without survivability in high scenario: Detailed description of CAPEX for this scenario.

4.1.3 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 4.31 with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

	Low Traffic	Medium Traffic	High Traffic
Traffic (Gbit/s)	500	5 000	10 000
Bidirectional Links used	6	8	8
Number of Line ports	18	150	296
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	18	150	296
Link Cost	9 404 000 €	75 520 000 €	148 520 000 €
Node Cost	1 862 590 €	15 085 900 €	29 711 800 €
CAPEX	**11 266 590 €**	**90 605 900 €**	**178 231 800 €**
CAPEX/Gbit/s	**22 533 €/Gbit/s**	**18 121 €/Gbit/s**	**17 823 €/Gbit/s**

Table 4.31: Opaque without survivability: Table with the various CAPEX values obtained in the different traffic scenarios.

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

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

4.2 Opaque with 1+1 Protection

4.2.1 Model description

Once more, firstly in order to be able to apply the ILP model we have to take into account the physical and logical topologies allowed by this mode of transport and the type of survivability. Through the following figures it is possible to see these topologies.

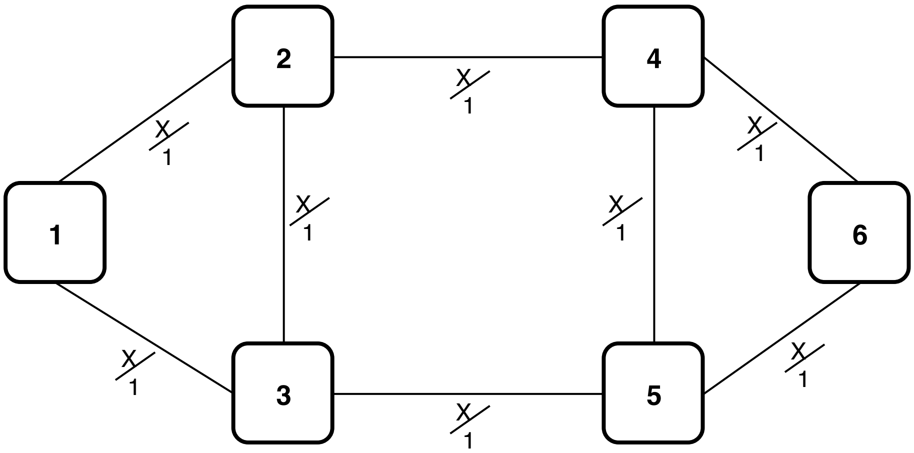

Figure 4.9: Opaque with 1+1 protection: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

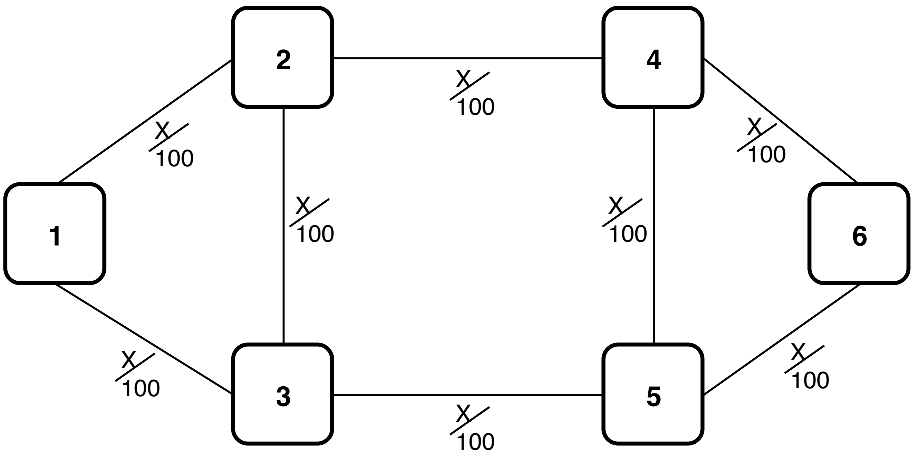

Figure 4.10: Opaque with 1+1 protection: Allowed optical topology. The allowed optical topology is defined by the transport mode. It is assumed that each transmission system supports up to 100 optical channels.

Now taking this into account and based on the specific constraints of the opaque mode with 1+1 protection it is possible to define the ILP model.

The objective function, to be minimized, is the expression 3.7, i.e.,

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

$subject\ to$

$$\sum_{j\backslash\{o\}} fb_{ij}^{od} = 2 \qquad \forall(o,d) : o < d, \forall i : i = o \quad (4.8)$$

This constraint is equal to the constraint 3.8 assuming that Z variable has the value of 2 (work and protection).

$$\sum_{j\backslash\{o\}} fb_{ij}^{od} = \sum_{j\backslash\{d\}} fb_{ji}^{od} \qquad \forall(o,d) : o < d, \forall i : i \neq o, d \quad (4.9)$$

This constraint is equal to the constraint 3.9.

$$\sum_{j\backslash\{d\}} fb_{ji}^{od} = 2 \qquad \forall(o,d) : o < d, \forall i : i = d \quad (4.10)$$

This constraint is equal to the constraint 3.10 assuming that Z variable has the value of 2 (work and protection).

$$\sum_{o=1} \sum_{d=o+1} \left(fb_{ij}^{od} + fb_{ji}^{od} \right) \sum_{c \in C} (B\,(c)\, D_{odc} \leq \tau W_{ij} G_{ij} \qquad \forall(i,j) : i < j \quad (4.11)$$

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

$$W_{ij} \leq K_{ij} L_{ij} \qquad \forall(i,j) : i < j \quad (4.12)$$

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

$$L_{ij}, fb_{ij}^{od}, fb_{ji}^{od} \in \{0,1\} \qquad \forall (i,j) : i < j, \forall (o,d) : o < d \tag{4.13}$$

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

$$W_{ij} \in \mathbb{N} \qquad \forall (i,j) : i < j \tag{4.14}$$

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

4.2.2 Result description

One more time, we already have all the necessary to obtain the CAPEX value for the reference network 2.4. As described in the subsection of network traffic 2.5, we have three values of network traffic so we have to obtain three different CAPEX. The value of the CAPEX of the network will be calculated based on the costs of the equipment present in the table 3.2.

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.1. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODU's mentioned in the section 2.5.1.

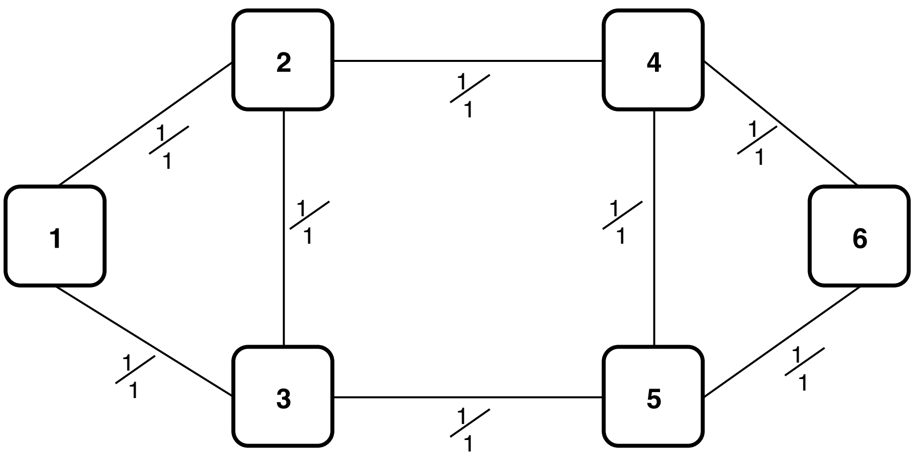

Figure 4.11: Opaque with 1+1 protection in low scenario: Physical topology after dimensioning.

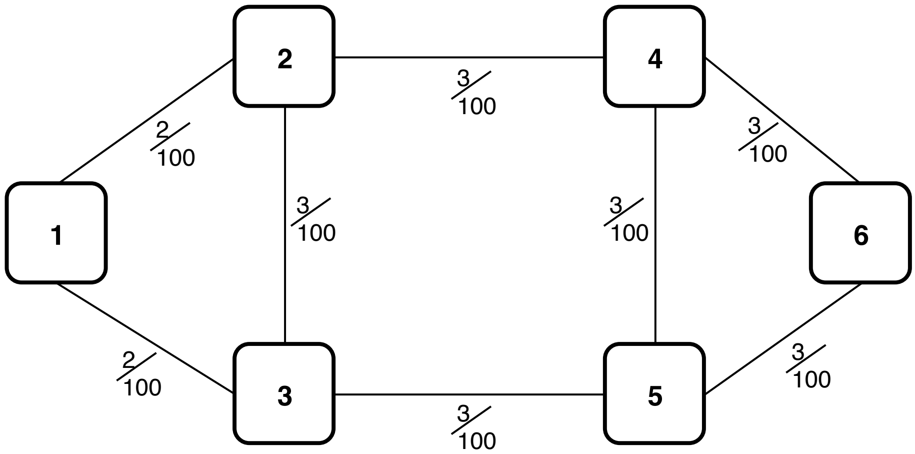

Figure 4.12: Opaque with 1+1 protection in low scenario: Optical topology after dimensioning.

In table 4.32 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3.

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

Table 4.32: Table with information regarding links for opaque mode with 1+1 protection in low scenario.

In table 4.33 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports calculated using 3.11 and the number of tributary ports calculated using 3.12 for each node.

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

Table 4.33: Table with information regarding nodes for opaque mode with 1+1 protection in low scenario.

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

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

Table 4.34: Opaque with 1+1 protection in low scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.35: Opaque with 1+1 protection in low scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.36: Opaque with 1+1 protection in low scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.37: Opaque with 1+1 protection in low scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.38: Opaque with 1+1 protection in low scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.39: Opaque with 1+1 protection in low scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

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

Table 4.40: Opaque with 1+1 protection in low scenario: Description of routing. We are assuming that between a pair of nodes all demands follow the same route.

Finally, in next page, through table 4.41 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

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

Table 4.41: Opaque with 1+1 protection in low scenario: Detailed description of CAPEX for this scenario.

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.2. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODU's mentioned in the section 2.5.2.

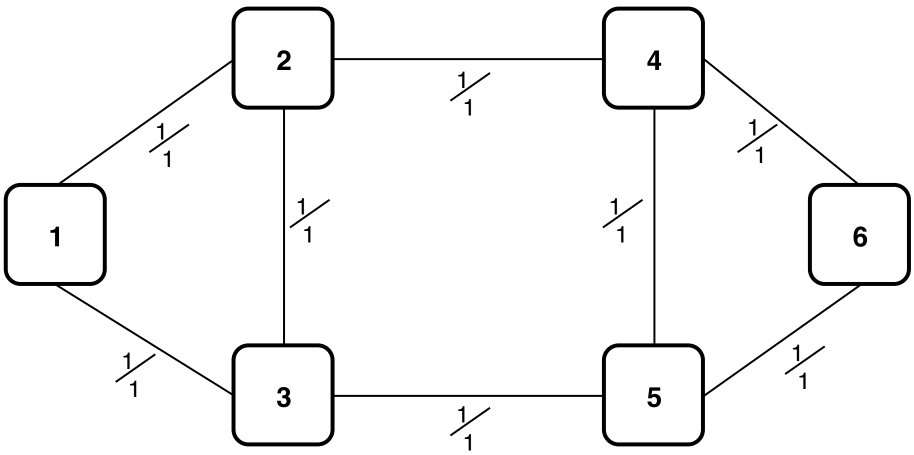

Figure 4.13: Opaque with 1+1 protection in medium scenario: Physical topology after dimensioning.

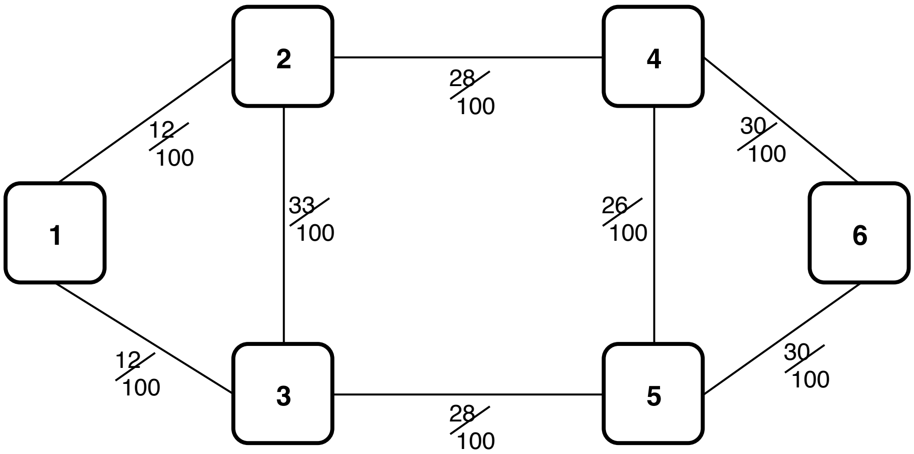

Figure 4.14: Opaque with 1+1 protection in medium scenario: Optical topology after dimensioning.

In table 4.42 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3.

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

Table 4.42: Table with information regarding links for opaque mode with 1+1 protection in medium scenario.

In table 4.43 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports calculated using 3.11 and the number of tributary ports calculated using 3.12 for each node.

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

Table 4.43: Table with information regarding nodes for opaque mode with 1+1 protection in medium scenario.

Once more through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate and how many ports are assigned to each different bit rate.

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

Table 4.44: Opaque with 1+1 protection in medium scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.45: Opaque with 1+1 protection in medium scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.46: Opaque with 1+1 protection in medium scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.47: Opaque with 1+1 protection in medium scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.48: Opaque with 1+1 protection in medium scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.49: Opaque with 1+1 protection in medium scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

Now let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 4.50 we can see all the routing obtained for all nodes. In the Links column we can see that there are two paths but it is not possible to distinguish them because we do not know which is protection and which is working.

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

Table 4.50: Table with description of routing. We are assuming that between a pair of nodes all demands follow the same route.

Once more in next page, through table 4.51 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

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

Table 4.51: Table with detailed description of CAPEX for this scenario.

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.3. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODU's mentioned in the section 2.5.3.

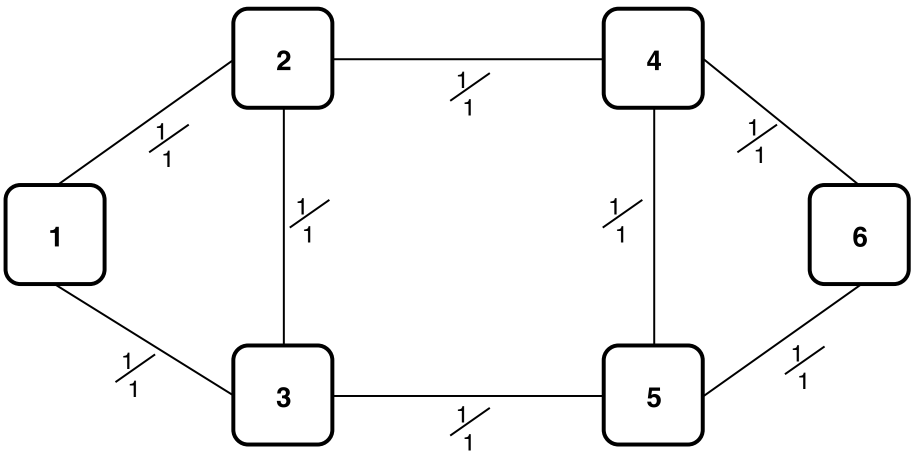

Figure 4.15: Opaque with 1+1 protection in high scenario: Physical topology after dimensioning.

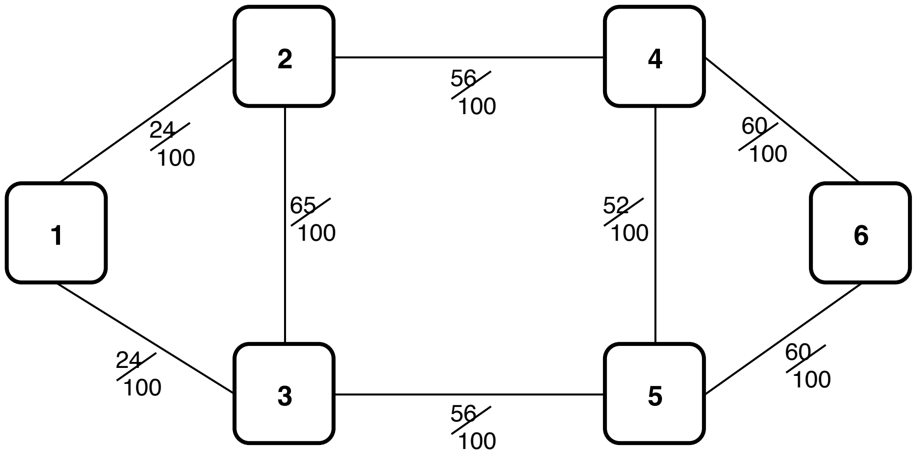

Figure 4.16: Opaque with 1+1 protection in high scenario: Optical topology after dimensioning.

In table 4.52 we can see the number of optical channels calculated using 3.2 and 3.1 and the number of amplifiers for each link calculated using 3.21.

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

Table 4.52: Table with information regarding links for opaque mode with 1+1 protection in high scenario.

In table 4.53 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports calculated using 3.11 and the number of tributary ports calculated using 3.12 for each node.

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

Table 4.53: Table with information regarding nodes for opaque mode with 1+1 protection in high scenario.

Once again, through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate and how many ports are assigned to each different bit rate.

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

Table 4.54: Opaque with 1+1 protection in high scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

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

Table 4.55: Opaque with 1+1 protection in high scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

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

Table 4.56: Opaque with 1+1 protection in high scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

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

Table 4.57: Opaque with 1+1 protection in high scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

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

Table 4.58: Opaque with 1+1 protection in high scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

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

Table 4.59: Opaque with 1+1 protection in high scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

Now through the table 4.60 we can see all the routing obtained for all nodes. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In the Links column we can see that there are two paths but it is not possible to distinguish them because we do not know which is protection and which is working.

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

Table 4.60: Opaque with 1+1 protection in high scenario: Description of routing. We are assuming that between a pair of nodes all demands follow the same route.

Finally in next page, through table 4.61 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

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 €	
		Line Ports	794	100 000 €/port	79 400 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/porto	0 €	
Total Network Cost						477 031 800 €

Table 4.61: Opaque with 1+1 protection in high scenario: Detailed description of CAPEX for this scenario.

4.2.3 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 6.2 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	11 266 590 €	90 605 900 €	178 231 800 €
CAPEX/Gbit/s without survivability	22 533 €/Gbit/s	18 121 €/Gbit/s	17 823 €/Gbit/s
Traffic (Gbit/s)	500	5 000	10 000
Bidirectional Links used	8	8	8
Number of Line ports	44	398	794
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	44	398	794
Link Cost	22 520 000 €	199 520 000 €	397 520 000 €
Node Cost	4 462 590 €	39 885 900 €	79 511 800 €
CAPEX	**26 982 590 €**	**239 405 900 €**	**477 031 800 €**
CAPEX/Gbit/s	**53 965 €/Gbit/s**	**47 881 €/Gbit/s**	**47 703 €/Gbit/s**

Table 4.62: Opaque with 1+1 protection: Table with the various CAPEX values obtained in the different traffic scenarios.

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

- All scenarios uses all available links. This is because in this case regardless of traffic we always need two possible paths.
- Comparing the low traffic 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.
- Comparing this cost with the without survivability cost we can conclude that protection is significantly more expensive. As can be seen in the table this increase is more than double as with 1+1 protection we have a cost more than twice than the cost without survivability.

4.3 Transparent without Survivability

4.3.1 Model description

To apply the ILP model we have to take into account the physical and logical topologies allowed by this mode of transport and the type of survivability. Through the following figures it is possible to see these topologies.

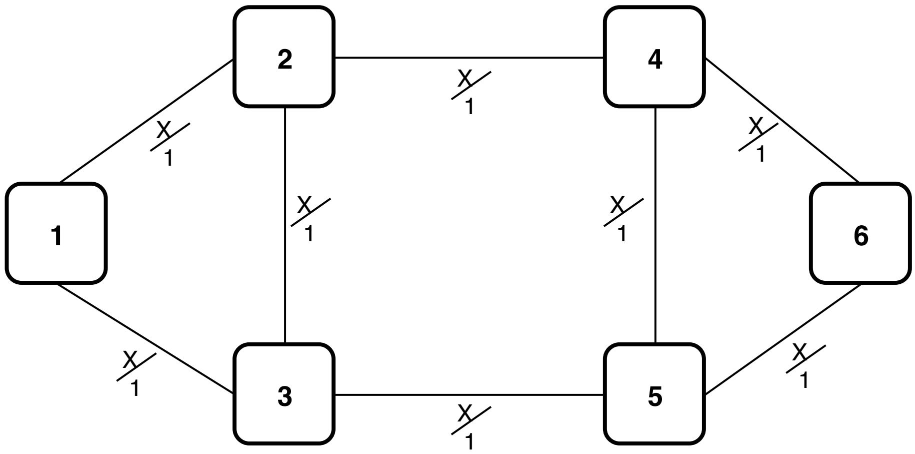

Figure 4.17: Transparent without survivability: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

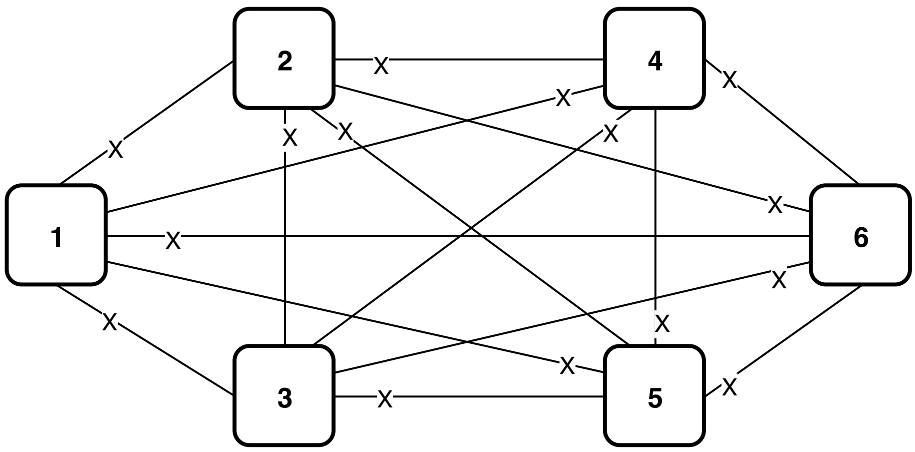

Figure 4.18: Transparent without survivability: Allowed optical topology. The allowed optical topology is defined by the transport mode. It is assumed that each connections between demands supports up to 100 lightpaths.

Now taking this into consideration and based on the specific constraints of the transparent mode without survivability it is possible to define the ILP model.

The objective function, to be minimized, is the expression 3.7, i.e.,

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

$subject\ to$

$$\sum_{c \in C} B(c)\, D_{odc} \leq \tau \lambda_{od} \qquad \forall (o,d) : o < d \tag{4.15}$$

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

$$\sum_{j \backslash \{o\}} f_{ij}^{od} = \lambda_{od} \qquad \forall (o,d) : o < d, \forall i : i = o \tag{4.16}$$

This constraint is equal to the constraint 3.8 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{j \backslash \{o\}} f_{ij}^{od} = \sum_{j \backslash \{d\}} f_{ji}^{od} \qquad \forall (o,d) : o < d, \forall i : i \neq o, d \tag{4.17}$$

This constraint is equal to the constraint 3.9.

$$\sum_{j \backslash \{d\}} f_{ji}^{od} = \lambda_{od} \qquad \forall (o,d) : o < d, \forall i : i = d \tag{4.18}$$

This constraint is equal to the constraint 3.10 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{o=1} \sum_{d=o+1} \left(f_{ij}^{od} + f_{ji}^{od} \right) \leq K_{ij} G_{ij} L_{ij} \qquad \forall (i,j) : i < j \tag{4.19}$$

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

$$f_{ij}^{od}, f_{ji}^{od}, \lambda_{od} \in \mathbb{N} \qquad \forall (i,j) : i < j, \forall (o,d) : o < d \tag{4.20}$$

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

4.3.2 Result description

To perform the calculations using the implementation of the models described previously it is necessary to use the MATLAB which is ideal for dealing with linear programming problems. We already have all the necessary to obtain the CAPEX value for the reference network 2.4. As described in the subsection of network traffic 2.5, we have three values of network traffic (low, medium and high traffic) so we have to obtain three different CAPEX. The value of the CAPEX of the network will be calculated based on the costs of the equipment present in the table 3.2.

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.1. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.1.

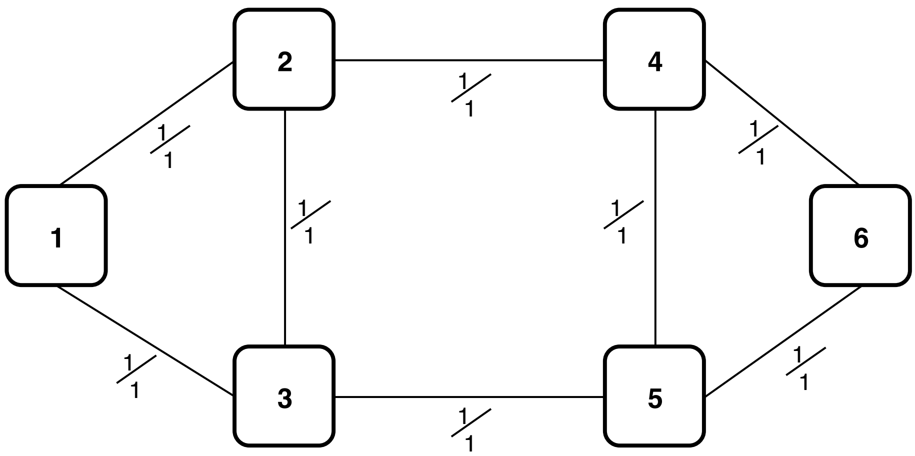

Figure 4.19: Transparent without survivability in low scenario: Physical topology after dimensioning.

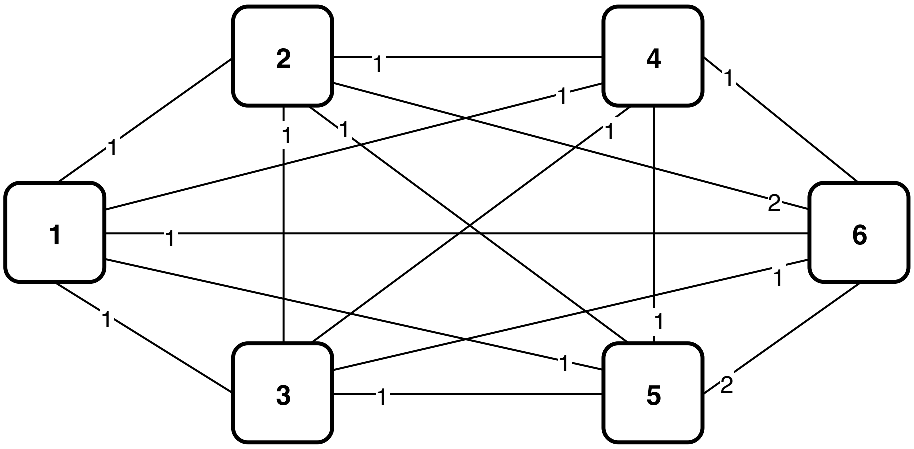

Figure 4.20: Transparent without survivability in low scenario: Optical topology after dimensioning.

In table 4.63 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3.

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

Table 4.63: Table with information regarding links for transparent mode without survivability in low scenario.

In table 4.64 we can see the number of line ports and add ports using 3.15 the number of long-reach transponders using 3.14 and the number of tributary ports using 3.13.

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

Table 4.64: Table with information regarding nodes for transparent mode without survivability in low scenario.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate, the number os long-reach transponders and how many ports are assigned to each different bit rate.

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

Table 4.65: Transparent without survivability in low scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

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

Table 4.66: Transparent without survivability in low scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.67: Transparent without survivability in low scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.68: Transparent without survivability in low scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.69: Transparent without survivability in low scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.70: Transparent without survivability in low scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

Now, in next page, let's focus on the routing information in table 4.71. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

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

Table 4.71: Transparent without survivability in low scenario: Description of routing.

Finally through table 4.72 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

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 €

Table 4.72: Transparent without survivability in low scenario: Detailed description of CAPEX for this scenario.

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.2. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODU's mentioned in the section 2.5.2.

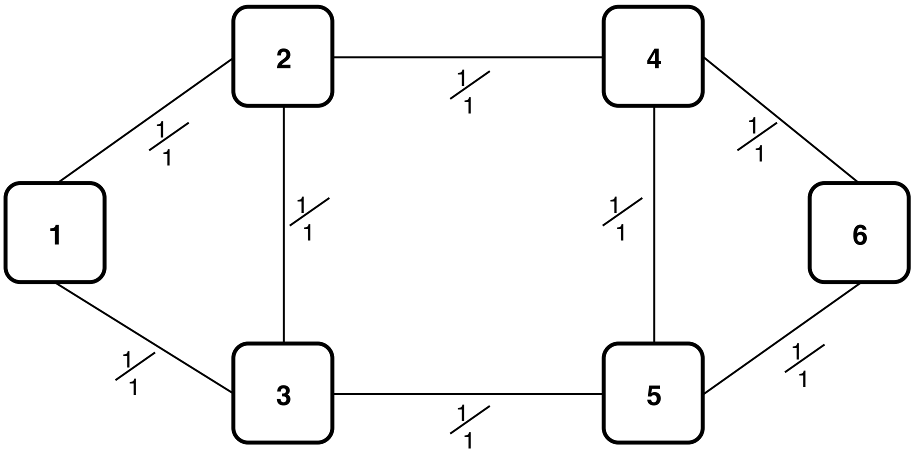

Figure 4.21: Transparent without survivability in medium scenario: Physical topology after dimensioning.

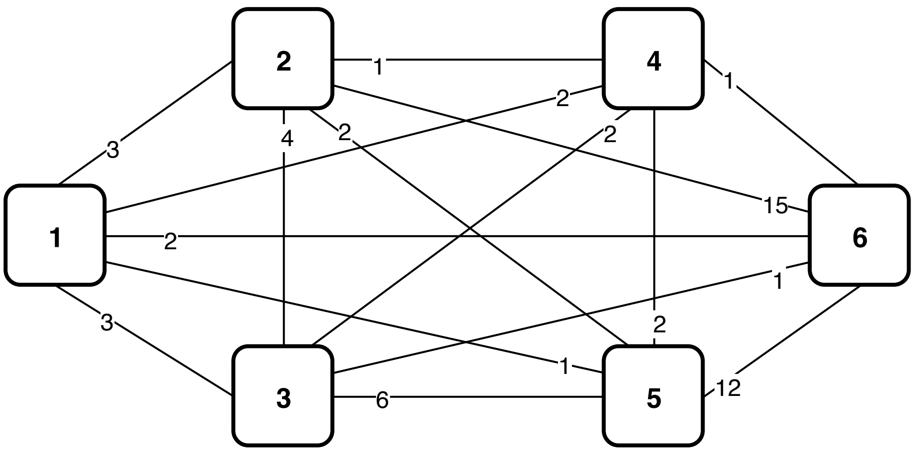

Figure 4.22: Transparent without survivability in medium scenario: Optical topology after dimensioning.

In table 4.73 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3.

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

Table 4.73: Table with information regarding links for transparent mode without survivability in medium scenario.

In table 4.74 we can see the number of line ports and add ports using 3.15 the number of long-reach transponders using 3.14 and the number of tributary ports using 3.13.

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

Table 4.74: Table with information regarding nodes for transparent mode without survivability in medium scenario.

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

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

Table 4.75: Transparent without survivability in medium scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

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

Table 4.76: Transparent without survivability in medium scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.77: Transparent without survivability in medium scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.78: Transparent without survivability in medium scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.79: Transparent without survivability in medium scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.80: Transparent without survivability in medium scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

Now, in next page, let's focus on the routing information in table 4.81. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

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

Table 4.81: Transparent without survivability in medium scenario: Description of routing

Finally and most importantly through table 4.82 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

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 €	12 310 900 €
		ODU0 Ports	600	10 €/port	6 000 €	
		ODU1 Ports	500	15 €/port	7 500 €	
		ODU2 Ports	160	30 €/port	4 800 €	
		ODU3 Ports	60	60 €/port	3 600 €	
		ODU4 Ports	40	100 €/port	4 000 €	
		Transponders	114	100 000 €/port	11 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	168	2 500 €/port	420 000 €	
		Add Ports	114	2 500 €/port	285 000 €	
Total Network Cost						96 830 900 €

Table 4.82: Transparent without survivability in medium scenario: Detailed description of CAPEX

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.3. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUâ€™s mentioned in the section 2.5.3.

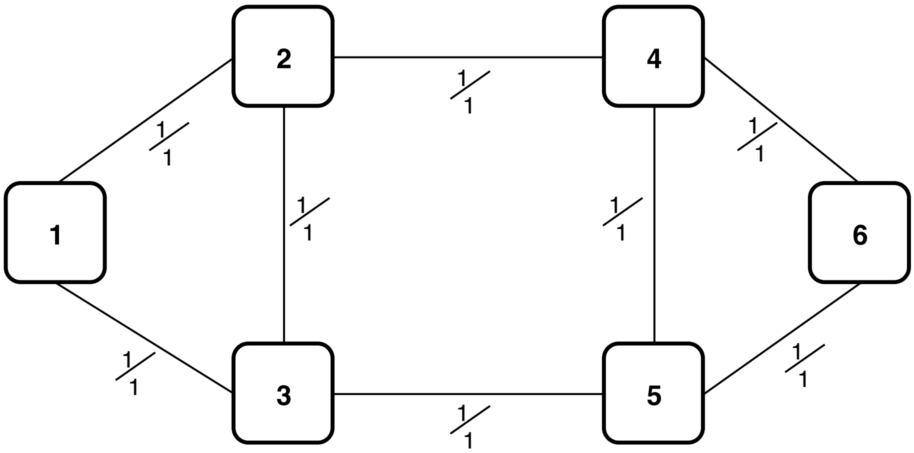

Figure 4.23: Transparent without survivability in high scenario: Physical topology after dimensioning.

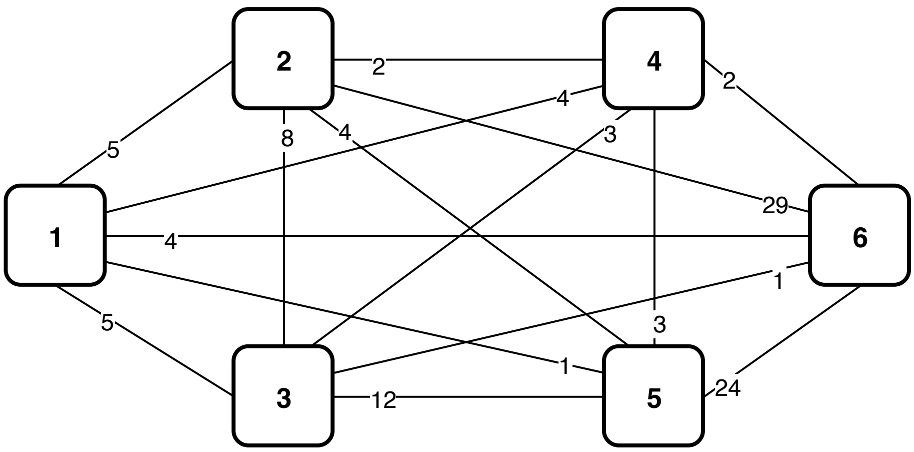

Figure 4.24: Transparent without survivability in high scenario: Optical topology after dimensioning.

In table 4.83 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3.

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

Table 4.83: Table with information regarding links for transparent mode without survivability in high scenraio.

In table 4.84 we can see the number of line ports and add ports using 3.15 the number of long-reach transponders using 3.14 and the number of tributary ports using 3.13.

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

Table 4.84: Table with information regarding nodes for transparent mode without survivability in high scenario.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate, the number of LR transponders and how many ports are assigned to each different bit rate.

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

Table 4.85: Transparent without survivability in high scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

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

Table 4.86: Transparent without survivability in high scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.87: Transparent without survivability in high scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.88: Transparent without survivability in high scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.89: Transparent without survivability in high scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.90: Transparent without survivability in high scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In this node as we can see there are no through ports.

Now, in next page, let's focus on the routing information in table 4.91. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

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

Table 4.91: Transparent without survivability in high scenario: Description of routing.

Finally and most importantly through table 4.92 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

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

Table 4.92: Transparent without survivability in high scenario: Detailed description of CAPEX for this scenario.

4.3.3 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 4.93 with the number of line ports and add ports of the optical part, the tributary ports, the transponders and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

	Low Traffic	Medium Traffic	High Traffic
Traffic (Gbit/s)	500	5 000	10 000
Number of Add ports	34	114	214
Number of Line ports	52	168	314
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	52	168	314
Number of Transponders	34	114	214
Link Cost	26 520 000 €	84 520 000 €	157 520 000 €
Node Cost	3 797 590 €	12 310 900 €	22 951 800 €
CAPEX	**30 317 590 €**	**96 830 900 €**	**180 471 800 €**
CAPEX/Gbit/s	**60 635 €/Gbit/s**	**19 366 €/Gbit/s**	**18 047 €/Gbit/s**

Table 4.93: Transparent without survivability: Table with the various CAPEX values obtained in the different traffic scenarios.

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

- Comparing the low traffic 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/Gbit/s will be. We can see that in medium and high traffic the results tend to be one closer and lower value.

4.4 Transparent with 1+1 Protection

4.4.1 Model description

Once more, to apply the ILP model we have to take into account the physical and logical topologies allowed by this mode of transport and the type of survivability. Through the following figures it is possible to see these topologies.

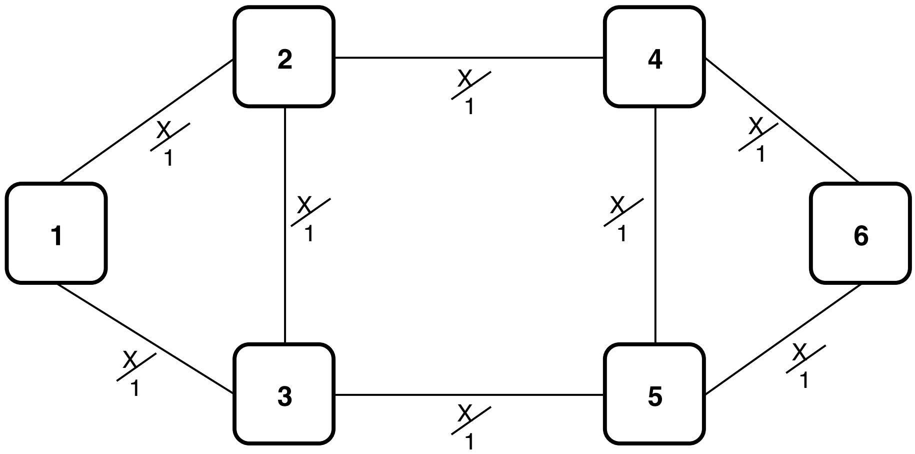

Figure 4.25: Transparent with 1+1 protection: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

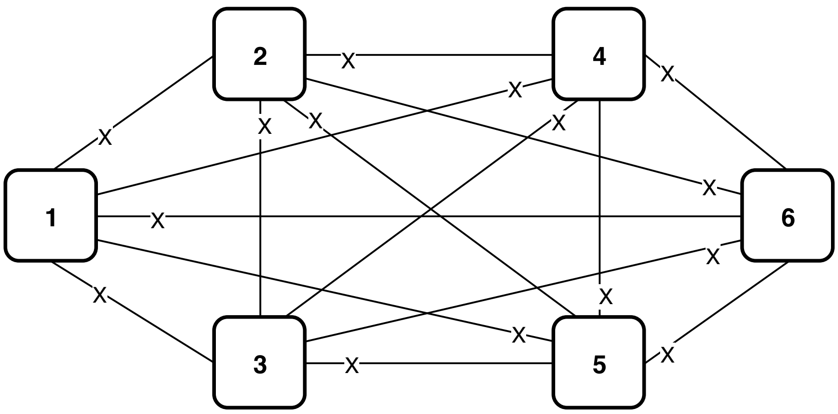

Figure 4.26: Transparent with 1+1 protection: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

Now taking this into consideration and based on the specific constraints of the transparent mode with 1+1 protection it is possible to define the ILP model.

The objective function, to be minimized, is the expression 3.7, i.e.,

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

$subject\ to$

$$\sum_{c\in C} B\left(c\right) D_{odc} \leq \tau\lambda_{od} \qquad \forall(o,d): o<d \tag{4.21}$$

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

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = \lambda_{od} \qquad \forall(o,d): o<d, \forall i: i=o \tag{4.22}$$

This constraint is equal to the constraint 3.8 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{j\backslash\{o\}} f_{ij}^{od} = \sum_{j\backslash\{d\}} f_{ji}^{od} \qquad \forall(o,d): o<d, \forall i: i\neq o,d \tag{4.23}$$

This constraint is equal to the constraint 3.9.

$$\sum_{j\backslash\{d\}} f_{ji}^{od} = \lambda_{od} \qquad \forall(o,d): o<d, \forall i: i=d \tag{4.24}$$

This constraint is equal to the constraint 3.10 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{j\backslash\{o\}} fp_{ij}^{od} = \lambda_{od} \qquad \forall(o,d): o<d, \forall i: i=o \tag{4.25}$$

This is the protection flow conservation constraints and ensure that, for each (o,d) pair, we route the number of optical channels of flow from node o to node d, the source node sends the number of optical channels units of flow.

$$\sum_{j\setminus\{o\}} fp_{ij}^{od} = \sum_{j\setminus\{d\}} fp_{ji}^{od} \qquad \forall(o,d) : o < d, \forall i : i \neq o, d \qquad (4.26)$$

This constraint ensure that the remaining nodes, being neither origin or destination, the receive flow have to be send.

$$\sum_{j\setminus\{d\}} fp_{ji}^{od} = \lambda_{od} \qquad \forall(o,d) : o < d, \forall i : i = d \qquad (4.27)$$

This is the protection flow conservation constraints and ensure that, for each (o, d) pair, we route the number of optical channels units of flow from node o to node d, the destination node has to receive those the number of optical channels units of flow.

$$\sum_{o=1} \sum_{d=o+1} \left(f_{ij}^{od} + fp_{ij}^{od} \right) \leq \lambda_{od} \qquad \forall(o,d), (i,j) \qquad (4.28)$$

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

$$\sum_{o=1} \sum_{d=o+1} \left(f_{ij}^{od} + f_{ji}^{od} + fp_{ij}^{od} + fp_{ji}^{od} \right) \leq K_{ij} G_{ij} L_{ij} \qquad \forall(i,j) : i < j \qquad (4.29)$$

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

$$f_{ij}^{od}, f_{ji}^{od}, fp_{ij}^{od}, fp_{ji}^{od}, \lambda_{od} \in \mathbb{N} \qquad \forall(i,j) : i < j, \forall(o,d) : o < d \qquad (4.30)$$

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

$$L_{i,j} \in \{0, 1\} \qquad \forall(i,j) \qquad (4.31)$$

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

4.4.2 Result description

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.1. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.1.

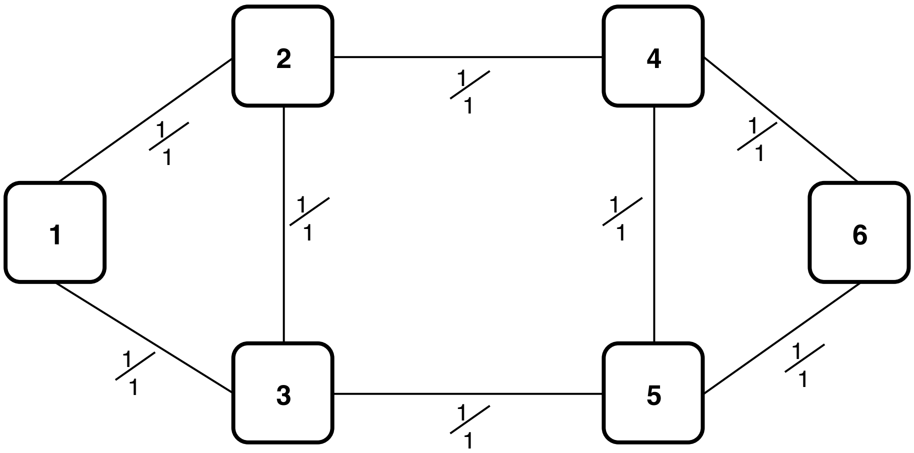

Figure 4.27: Transparent with 1+1 protection in low scenario: Physical topology after dimensioning.

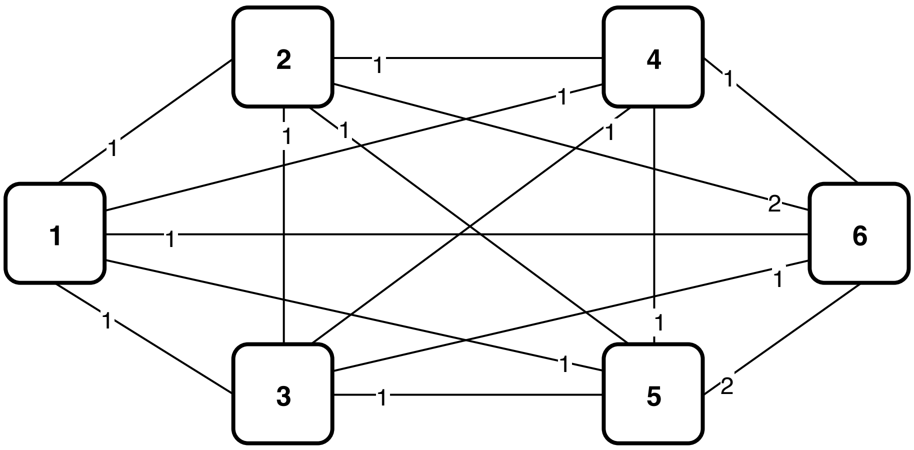

Figure 4.28: Transparent with 1+1 protection in low scenario: Optical topology after dimensioning.

In table 4.94 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3.

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

Table 4.94: Table with information regarding links for transparent mode with 1+1 protection in low scenario.

In table 4.95 we can see the resulting nodal degree at the physical layer, the number of line ports and the number of add ports for the optical part calculated using 3.15 the number of LR transponders calculated using 3.14 and the number of tributary ports calculated using 3.13 for each node.

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

Table 4.95: Table with information regarding nodes for transparent mode with 1+1 protection in low scenario.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node.

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

Table 4.96: Transparent with 1+1 protection in low scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used.

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

Table 4.97: Transparent with 1+1 protection in low scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

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

Table 4.98: Transparent with 1+1 protection in low scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

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

Table 4.99: Transparent with 1+1 protection in low scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

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

Table 4.100: Transparent with 1+1 protection in low scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

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

Table 4.101: Transparent with 1+1 protection in low scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

In next step let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 4.102 we can see all the routing obtained for all nodes.

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

Table 4.102: Transparent with 1+1 protection in low scenario: Description of routing.

Finally through table 4.103 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

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

Table 4.103: Transparent with 1+1 protection in low scenario: Detailed description of CAPEX for this scenario.

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.2. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.2.

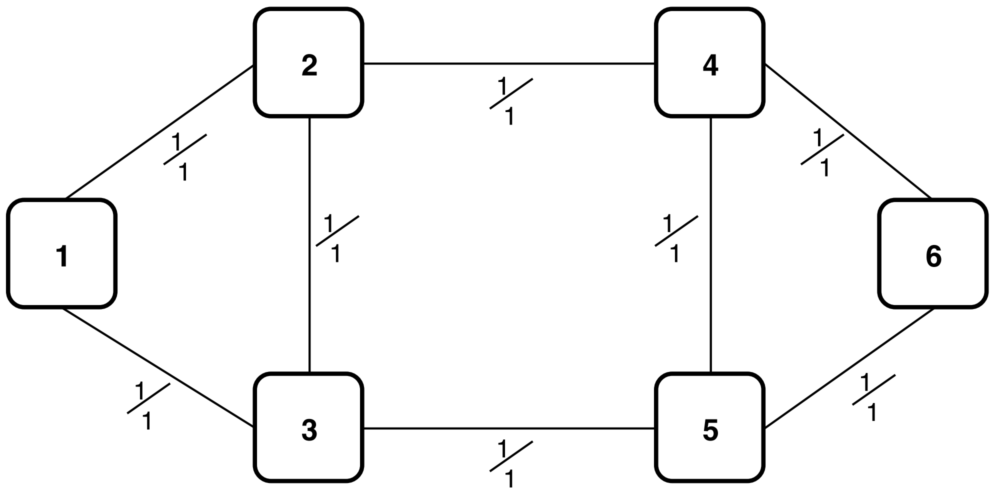

Figure 4.29: Transparent with 1+1 protection in medium scenario: Physical topology after dimensioning.

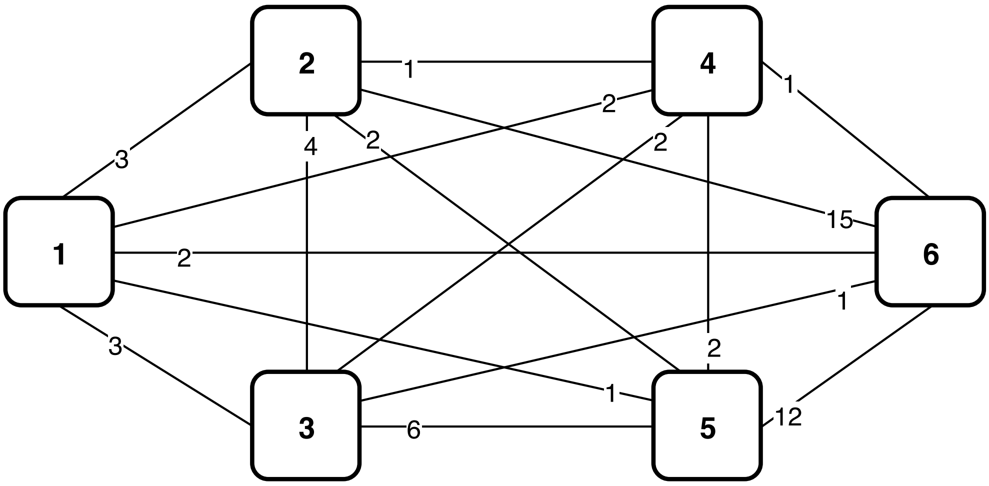

Figure 4.30: Transparent with 1+1 protection in medium scenario: Optical topology after dimensioning.

In table 4.104 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	15	4
Node 1 <-> Node 3	15	6
Node 2 <-> Node 3	37	0
Node 2 <-> Node 4	32	6
Node 3 <-> Node 5	32	8
Node 4 <-> Node 5	29	1
Node 4 <-> Node 6	33	7
Node 5 <-> Node 6	33	3

Table 4.104: Table with information regarding links for transparent mode with 1+1 protection.

In table 4.105 we can see the resulting nodal degree at the physical layer, the number of line ports and the number of add ports for the optical part calculated using 3.15 the number of LR transponders calculated using 3.14 and the number of tributary ports calculated using 3.13 for each node.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	290	11	11	30
2	3	230	25	25	84
3	3	180	16	16	84
4	3	200	8	8	94
5	3	240	23	23	94
6	2	220	31	31	66

Table 4.105: Table with information regarding nodes for transparent mode with 1+1 protection.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node.

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

Table 4.106: Transparent with 1+1 protection in medium scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used.

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

Table 4.107: Transparent with 1+1 protection in medium scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

Detailed description of Node 3		
Electrical part	Number of tributary ports	Bit rate
180 tributary ports	70	ODU0
	60	ODU1
	30	ODU2
	20	ODU3
	Node<–Optical Channels–>Node	Bit rate
16 LR Transponders	3 <—- 3 —-> 1	100 Gbits/s
	3 <—- 4 —-> 2	
	3 <—- 2 —-> 4	
	3 <—- 6 —-> 5	
	3 <—- 1 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
16 add ports	3 <—- 3 —-> 1	100 Gbits/s
	3 <—- 4 —-> 2	
	3 <—- 2 —-> 4	
	3 <—- 6 —-> 5	
	3 <—- 1 —-> 6	
84 line ports	3 <—- 3 —-> 1	
	3 <—- 4 —-> 2	
	3 <—- 2 —-> 4	
	3 <—- 6 —-> 5	
	3 <—- 1 —-> 6	
	1 <—- 3 —-> 2	
	1 <—- 2 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 2 —-> 6	
	2 <—- 1 —-> 4	
	2 <—- 2 —-> 5	
	2 <—- 15 —-> 6	

Table 4.108: Transparent with 1+1 protection in medium scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

Detailed description of Node 4		
Electrical part	Number of tributary ports	Bit rate
200 tributary ports	70	ODU0
	100	ODU1
	30	ODU2
	Node<–Optical Channels–>Node	Bit rate
8 LR Transponders	4 <—- 2 —-> 1	100 Gbits/s
	4 <—- 1 —-> 2	
	4 <—- 2 —-> 3	
	4 <—- 2 —-> 5	
	4 <—- 1 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
8 add ports	4 <—- 2 —-> 1	100 Gbits/s
	4 <—- 1 —-> 2	
	4 <—- 2 —-> 3	
	4 <—- 2 —-> 5	
	4 <—- 1 —-> 6	
94 line ports	4 <—- 2 —-> 1	
	4 <—- 1 —-> 2	
	4 <—- 2 —-> 3	
	4 <—- 2 —-> 5	
	4 <—- 1 —-> 6	
	1 <—- 1 —-> 5	
	1 <—- 2 —-> 6	
	2 <—- 2 —-> 5	
	2 <—- 15 —-> 6	
	3 <—- 6 —-> 5	
	3 <—- 1 —-> 6	
	5 <—- 12 —-> 6	

Table 4.109: Transparent with 1+1 protection in medium scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

Detailed description of Node 5		
Electrical part	Number of tributary ports	Bit rate
240 tributary ports	140	ODU0
	40	ODU1
	40	ODU2
	10	ODU3
	10	ODU4
	Node<–Optical Channels–>Node	Bit rate
23 LR Transponders	5 <—- 1 —-> 1	100 Gbits/s
	5 <—- 2 —-> 2	
	5 <—- 6 —-> 3	
	5 <—- 2 —-> 4	
	5 <—- 12 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
23 add ports	5 <—- 1 —-> 1	100 Gbits/s
	5 <—- 2 —-> 2	
	5 <—- 6 —-> 3	
	5 <—- 2 —-> 4	
	5 <—- 12 —-> 6	
94 line ports	5 <—- 1 —-> 1	
	5 <—- 2 —-> 2	
	5 <—- 6 —-> 3	
	5 <—- 2 —-> 4	
	5 <—- 12 —-> 6	
	1 <—- 2 —-> 4	
	1 <—- 2 —-> 6	
	2 <—- 1 —-> 4	
	2 <—- 15 —-> 6	
	3 <—- 2 —-> 4	
	3 <—- 1 —-> 6	
	4 <—- 1 —-> 6	

Table 4.110: Transparent with 1+1 protection in medium scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

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

Table 4.111: Transparent with 1+1 protection in medium scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

In next step let's focus on the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. In table 4.112 we can see all the routing obtained for all nodes.

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

Table 4.112: Transparent with 1+1 protection in medium scenario: Description of routing.

Finally and most importantly through table 4.113 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

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 €	13 020 900 €
		ODU0 Ports	600	10 €/port	6 000 €	
		ODU1 Ports	500	15 €/port	7 500 €	
		ODU2 Ports	160	30 €/port	4 800 €	
		ODU3 Ports	60	60 €/port	3 600 €	
		ODU4 Ports	40	100 €/port	4 000 €	
		Transponders	114	100 000 €/port	11 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	452	2 500 €/port	1 130 000 €	
		Add Ports	114	2 500 €/port	285 000 €	
Total Network Cost						239 540 900 €

Table 4.113: Transparent with 1+1 protection in medium scenario: Detailed description of CAPEX for this scenario.

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.3. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODU's mentioned in the section 2.5.3.

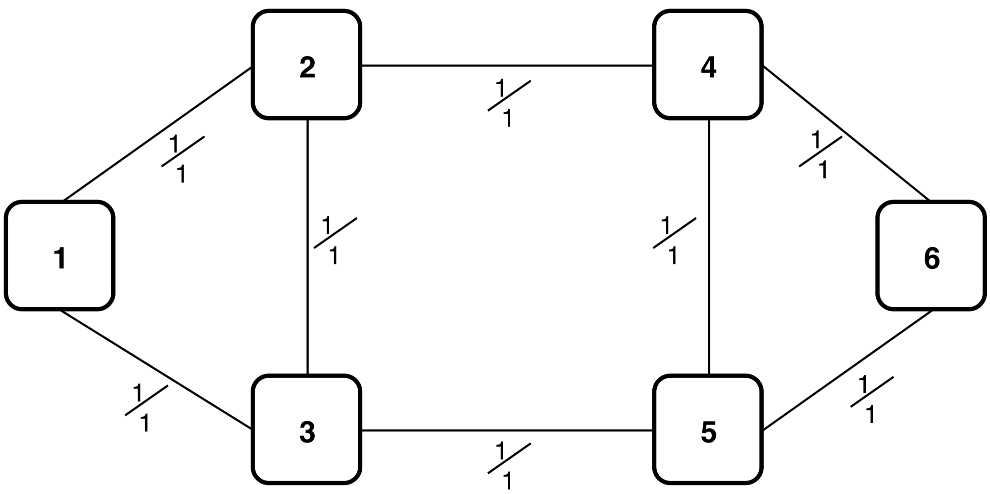

Figure 4.31: Transparent with 1+1 protection in high scenario: Physical topology after dimensioning.

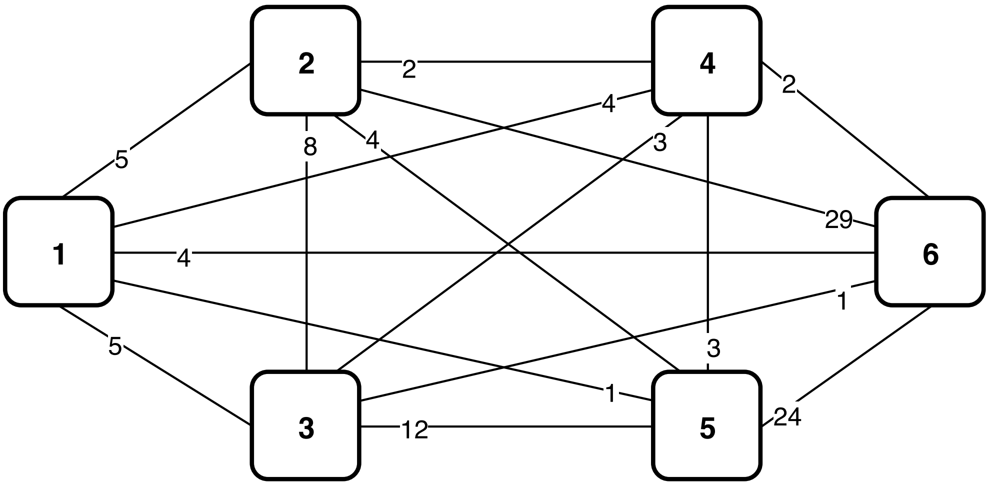

Figure 4.32: Transparent with 1+1 protection in high scenario: Optical topology after dimensioning.

In table 4.114 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	27	4
Node 1 <-> Node 3	27	6
Node 2 <-> Node 3	69	0
Node 2 <-> Node 4	60	6
Node 3 <-> Node 5	60	8
Node 4 <-> Node 5	55	1
Node 4 <-> Node 6	63	7
Node 5 <-> Node 6	63	3

Table 4.114: Table with information regarding links for transparent mode with 1+1 protection in high scenario.

In table 4.115 we can see the resulting nodal degree at the physical layer, the number of line ports and the number of add ports for the optical part calculated using 3.15 the number of LR transponders calculated using 3.14 and the number of tributary ports calculated using 3.13 for each node.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	580	19	19	54
2	3	460	48	48	156
3	3	360	29	29	156
4	3	400	14	14	178
5	3	480	44	44	178
6	2	440	60	60	126

Table 4.115: Table with information regarding nodes for transparent mode with 1+1 protection in high scenario.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node.

Detailed description of Node 1		
Electrical part	Number of tributary ports	Bit rate
580 tributary ports	260	ODU0
	260	ODU1
	60	ODU2
	Node<–Optical Channels–>Node	Bit rate
19 LR Transponders	1 <—- 5 —-> 2	100 Gbits/s
	1 <—- 5 —-> 3	
	1 <—- 4 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 4 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
19 add ports	1 <—- 5 —-> 2	100 Gbits/s
	1 <—- 5 —-> 3	
	1 <—- 4 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 4 —-> 6	
54 line ports	1 <—- 5 —-> 2	
	1 <—- 5 —-> 3	
	1 <—- 4 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 4 —-> 6	
	2 <—- 8 —-> 3	

Table 4.116: Transparent with 1+1 protection in high scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used.

Detailed description of Node 2		
Electrical part	Number of tributary ports	Bit rate
460 tributary ports	220	ODU0
	140	ODU1
	40	ODU2
	40	ODU3
	20	ODU4
Node<–Optical Channels–>Node	Bit rate	
48 LR Transponders	2 <—- 5 —-> 1	100 Gbits/s
	2 <—- 8 —-> 3	
	2 <—- 2 —-> 4	
	2 <—- 4 —-> 5	
	2 <—- 29 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
48 add ports	2 <—- 5 —-> 1	100 Gbits/s
	2 <—- 8 —-> 3	
	2 <—- 2 —-> 4	
	2 <—- 4 —-> 5	
	2 <—- 29 —-> 6	
156 line ports	2 <—- 5 —-> 1	
	2 <—- 8 —-> 3	
	2 <—- 2 —-> 4	
	2 <—- 4 —-> 5	
	2 <—- 29 —-> 6	
	1 <—- 5 —-> 3	
	1 <—- 4 —-> 4	
	1 <—- 1 —-> 5	
	1 <—- 4 —-> 6	
	3 <—- 3 —-> 4	
	3 <—- 12 —-> 5	
	3 <—- 1 —-> 6	

Table 4.117: Transparent with 1+1 protection in high scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

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

Table 4.118: Transparent with 1+1 protection in high scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

Detailed description of Node 4		
Electrical part	Number of tributary ports	Bit rate
400 tributary ports	140	ODU0
	200	ODU1
	60	ODU2
	Node<–Optical Channels–>Node	Bit rate
14 LR Transponders	4 <—- 4 —-> 1	100 Gbits/s
	4 <—- 2 —-> 2	
	4 <—- 3 —-> 3	
	4 <—- 3 —-> 5	
	4 <—- 2 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
14 add ports	4 <—- 4 —-> 1	100 Gbits/s
	4 <—- 2 —-> 2	
	4 <—- 3 —-> 3	
	4 <—- 3 —-> 5	
	4 <—- 2 —-> 6	
178 line ports	4 <—- 4 —-> 1	
	4 <—- 2 —-> 2	
	4 <—- 3 —-> 3	
	4 <—- 3 —-> 5	
	4 <—- 2 —-> 6	
	1 <—- 1 —-> 5	
	1 <—- 4 —-> 6	
	2 <—- 4 —-> 5	
	2 <—- 29 —-> 6	
	3 <—- 12 —-> 5	
	3 <—- 1 —-> 6	
	5 <—- 24 —-> 6	

Table 4.119: Transparent with 1+1 protection in high scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

Detailed description of Node 5		
Electrical part	Number of tributary ports	Bit rate
480 tributary ports	280 80 80 20 20	ODU0 ODU1 ODU2 ODU3 ODU4
Node<–Optical Channels–>Node	Bit rate	
44 LR Transponders	5 <—- 1 —-> 1 5 <—- 4 —-> 2 5 <—- 12 —-> 3 5 <—- 3 —-> 4 5 <—- 24 —-> 6	100 Gbits/s
Optical part	Node<–Optical Channels–>Node	Bit rate
44 add ports	5 <—- 1 —-> 1 5 <—- 4 —-> 2 5 <—- 12 —-> 3 5 <—- 3 —-> 4 5 <—- 24 —-> 6	100 Gbits/s
178 line ports	5 <—- 1 —-> 1 5 <—- 4 —-> 2 5 <—- 12 —-> 3 5 <—- 3 —-> 4 5 <—- 24 —-> 6 1 <—- 4 —-> 4 1 <—- 4 —-> 6 2 <—- 2 —-> 4 2 <—- 29 —-> 6 3 <—- 3 —-> 4 3 <—- 1 —-> 6 4 <—- 2 —-> 6	

Table 4.120: Transparent with 1+1 protection in high scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

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

Table 4.121: Transparent with 1+1 protection in high scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3 . Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used. In both cases the number of ports is double the number of optical channels.

Now let's focus on the routing information in table 4.122. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

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

Table 4.122: Transparent with 1+1 protection in high scenario: Description of routing.

Finally and most importantly through table 4.92 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

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 €	24 286 800 €
		ODU0 Ports	1 200	10 €/port	12 000 €	
		ODU1 Ports	1 000	15 €/port	15 000 €	
		ODU2 Ports	320	30 €/port	9 600 €	
		ODU3 Ports	120	60 €/port	7 200 €	
		ODU4 Ports	80	100 €/port	8 000 €	
		Transponders	214	100 000 €/port	21 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	848	2 500 €/port	2 120 000 €	
		Add Ports	214	2 500 €/port	535 000 €	
Total Network Cost						448 806 800 €

Table 4.123: Transparent with 1+1 protection in high scenario: Detailed description of CAPEX for this scenario.

4.4.3 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 4.93.

	Low Traffic	Medium Traffic	High Traffic
CAPEX without survivability	30 317 590 €	96 830 900 €	180 471 800 €
CAPEX/Gbit/s without survivability	60 630 €/Gbit/s	19 366 €/Gbit/s	18 047 €/Gbit/s
Traffic (Gbit/s)	500	5 000	10 000
Number of Add ports	34	114	214
Number of Line ports	136	452	848
Number of Tributary ports	138	1 380	2 760
Number of Transceivers	136	452	848
Number of Transponders	34	114	214
Link Cost	68 520 000 €	226 520 000 €	424 520 000 €
Node Cost	3 947 590 €	13 020 900 €	24 286 800 €
CAPEX	**72 467 590 €**	**239 540 900€**	**448 806 800 €**
CAPEX/Gbit/s	**144 935 €/Gbit/s**	**47 908 €/Gbit/s**	**44 880 €/Gbit/s**

Table 4.124: Transparent with 1+1 protection in high scenario: Table with different value of CAPEX for this case.

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

- Comparing the low traffic scenario with the others, we can see that, despite having an increase of factor ten (average scenario) and factor twenty (high scenario), the same increase does not occur in the final cost (it is lower). This happens because the number of transceivers is smaller than expected (an medium scenario of 1360 would be expected and a high scenario would be expected in 2720);
- Comparing the medium traffic scenario with the high traffic scenario, we can see that the factor increase is double and in the final cost this factor is very close but still lower. Again, this happens because the number of transceivers is smaller, but very close to what was expected (the high scenario would be expected at 904);
- Comparing the cost with the traffic, we see that, for the low traffic scenario, the cost per traffic is very high in relation to the other two. We can conclude that a low traffic scenario becomes more expensive than a high traffic scenario.
- Comparing this cost with the without survivability cost we can conclude that protection is significantly more expensive. As can be seen in the table this increase is more than double as with 1+1 protection we have a cost more than twice than the cost without survivability.

4.5 Translucent without Survivability

4.5.1 Model description

First of all, in order to use the ILP model, we must take into account the physical and logical topologies allowed by this mode of transport and the type of survivability. Through the following figures, you can see these topologies.

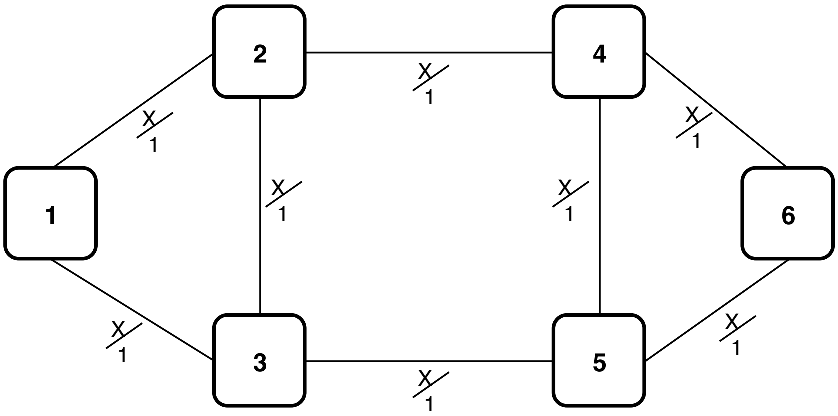

Figure 4.33: Translucent without survivability: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

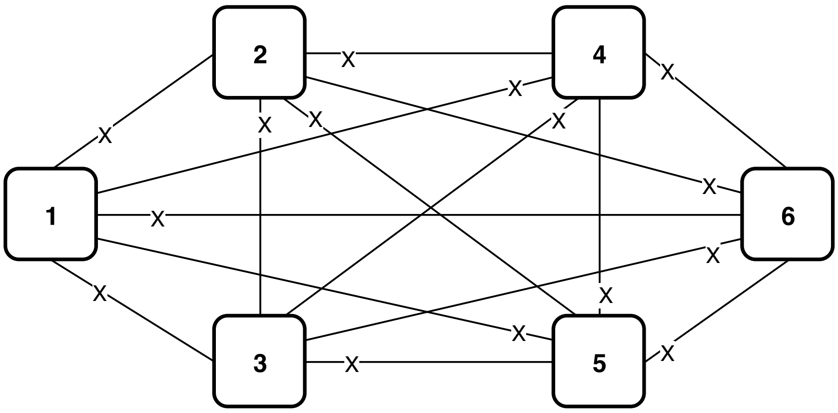

Figure 4.34: Translucent without survivability: Allowed optical topology. The allowed optical topology is defined by the transport mode. It is assumed that each connections between demands supports up to 100 lightpaths.

Now taking this into consideration and based on the specific constraints of the translucent mode without survivability it is possible to define the ILP model.

The objective function, to be minimized, is the expression 3.7, i.e.,

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

$subject\ to$

$$\sum_{k\backslash\{o\}} Ls_{pk}^{odc} = D_{odc} \qquad \forall(o,d,c) : o < d, \forall p : p = o \qquad (4.32)$$

This are the virtual flow conservation constraints and ensure that, for each (o, d) pair, we route client demand units of flow from node o to node d, the source node sends client demand units of flow.

$$\sum_{k\backslash\{p,o\}} Ls_{pk}^{odc} = \sum_{k\backslash\{p,d\}} Ls_{kp}^{odc} \qquad \forall(o,d,c) : o < d, \forall p : p \neq o, d \qquad (4.33)$$

This constraint ensure that the remaining nodes, being neither origin or destination, the receive flow have to be send.

$$\sum_{k\backslash\{d\}} Ls_{kp}^{odc} = D_{odc} \qquad \forall(o,d,c) : o < d, \forall p : p = d \qquad (4.34)$$

This are the virtual flow conservation constraints and ensure that, for each (o, d) pair, we route client demand units of flow from node o to node d, the destination node has to receive those client demand units of flow.

$$\sum_{o=1} \sum_{d=o+1} B(c)(Ls_{pk}^{odc} + Ls_{kp}^{odc}) \leq \tau\lambda_{pk} \qquad \forall(p,k) : p < k, \forall c \qquad (4.35)$$

This restriction is considered grooming constraint and the variable τ is always 100 Gbits/s.

$$\sum_{j\backslash\{p\}} f_{ij}^{pk} = \lambda_{pk} \qquad \forall(p,k) : p < k, \forall i : i = p \qquad (4.36)$$

This constraint are equal to the constraint 3.8 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{j\backslash\{p\}} f_{ij}^{pk} = \sum_{j\backslash\{k\}} f_{ji}^{pk} \qquad \forall(p,k) : p < k, \forall i : i \neq p, k \qquad (4.37)$$

This constraint are equal to the constraint 3.9.

$$\sum_{j\backslash\{k\}} f_{ji}^{pk} = \lambda_{pk} \qquad \forall(p,k) : p < k, \forall i : i = k \qquad (4.38)$$

This constraint are equal to the constraint 3.10 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{p=1} \sum_{k=p+1} \left(f_{ij}^{pk} + f_{ji}^{pk} \right) \leq K_{ij} G_{ij} L_{ij} \qquad \forall(i,j) : i < j \qquad (4.39)$$

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

$$f_{ij}^{pk}, f_{ji}^{pk}, Ls_{pk}^{odc}, Ls_{kp}^{odc}, \lambda_{pk} \in \mathbb{N} \qquad \forall(i,j) : i < j, \forall(o,d) : o < d \qquad (4.40)$$

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

$$L_{i,j} \in \{0,1\} \qquad \forall(i,j) \qquad (4.41)$$

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

4.5.2 Result description

To perform the calculations using the implementation of the models described previously it is necessary to use once more the MATLAB. We have all the necessary to obtain the CAPEX value for the reference network 2.4.

Low Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.1. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.1.

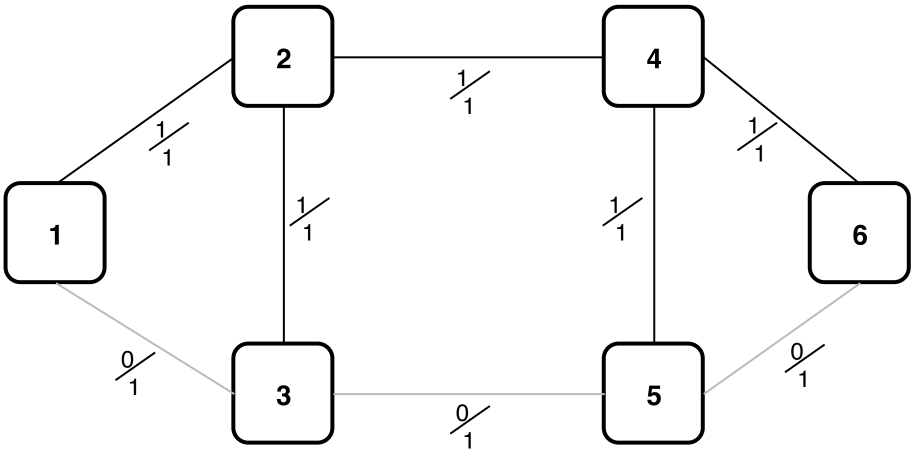

Figure 4.35: Translucent without survivability in low scenario: Physical topology after dimensioning.

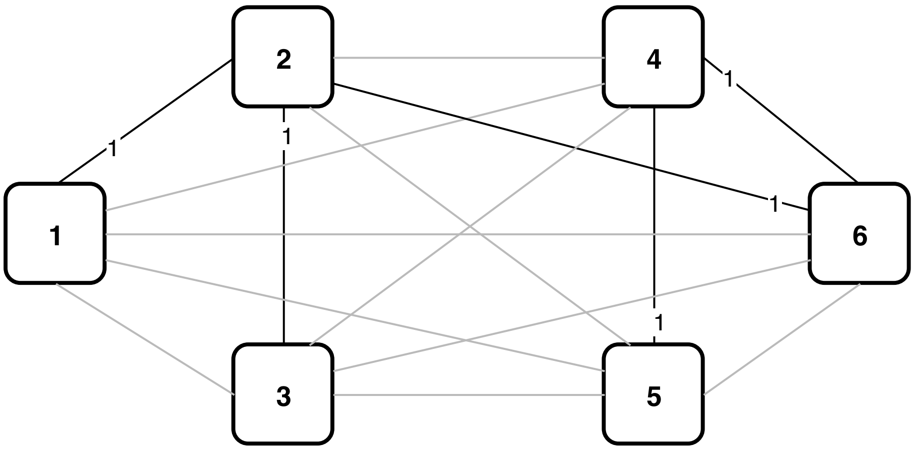

Figure 4.36: Translucent without survivability in low scenario: Optical topology after dimensioning.

In table 4.125 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3. In the case where there are no optical channels we assume that the number of amplifiers is zero.

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

Table 4.125: Table with information regarding links for translucent mode without survivability in low scenario.

In table 4.126 we can see the resulting nodal degree at the physical layer, the number of line ports and add ports using 3.18 the number of LR transponders using 3.17 and the number of tributary ports using 3.16.

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

Table 4.126: Table with information regarding nodes for translucent mode without survivability in low scenario.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node. In each table mentioned below we can see how many ports are connected to a given node and its bit rate, the number of LR transponders and how many ports are assigned to each different bit rate.

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

Table 4.127: Translucent without survivability in low scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.128: Translucent without survivability in low scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.129: Translucent without survivability in low scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.130: Translucent without survivability in low scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1. Regarding the number of line ports when this node is different to the source, it means that through ports are used. In the latter the number of ports is double the number of optical channels.

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

Table 4.131: Translucent without survivability in low scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.132: Translucent without survivability in low scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

Now, let's focus on the routing information in table 4.133. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

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

Table 4.133: Translucent without survivability in low scenario: Description of demands routing. In this case all the demands follow the same path for a certain pair of nodes, but this may not happen for other cases.

Lastly through table 4.134 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		10	15 000 €	150 000 €	6 294 000 €
	100 Gbits/s Transceivers		12	5 000 €/Gbit/s	6 000 000 €	
	Amplifiers		36	4 000 €	144 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	1 237 590 €
		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	10	100 000 €/port	1 000 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	12	2 500 €/port	30 000 €	
		Add Ports	10	2 500 €/port	25 000 €	
Total Network Cost						7 531 590 €

Table 4.134: Translucent without survivability in low scenario: Detailed description of CAPEX for this scenario.

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.2. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.2.

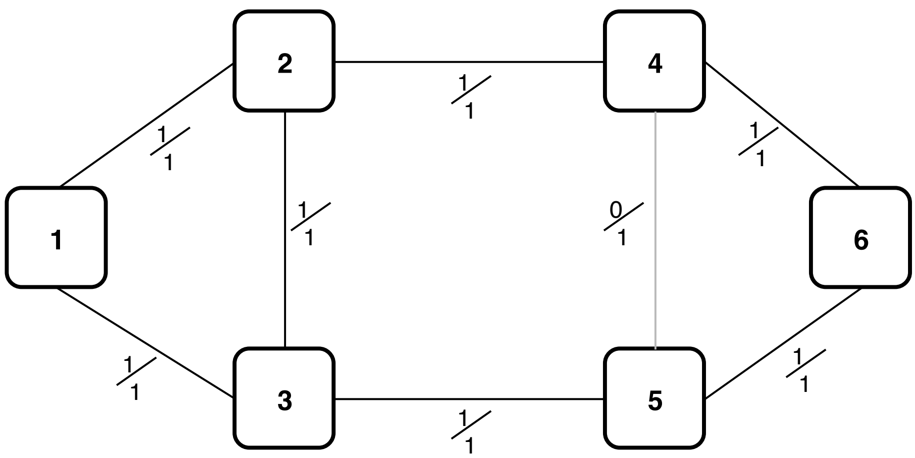

Figure 4.37: Translucent without survivability in medium scenario: Physical topology after dimensioning.

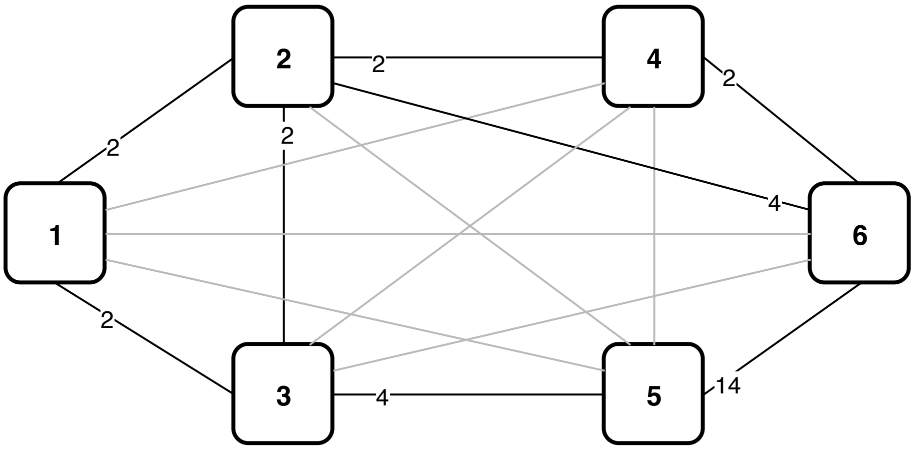

Figure 4.38: Translucent without survivability in medium scenario: Optical topology after dimensioning.

In table 4.135 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3. In table 4.136 we can see the resulting nodal degree at the physical layer, the number of line ports and add ports using 3.18 the number of LR transponders using 3.17 and the number of tributary ports using 3.16.

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

Table 4.135: Table with information regarding links for translucent mode without survivability in medium scenario.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	290	4	4	4
2	3	230	10	10	10
3	3	180	8	8	8
4	2	200	4	4	12
5	2	240	18	18	18
6	2	220	20	20	20

Table 4.136: Table with information regarding nodes for translucent mode without survivability in medium scenario.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node.

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

Optical part	Node<–Optical Channels–>Node	Bit rate
4 add ports	1 <—- 2 —-> 2	100 Gbits/s
	1 <—- 2 —-> 3	
4 line ports	1 <—- 2 —-> 2	
	1 <—- 2 —-> 3	

Table 4.137: Translucent without survivability in medium scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Optical part	Node<–Optical Channels–>Node	Bit rate
10 add ports	2 <—- 2 —-> 1	100 Gbits/s
	2 <—- 2 —-> 3	
	2 <—- 2 —-> 4	
	2 <—- 4 —-> 6	
10 line ports	2 <—- 2 —-> 1	
	2 <—- 2 —-> 3	
	2 <—- 2 —-> 4	
	2 <—- 4 —-> 6	

Table 4.138: Translucent without survivability in medium scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.139: Translucent without survivability in medium scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

Detailed description of Node 4		
Electrical part	Number of total demands	Bit rate
200 tributary ports	70 100 30	ODU0 ODU1 ODU2
	Node<–Optical Channels–>Node	Bit rate
4 LR Transponders	4 <—- 2 —-> 2 4 <—- 2 —-> 6	100 Gbits/s
Optical part	Node<–Optical Channels–>Node	Bit rate
4 add ports	4 <—- 2 —-> 2 4 <—- 2 —-> 6	100 Gbits/s
12 line ports	4 <—- 2 —-> 2 4 <—- 2 —-> 6 2 <—- 4 —-> 6	

Table 4.140: Translucent without survivability in medium scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2. Regarding the number of line ports when this node is equal to the source, it means that add ports are used, otherwise it means that through ports are used.

Detailed description of Node 5		
Electrical part	Number of total demands	Bit rate
240 tributary ports	140 40 40 10 10	ODU0 ODU1 ODU2 ODU3 ODU4
	Node<–Optical Channels–>Node	Bit rate
18 LR Transponders	5 <—- 4 —-> 3 5 <—- 14 —-> 6	100 Gbits/s
Optical part	Node<–Optical Channels–>Node	Bit rate
18 add ports	5 <—- 4 —-> 3 5 <—- 14 —-> 6	100 Gbits/s
18 line ports	5 <—- 4 —-> 3 5 <—- 14 —-> 6	

Table 4.141: Translucent without survivability in medium scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

Detailed description of Node 6		
Electrical part	Number of total demands	Bit rate
220 tributary ports	80 100 10 10 20	ODU0 ODU1 ODU2 ODU3 ODU4
	Node<–Optical Channels–>Node	Bit rate
20 LR Transponders	6 <—- 4 —-> 2 6 <—- 2 —-> 4 6 <—- 14 —-> 5	100 Gbits/s
Optical part	Node<–Optical Channels–>Node	Bit rate
20 add ports	6 <—- 4 —-> 2 6 <—- 2 —-> 4 6 <—- 14 —-> 5	100 Gbits/s
20 line ports	6 <—- 4 —-> 2 6 <—- 2 —-> 4 6 <—- 14 —-> 5	

Table 4.142: Translucent without survivability in medium scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

Now let's focus on the routing information in table 4.143. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

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

Table 4.143: Translucent without survivability in medium scenario: Description of demands routing. In this case some demands follow different paths for the same pair of nodes.

Finally and most importantly through table 4.144 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		14	15 000 €	210 000 €	36 482 000 €
	100 Gbits/s Transceivers		72	5 000 €/Gbit/s	36 000 000 €	
	Amplifiers		68	4 000 €	272 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	6 945 900 €
		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	64	100 000 €/port	6 400 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	72	2 500 €/port	180 000 €	
		Add Ports	64	2 500 €/port	160 000 €	
Total Network Cost						43 427 900 €

Table 4.144: Translucent without survivability in medium scenario: Detailed description of CAPEX for this scenario.

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.3. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.3.

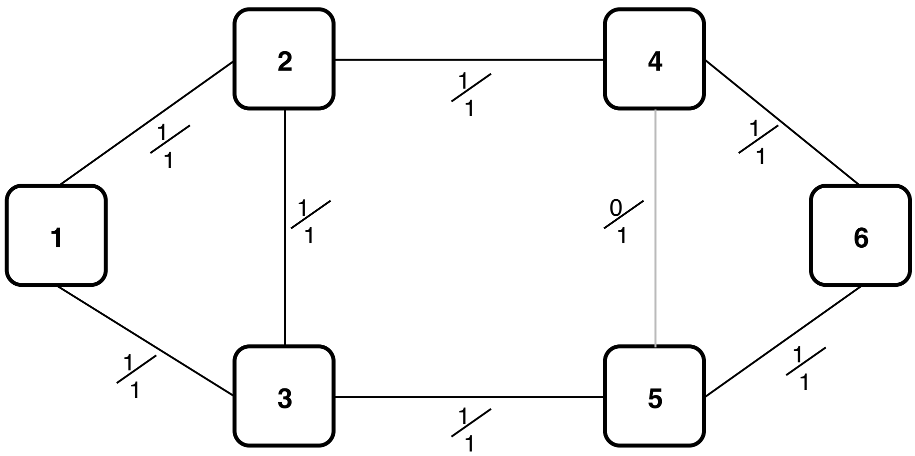

Figure 4.39: Translucent without survivability in high scenario: Physical topology after dimensioning.

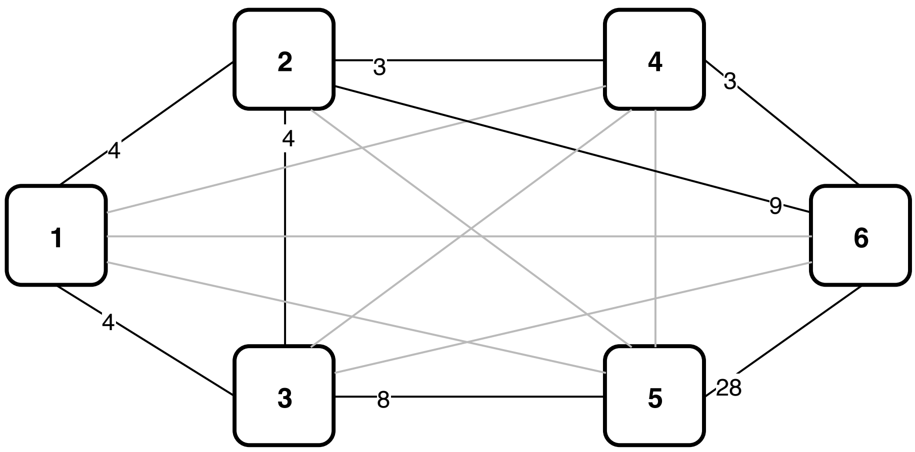

Figure 4.40: Translucent without survivability in high scenario: Optical topology after dimensioning.

In table 4.145 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3. In table 4.146 we can see the resulting nodal degree at the physical layer, the number of line ports and add ports using 3.18 the number of LR transponders using 3.17 and the number of tributary ports using 3.16.

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

Table 4.145: Table with information regarding links for translucent mode without survivability in high scenario.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	580	8	8	8
2	3	460	20	20	20
3	3	360	16	16	16
4	2	400	6	6	24
5	2	480	36	36	36
6	2	440	40	40	40

Table 4.146: Table with information regarding nodes for translucent mode without survivability in high scenario.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node.

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

Table 4.147: Translucent without survivability in high scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

Detailed description of Node 2		
Electrical part	Number of total demands	Bit rate
230 tributary ports	110	ODU0
	70	ODU1
	20	ODU2
	20	ODU3
	10	ODU4
	Node<–Optical Channels–>Node	Bit rate
20 LR Transponders	2 <—- 4 —-> 1	100 Gbits/s
	2 <—- 4 —-> 3	
	2 <—- 3 —-> 4	
	2 <—- 9 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
20 add ports	2 <—- 4 —-> 1	100 Gbits/s
	2 <—- 4 —-> 3	
	2 <—- 3 —-> 4	
	2 <—- 9 —-> 6	
20 line ports	2 <—- 4 —-> 1	
	2 <—- 4 —-> 3	
	2 <—- 3 —-> 4	
	2 <—- 9 —-> 6	

Table 4.148: Translucent without survivability in high scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

Detailed description of Node 3		
Electrical part	Number of total demands	Bit rate
180 tributary ports	70	ODU0
	60	ODU1
	30	ODU2
	20	ODU3
	Node<–Optical Channels–>Node	Bit rate
16 LR Transponders	3 <—- 4 —-> 1	100 Gbits/s
	3 <—- 4 —-> 2	
	3 <—- 8 —-> 5	
Optical part	Node<–Optical Channels–>Node	Bit rate
16 add ports	3 <—- 4 —-> 1	100 Gbits/s
	3 <—- 4 —-> 2	
	3 <—- 8 —-> 5	
16 line ports	3 <—- 4 —-> 1	
	3 <—- 4 —-> 2	
	3 <—- 8 —-> 5	

Table 4.149: Translucent without survivability in high scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

Detailed description of Node 4		
Electrical part	Number of total demands	Bit rate
200 tributary ports	70	ODU0
	100	ODU1
	30	ODU2
	Node<–Optical Channels–>Node	Bit rate
6 LR Transponders	4 <—- 3 —-> 2	100 Gbits/s
	4 <—- 3 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
6 add ports	4 <—- 3 —-> 2	100 Gbits/s
	4 <—- 3 —-> 6	
24 line ports	4 <—- 3 —-> 2	
	4 <—- 3 —-> 6	
	2 <—- 9 —-> 6	

Table 4.150: Translucent without survivability in high scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

Detailed description of Node 5		
Electrical part	Number of total demands	Bit rate
240 tributary ports	140	ODU0
	40	ODU1
	40	ODU2
	10	ODU3
	10	ODU4
	Node<–Optical Channels–>Node	Bit rate
36 LR Transponders	5 <—- 8 —-> 3	100 Gbits/s
	5 <—- 28 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
36 add ports	5 <—- 8 —-> 3	100 Gbits/s
	5 <—- 28 —-> 6	
36 line ports	5 <—- 8 —-> 3	
	5 <—- 28 —-> 6	

Table 4.151: Translucent without survivability in high scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

Detailed description of Node 6		
Electrical part	Number of total demands	Bit rate
220 tributary ports	80 100 10 10 20	ODU0 ODU1 ODU2 ODU3 ODU4
	Node<–Optical Channels–>Node	Bit rate
40 LR Transponders	6 <—- 9 —-> 2 6 <—- 9 —-> 4 6 <—- 28 —-> 5	100 Gbits/s
Optical part	Node<–Optical Channels–>Node	Bit rate
40 add ports	6 <—- 9 —-> 2 6 <—- 3 —-> 4 6 <—- 28 —-> 5	100 Gbits/s
40 line ports	6 <—- 9 —-> 2 6 <—- 3 —-> 4 6 <—- 28 —-> 5	

Table 4.152: Translucent without survivability in high scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

In next page, we can see the routing information in table 4.154. These paths are bidirectional so the path from one node to another is the same path in the opposite direction. Lastly through table 4.153 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		14	15 000 €	210 000 €	72 482 000 €
	100 Gbits/s Transceivers		144	5 000 €/Gbit/s	72 000 000 €	
	Amplifiers		68	4 000 €	272 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	13 506 800 €
		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	126	100 000 €/port	12 600 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	144	2 500 €/port	360 000 €	
		Add Ports	126	2 500 €/port	315 000 €	
Total Network Cost						85 988 800 €

Table 4.153: Translucent without survivability in high scenario: Detailed description of CAPEX for this scenario.

Routing			
o	d	Links	Demands
1	2	{(1,2)}	100 ODU0, 40 ODU1, 20 ODU2
1	3	{(1,3)}	20 ODU0, 80 ODU1, 20 ODU2
1	4	{(1,2),(2,4)} {(1,2),(2,4),(4,6),(6,4)}	60 ODU0, 20 ODU1, 10 ODU2 20 ODU1, 10 ODU2
1	5	{(1,3),(3,5)}	20 ODU0
1	6	{(1,2),(2,4),(4,6)} {(1,3),(3,5),(5,6)}	60 ODU0, 80 ODU1 20 ODU1
2	3	{(2,1),(1,3)} {(2,3)}	10 ODU3 10 ODU3
2	4	{(2,4)}	20 ODU0, 60 ODU1
2	5	{(2,3),(3,5)}	100 ODU0, 20 ODU1, 20 ODU2
2	6	{(2,4),(4,6)} {(2,1),(1,3),(3,5),(5,6)} {(2,3),(3,5),(5,6)}	20 ODU1, 20 ODU3, 12 ODU4 4 ODU4 4 ODU4
3	4	{(3,2),(2,4)} {(3,5),(5,6),(6,4)}	20 ODU0, 20 ODU1 20 ODU2
3	5	{(3,2),(2,4),(4,6),(6,4),(4,5)}	80 ODU0, 20 ODU1, 20 ODU2, 20 ODU3
3	6	{(3,2),(2,4),(4,6)}	20 ODU0
4	5	{(4,5)}	20 ODU0, 20 ODU1, 20 ODU2
4	6	{(4,6)}	20 ODU0, 60 ODU1
5	6	{(5,4),(4,6)}	60 ODU0, 20 ODU1, 20 ODU2, 20 ODU4

Table 4.154: Translucent without survivability in high scenario: Description of demands routing. In this case some demands follow different paths for the same pair of nodes.

4.5.3 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 4.155 with the number of line ports and add ports of the optical part, the tributary ports, the transponders and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

	Low Traffic	Medium Traffic	High Traffic
Traffic (Gbit/s)	500	5 000	10 000
Number of Add ports	10	64	126
Number of Line ports	12	72	144
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	12	72	144
Number of Transponders	10	64	126
Link Cost	6 294 000 €	36 482 000 €	72 482 000 €
Node Cost	1 237 590 €	6 945 900 €	13 506 800 €
CAPEX	**7 531 590 €**	**43 427 900 €**	**85 988 800 €**
CAPEX/Gbit/s	**15 063 €/Gbit/s**	**8 686 €/Gbit/s**	**8 599 €/Gbit/s**

Table 4.155: Translucent without survivability: Table with the various CAPEX values obtained in the different traffic scenarios.

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

- Comparing the low traffic scenario with the others, we can see that, despite having an increase of factor ten (average scenario) and factor twenty (high scenario), the same increase does not occur in the final cost (it is lower). This happens because the number of transceivers is smaller than expected (an medium scenario of 120 would be expected and a high scenario would be expected in 240);
- Comparing the medium traffic scenario with the high traffic scenario, we can see that the factor increase is double and in the final cost this factor is very close but still lower;
- Comparing the cost with the traffic, we see that, for the low traffic scenario, the cost per traffic is very high in relation to the other two. We can conclude that a low traffic scenario becomes more expensive than a high traffic scenario.

4.6 Translucent with 1+1 Protection

4.6.1 Model description

Once more first of all, in order to use the ILP model, we must take into account the physical and logical topologies allowed by this mode of transport and the type of survivability. Through the following figures, you can see these topologies.

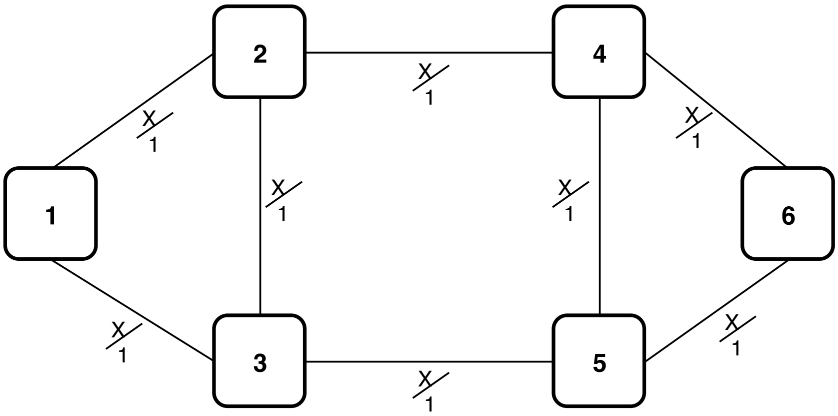

Figure 4.41: Translucent with 1+1 protection: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

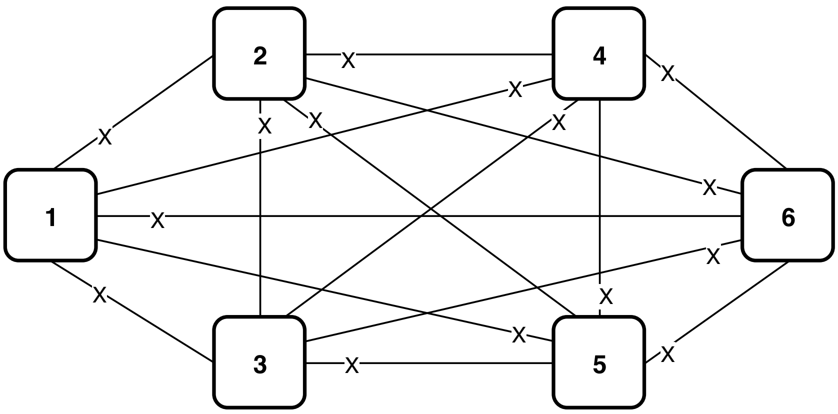

Figure 4.42: Translucent with 1+1 protection: Allowed optical topology. The allowed optical topology is defined by the transport mode. It is assumed that each connections between demands supports up to 100 lightpaths.

Now taking this into consideration and based on the specific constraints of the translucent mode with 1+1 protection it is possible to define the ILP model.

The objective function, to be minimized, is the expression 3.7, i.e.,

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

subject to

$$\sum_{k\backslash\{o\}} Ls_{pk}^{odc} = D_{odc} \qquad \forall(o,d,c) : o < d, \forall p : p = o \qquad (4.42)$$

This are the virtual flow conservation constraints and ensure that, for each (o,d) pair, we route client demand units of flow from node o to node d, the source node sends client demand units of flow.

$$\sum_{k\backslash\{p,o\}} Ls_{pk}^{odc} = \sum_{k\backslash\{p,d\}} Ls_{kp}^{odc} \qquad \forall(o,d,c) : o < d, \forall p : p \neq o, d \qquad (4.43)$$

This constraint ensure that the remaining nodes, being neither origin or destination, the receive flow have to be send.

$$\sum_{k\backslash\{d\}} Ls_{kp}^{odc} = D_{odc} \qquad \forall(o,d,c) : o < d, \forall p : p = d \qquad (4.44)$$

This are the virtual flow conservation constraints and ensure that, for each (o,d) pair, we route client demand units of flow from node o to node d, the destination node has to receive those client demand units of flow.

$$\sum_{k\backslash\{o\}} Lsp_{pk}^{odc} = D_{odc} \qquad \forall(o,d,c) : o < d, \forall p : p = o \qquad (4.45)$$

This are the virtual protection flow conservation constraints and ensure that, for each (o,d) pair, we route client demand units of flow from node o to node d, the source node sends client demand units of flow.

$$\sum_{k\backslash\{p,o\}} Lsp_{pk}^{odc} = \sum_{k\backslash\{p,d\}} Lsp_{kp}^{odc} \qquad \forall(o,d,c) : o < d, \forall p : p \neq o, d \qquad (4.46)$$

This constraint ensure that the remaining nodes for protection, being neither origin or destination, the receive flow have to be send.

$$\sum_{k\backslash\{d\}} Lsp_{kp}^{odc} = D_{odc} \qquad \forall(o,d,c) : o < d, \forall p : p = d \qquad (4.47)$$

This are the virtual protection flow conservation constraints and ensure that, for each (o,d) pair, we route client demand units of flow from node o to node d, the destination node has to receive those client demand units of flow.

$$(Ls_{pk}^{odc} + Lsp_{pk}^{odc}) \leq D_{odc} \qquad \forall(p,k), \forall(o,d,c) : o < d \quad (4.48)$$

This constraint assures us that the variable Ls_{pk}^{odc} (working flow) and Lsp_{pk}^{odc} (protection flow) are different.

$$\sum_{o=1} \sum_{d=o+1} \sum_{c=1} B(c)(Ls_{pk}^{odc} + Ls_{kp}^{odc} + Lsp_{pk}^{odc} + Lsp_{kp}^{odc}) \leq \tau\lambda_{pk} \qquad \forall(p,k) : p < k \quad (4.49)$$

This restriction is considered grooming constraint and the variable τ is always 100 Gbits/s.

$$\sum_{j\backslash\{p\}} f_{ij}^{pk} = \lambda_{pk} \qquad \forall(p,k) : p < k, \forall i : i = p \quad (4.50)$$

This constraint are equal to the constraint 3.8 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{j\backslash\{p\}} f_{ij}^{pk} = \sum_{j\backslash\{k\}} f_{ji}^{pk} \qquad \forall(p,k) : p < k, \forall i : i \neq p,k \quad (4.51)$$

This constraint are equal to the constraint 3.9.

$$\sum_{j\backslash\{k\}} f_{ji}^{pk} = \lambda_{pk} \qquad \forall(p,k) : p < k, \forall i : i = k \quad (4.52)$$

This constraint are equal to the constraint 3.10 assuming that Z variable has the value of number of optical channels between this demand for all bidirectional links.

$$\sum_{p=1} \sum_{k=p+1} \left(f_{ij}^{pk} + f_{ji}^{pk} \right) \leq K_{ij}G_{ij}L_{ij} \qquad \forall(i,j) : i < j \quad (4.53)$$

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

$$f_{ij}^{pk}, f_{ji}^{pk}, Ls_{pk}^{odc}, Ls_{kp}^{odc}, \lambda_{pk} \in \mathbb{N} \qquad \forall(i,j) : i < j, \forall(o,d) : o < d \quad (4.54)$$

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

$$L_{i,j} \in \{0,1\} \qquad \forall(i,j) \quad (4.55)$$

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

4.6.2 Result description

Low Traffic Scenario:

In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.1.

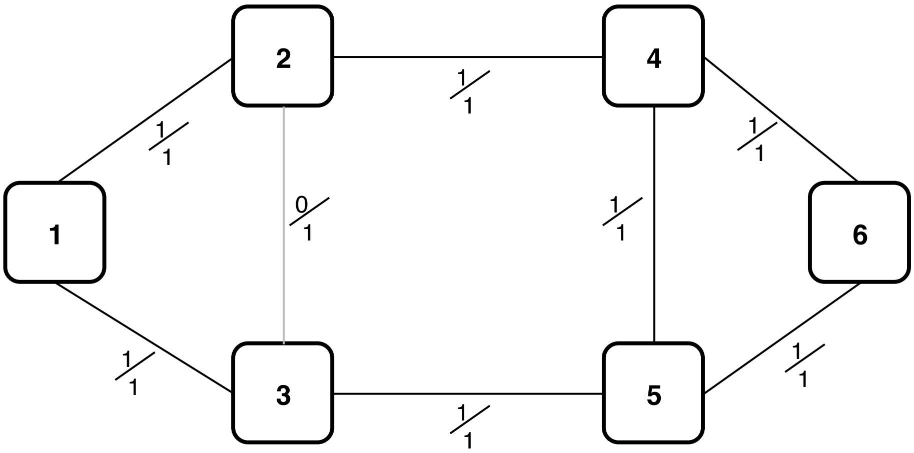

Figure 4.43: Translucent with 1+1 protection in low scenario: Physical topology after dimensioning.

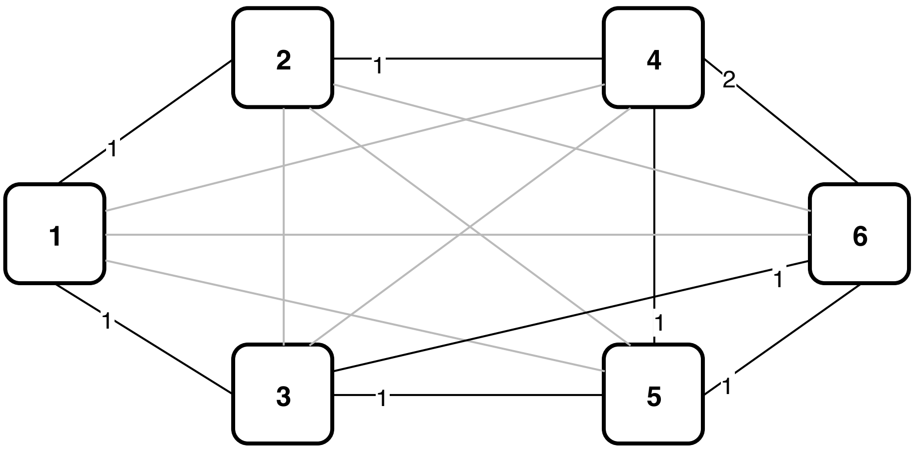

Figure 4.44: Translucent with 1+1 protection in low scenario: Optical topology after dimensioning.

In table 4.156 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3. In the case where there are no optical channels we assume that the number of amplifiers is zero.

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

Table 4.156: Table with information regarding links for translucent mode with 1+1 protection in low scenario.

In table 4.157 we can see the resulting nodal degree at the physical layer, calculated based on the number of connections that the node in question performs, the number of line ports and add ports using 3.18 the number of long-reach transponders using 3.17 and the number of tributary ports using 3.16.

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

Table 4.157: Table with information regarding nodes for translucent mode with 1+1 protection in low scenario.

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

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

Table 4.158: Translucent with 1+1 protection in low scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.159: Translucent with 1+1 protection in low scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.160: Translucent with 1+1 protection in low scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.161: Translucent with 1+1 protection in low scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.162: Translucent with 1+1 protection in low scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

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

Table 4.163: Translucent with 1+1 protection in low scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.1.

Now let's focus on the routing information in table 4.164. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

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

Table 4.164: Translucent with 1+1 protection in low scenario: Description of demands routing. The type W means that it is working path and type P protection path.

Lastly and most importantly through table 4.165 we can see the CAPEX result for this model. This value is obtained using equation 3.7 and all of the constraints mentioned above.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		14	15 000 €	210 000 €	10 490 000 €
	100 Gbits/s Transceivers		20	5 000 €/Gbit/s	10 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	2 077 590 €
		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	20	2 500 €/port	50 000 €	
		Add Ports	18	2 500 €/port	45 000 €	
Total Network Cost						12 567 590 €

Table 4.165: Translucent with 1+1 protection in low scenario: Detailed description of CAPEX for this scenario.

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.2. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.2.

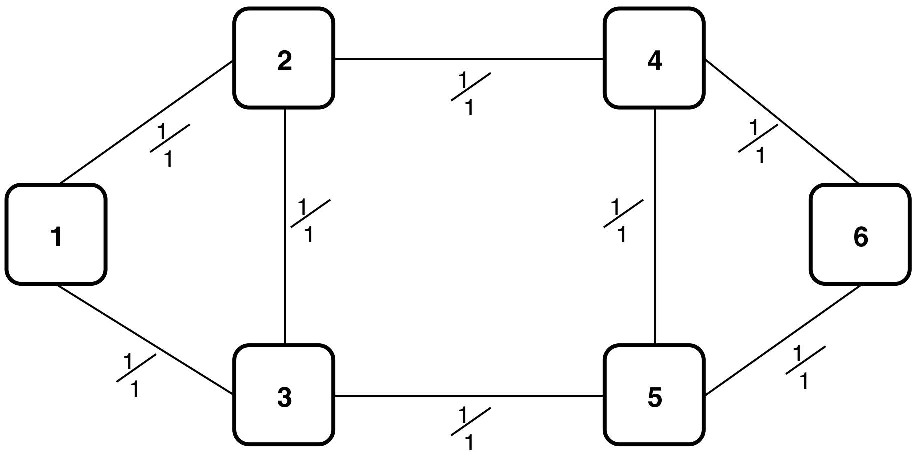

Figure 4.45: Translucent with 1+1 protection in medium scenario: Physical topology after dimensioning.

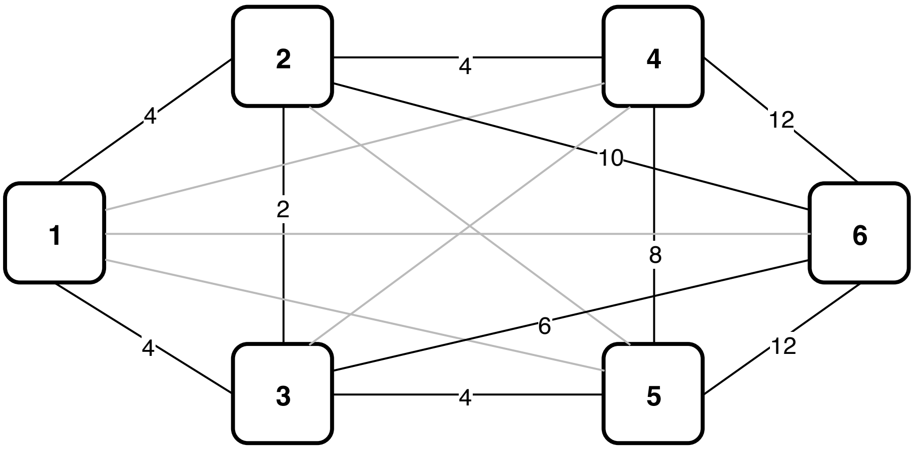

Figure 4.46: Translucent with 1+1 protection in medium scenario: Optical topology after dimensioning.

In table 4.166 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	4	4
Node 1 <-> Node 3	4	6
Node 2 <-> Node 3	2	0
Node 2 <-> Node 4	14	6
Node 3 <-> Node 5	10	8
Node 4 <-> Node 5	8	1
Node 4 <-> Node 6	22	7
Node 5 <-> Node 6	18	3

Table 4.166: Table with information regarding links for translucent mode with 1+1 protection in medium scenario.

In table 4.167 we can see the resulting nodal degree at the physical layer, the number of line ports and add ports using 3.18 the number of long-reach transponders using 3.17 and the number of tributary ports using 3.16.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	290	8	8	8
2	3	230	20	20	20
3	3	180	16	16	16
4	3	200	24	24	44
5	3	240	24	24	36
6	2	220	40	40	40

Table 4.167: Table with information regarding nodes for translucent mode with 1+1 protection in medium scenario.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node.

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

Table 4.168: Translucent with 1+1 protection in medium scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.169: Translucent with 1+1 protection in medium scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

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

Table 4.170: Translucent with 1+1 protection in medium scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

Detailed description of Node 4		
Electrical part	Number of total demands	Bit rate
200 tributary ports	70	ODU0
	100	ODU1
	30	ODU2
	Node<–Optical Channels–>Node	Bit rate
24 LR Transponders	4 <—- 4 —-> 2	100 Gbits/s
	4 <—- 8 —-> 5	
	4 <—- 12 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
24 add ports	4 <—- 4 —-> 2	100 Gbits/s
	4 <—- 8 —-> 5	
	4 <—- 12 —-> 6	
44 line ports	4 <—- 4 —-> 2	
	4 <—- 8 —-> 5	
	4 <—- 12 —-> 6	
	2 <—- 10 —-> 6	

Table 4.171: Translucent with 1+1 protection in medium scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

Detailed description of Node 5		
Electrical part	Number of total demands	Bit rate
240 tributary ports	140	ODU0
	40	ODU1
	40	ODU2
	10	ODU3
	10	ODU4
	Node<–Optical Channels–>Node	Bit rate
24 LR Transponders	5 <—- 4 —-> 3	100 Gbits/s
	5 <—- 8 —-> 4	
	5 <— 12 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
24 add ports	5 <—- 4 —-> 3	100 Gbits/s
	5 <—- 8 —-> 4	
	5 <— 12 —-> 6	
36 line ports	5 <—- 4 —-> 3	
	5 <—- 8 —-> 4	
	5 <— 12 —-> 6	
	3 <—- 6 —-> 6	

Table 4.172: Translucent with 1+1 protection in medium scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.2.

Detailed description of Node 6		
Electrical part	Number of total demands	Bit rate
220 tributary ports	80	ODU0
	100	ODU1
	10	ODU2
	10	ODU3
	20	ODU4
	Node<–Optical Channels–>Node	Bit rate
20 LR Transponders	6 <—- 4 —-> 2	100 Gbits/s
	6 <—- 2 —-> 4	
	6 <— 14 —-> 5	
Optical part	Node<–Optical Channels–>Node	Bit rate
20 add ports	6 <—- 4 —-> 2	100 Gbits/s
	6 <—- 2 —-> 4	
	6 <— 14 —-> 5	
20 line ports	6 <—- 4 —-> 2	
	6 <—- 2 —-> 4	
	6 <— 14 —-> 5	

Table 4.173: Translucent with 1+1 protection in medium scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, can be observed in section 2.5.2.

Now through table 4.174 we can see the CAPEX result for this model. This value is obtained using equation 3.1 and all of the constraints mentioned above.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	82 520 000 €
	100 Gbits/s Transceivers		164	5 000 €/Gbit/s	82 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	14 145 900 €
		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	132	100 000 €/port	13 200 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	164	2 500 €/port	410 000 €	
		Add Ports	132	2 500 €/port	330 000 €	
Total Network Cost						96 665 900 €

Table 4.174: Translucent with 1+1 protection in medium scenario: Detailed description of CAPEX for this scenario.

In next page, we can see the routing information. These paths are bidirectional so the path from one node to another is the same path in the opposite direction.

Routing				
o	d	Type	Links	Demands
1	2	W	{(1,3),(3,5),(5,6),(6,4),(4,2)}	50 ODU0, 20 ODU1, 10 ODU2
		P	{(1,2)}	50 ODU0, 20 ODU1, 10 ODU2
1	3	W	{(1,2),(2,3)}	10 ODU0, 40 ODU1, 10 ODU2
		P	{(1,3)}	10 ODU0, 40 ODU1, 10 ODU2
1	4	W	{(1,3),(3,5),(5,6),(6,4)}	30 ODU0, 20 ODU1, 10 ODU2
		P	{(1,2),(2,4)}	30 ODU0, 20 ODU1, 10 ODU2
1	5	W	{(1,2),(2,4),(4,5)}	10 ODU0
		P	{(1,3),(3,5)}	10 ODU0
1	6	W	{(1,3),(3,5),(5,6)}	30 ODU0, 50 ODU1
		P	{(1,2),(2,4),(4,6)}	30 ODU0, 50 ODU1
2	3	W	{(2,1),(1,3)}	5 ODU3
		W	{(2,4),(4,6),(6,5),(5,3)}	5 ODU3
		P	{(2,3)}	5 ODU3
		P	{(2,1),(1,3)}	5 ODU3
2	4	W	{(2,4),(4,6),(6,4)}	10 ODU0, 30 ODU1
		P	{(2,4)}	10 ODU0, 30 ODU1
2	5	W	{(2,4),(4,5)}	50 ODU0, 10 ODU1
		W	{(2,1),(1,3),(3,5)}	1 ODU2
		P	{(2,3),(3,5)}	50 ODU0, 10 ODU1
		P	{(2,4),(4,5)}	1 ODU2
2	6	W	{(2,3),(3,5),(5,6)}	10 ODU1, 2 ODU4
		W	{(2,4),(4,6)}	10 0DU3, 4 ODU4
		W	{(2,1),(1,3),(3,5),(5,6)}	4 ODU4
		P	{(2,4),(4,6)}	10 ODU1, 10 ODU3, 10 ODU4
3	4	W	{(3,5),(5,6),(6,4)}	10 ODU0, 10 ODU1, 10 ODU2
		P	{(3,2),(2,4)}	10 ODU0, 10 ODU1, 10 ODU2
3	5	W	{(3,2),(2,4),(4,5)}	40 ODU0, 10 ODU1
		W	{(3,5),(5,6),(6,4),(4,5)}	10 ODU2, 10 ODU3
		P	{(3,5)}	40 ODU0, 10 ODU1, 10 ODU2, 10 ODU3
3	6	W	{(3,2),(2,4),(4,6)}	10 ODU0
		P	{(3,6)}	10 ODU0
4	5	W	{(4,2),(2,3),(3,5)}	10 ODU0
		W	{(4,6),(6,5),(5,3),(3,5)}	10 ODU1, 10 ODU2
		P	{(4,5)}	10 ODU0, 10 ODU1, 10 ODU2
4	6	W	{(4,2),(2,4),(4,6)}	10 ODU0, 30 ODU1
		P	{(4,6)}	10 ODU0, 30 ODU1
5	6	W	{(5,3),(3,5),(5,6)}	30 ODU0, 10 ODU1, 10 ODU2, 2 ODU4
		W	{(5,4),(4,6)}	8 ODU4
		P	{(5,6)}	30 ODU0, 10 ODU1, 10 ODU2, 10 ODU4

Table 4.175: Translucent with 1+1 protection in medium scenario: Description of demands routing. The type W means that it is working path and type P protection path.

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.3. In a first phase, we will show the resulting physical and optical topology. These topologies are based on the allowed topologies referred to in the model description and also taking into account the logical topology for all ODUs mentioned in the section 2.5.3.

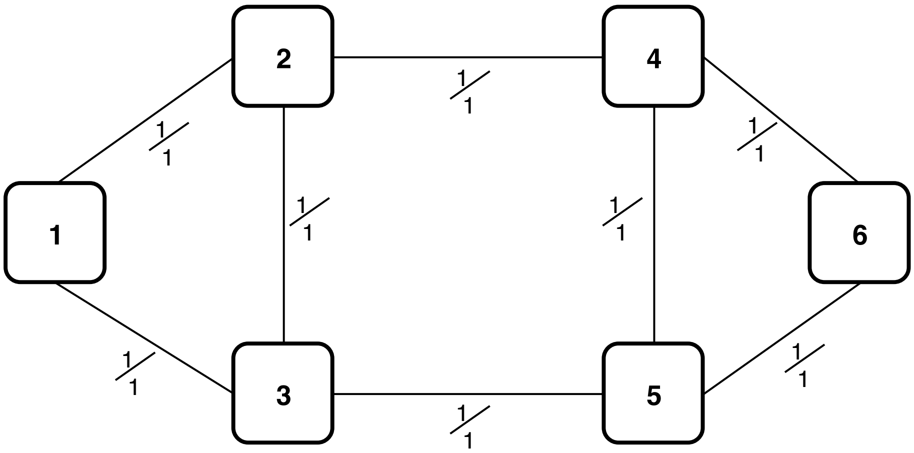

Figure 4.47: Translucent with 1+1 protection in high scenario: Physical topology after dimensioning.

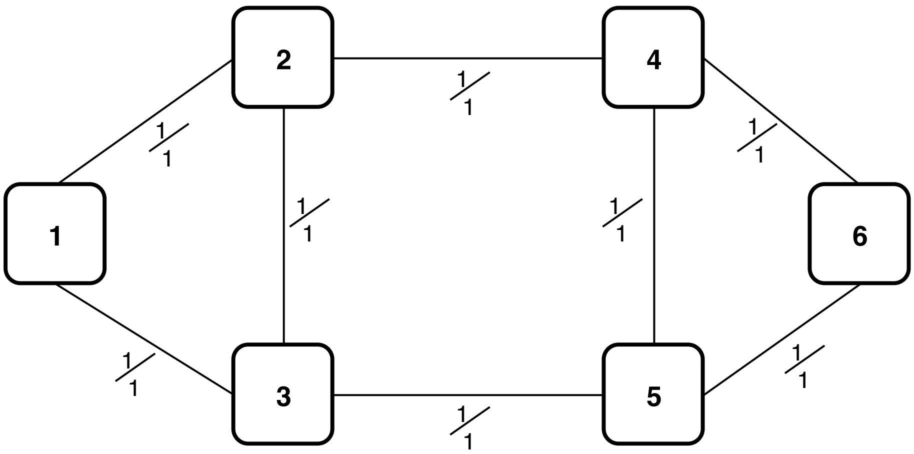

Figure 4.48: Translucent with 1+1 protection in high scenario: Optical topology after dimensioning.

In table 4.176 we can see the number of optical channels calculated using 3.2 and 3.7 and the number of amplifiers for each link calculated using 3.3.
In table 4.177 we can see the resulting nodal degree at the physical layer, the number of line ports and add ports using 3.18 the number of long-reach transponders using 3.17 and the number of tributary ports using 3.16.

Information regarding links		
Bidirectional Link	Optical Channels	Amplifiers
Node 1 <-> Node 2	4	4
Node 1 <-> Node 3	4	6
Node 2 <-> Node 3	2	0
Node 2 <-> Node 4	14	6
Node 3 <-> Node 5	10	8
Node 4 <-> Node 5	8	1
Node 4 <-> Node 6	22	7
Node 5 <-> Node 6	18	3

Table 4.176: Table with information regarding links for translucent mode with 1+1 protection in high scenario.

Information regarding nodes					
		Electrical part		Optical part	
Node	Resulting Nodal Degree	Tributary Ports	LR Transponders	Add Ports	Line Ports
1	2	290	8	8	8
2	3	230	20	20	20
3	3	180	16	16	16
4	3	200	24	24	44
5	3	240	24	24	36
6	2	220	40	40	40

Table 4.177: Table with information regarding nodes for translucent mode with 1+1 protection in high scenario.

Through the information obtained previously on the nodes we can now create tables with detailed information about each node.

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

Table 4.178: Translucent with 1+1 protection in high scenario: Detailed description of node 1. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

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

Table 4.179: Translucent with 1+1 protection in high scenario: Detailed description of node 2. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

Detailed description of Node 4		
Electrical part	Number of total demands	Bit rate
200 tributary ports	70	ODU0
	100	ODU1
	30	ODU2
	Node<–Optical Channels–>Node	Bit rate
24 LR Transponders	4 <—- 4 —-> 2	100 Gbits/s
	4 <—- 8 —-> 5	
	4 <—- 12 —-> 6	
Optical part	Node<–Optical Channels–>Node	Bit rate
24 add ports	4 <—- 4 —-> 2	100 Gbits/s
	4 <—- 8 —-> 5	
	4 <—- 12 —-> 6	
44 line ports	4 <—- 4 —-> 2	
	4 <—- 8 —-> 5	
	4 <—- 12 —-> 6	
	2 <—- 10 —-> 6	

Table 4.180: Translucent with 1+1 protection in high scenario: Detailed description of node 4. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

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

Table 4.181: Translucent with 1+1 protection in high scenario: Detailed description of node 3. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

Detailed description of Node 6		
Electrical part	Number of total demands	Bit rate
220 tributary ports	80	ODU0
	100	ODU1
	10	ODU2
	10	ODU3
	20	ODU4
	Node<–Optical Channels–>Node	Bit rate
20 LR Transponders	6 <—- 4 —-> 2	100 Gbits/s
	6 <—- 2 —-> 4	
	6 <—- 14 —-> 5	
Optical part	Node<–Optical Channels–>Node	Bit rate
20 add ports	6 <—- 4 —-> 2	100 Gbits/s
	6 <—- 2 —-> 4	
	6 <—- 14 —-> 5	
20 line ports	6 <—- 4 —-> 2	
	6 <—- 2 —-> 4	
	6 <—- 14 —-> 5	

Table 4.182: Translucent with 1+1 protection in high scenario: Detailed description of node 6. The number of demands is distributed to the various destination nodes, can be observed in section 2.5.3.

Detailed description of Node 5		
Electrical part	Number of total demands	Bit rate
240 tributary ports	140 40 40 10 10	ODU0 ODU1 ODU2 ODU3 ODU4
	Node<–Optical Channels–>Node	Bit rate
24 LR Transponders	5 <—- 4 —-> 3 5 <—- 8 —-> 4 5 <—- 12 —-> 6	100 Gbits/s
Optical part	Node<–Optical Channels–>Node	Bit rate
24 add ports	5 <—- 4 —-> 3 5 <—- 8 —-> 4 5 <—- 12 —-> 6	100 Gbits/s
36 line ports	5 <—- 4 —-> 3 5 <—- 8 —-> 4 5 <—- 12 —-> 6 3 <—- 6 —-> 6	

Table 4.183: Translucent with 1+1 protection in high scenario: Detailed description of node 5. The number of demands is distributed to the various destination nodes, this distribution can be observed in section 2.5.3.

Now through table 4.184 we can see the CAPEX result for this model. This value is obtained using equation 3.1 and all of the constraints mentioned above.

CAPEX of the Network						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	82 520 000 €
	100 Gbits/s Transceivers		164	5 000 €/Gbit/s	82 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	14 145 900 €
		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	132	100 000 €/port	13 200 000 €	
	Optical	OXCs	6	20 000 €	120 000 €	
		Line Ports	164	2 500 €/port	410 000 €	
		Add Ports	132	2 500 €/port	330 000 €	
Total Network Cost						96 665 900 €

Table 4.184: Translucent with 1+1 protection in high scenario: Detailed description of CAPEX for this scenario.

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

Routing				
o	d	Type	Links	Demands
1	2	W	{(1,3),(3,5),(5,6),(6,4),(4,2)}	50 ODU0, 20 ODU1, 10 ODU2
		P	{(1,2)}	50 ODU0, 20 ODU1, 10 ODU2
1	3	W	{(1,2),(2,3)}	10 ODU0, 40 ODU1, 10 ODU2
		P	{(1,3)}	10 ODU0, 40 ODU1, 10 ODU2
1	4	W	{(1,3),(3,5),(5,6),(6,4)}	30 ODU0, 20 ODU1, 10 ODU2
		P	{(1,2),(2,4)}	30 ODU0, 20 ODU1, 10 ODU2
1	5	W	{(1,2),(2,4),(4,5)}	10 ODU0
		P	{(1,3),(3,5)}	10 ODU0
1	6	W	{(1,3),(3,5),(5,6)}	30 ODU0, 50 ODU1
		P	{(1,2),(2,4),(4,6)}	30 ODU0, 50 ODU1
2	3	W	{(2,1),(1,3)}	5 ODU3
		W	{(2,4),(4,6),(6,5),(5,3)}	5 ODU3
		P	{(2,3)}	5 ODU3
		P	{(2,1),(1,3)}	5 ODU3
2	4	W	{(2,4),(4,6),(6,4)}	10 ODU0, 30 ODU1
		P	{(2,4)}	10 ODU0, 30 ODU1
2	5	W	{(2,4),(4,5)}	50 ODU0, 10 ODU1
		W	{(2,1),(1,3),(3,5)}	1 ODU2
		P	{(2,3),(3,5)}	50 ODU0, 10 ODU1
		P	{(2,4),(4,5)}	1 ODU2
2	6	W	{(2,3),(3,5),(5,6)}	10 ODU1, 2 ODU4
		W	{(2,4),(4,6)}	10 0DU3, 4 ODU4
		W	{(2,1),(1,3),(3,5),(5,6)}	4 ODU4
		P	{(2,4),(4,6)}	10 ODU1, 10 ODU3, 10 ODU4
3	4	W	{(3,5),(5,6),(6,4)}	10 ODU0, 10 ODU1, 10 ODU2
		P	{(3,2),(2,4)}	10 ODU0, 10 ODU1, 10 ODU2
3	5	W	{(3,2),(2,4),(4,5)}	40 ODU0, 10 ODU1
		W	{(3,5),(5,6),(6,4),(4,5)}	10 ODU2, 10 ODU3
		P	{(3,5)}	40 ODU0, 10 ODU1, 10 ODU2, 10 ODU3
3	6	W	{(3,2),(2,4),(4,6)}	10 ODU0
		P	{(3,6)}	10 ODU0
4	5	W	{(4,2),(2,3),(3,5)}	10 ODU0
		W	{(4,6),(6,5),(5,3),(3,5)}	10 ODU1, 10 ODU2
		P	{(4,5)}	10 ODU0, 10 ODU1, 10 ODU2
4	6	W	{(4,2),(2,4),(4,6)}	10 ODU0, 30 ODU1
		P	{(4,6)}	10 ODU0, 30 ODU1
5	6	W	{(5,3),(3,5),(5,6)}	30 ODU0, 10 ODU1, 10 ODU2, 2 ODU4
		W	{(5,4),(4,6)}	8 ODU4
		P	{(5,6)}	30 ODU0, 10 ODU1, 10 ODU2, 10 ODU4

Table 4.185: Translucent with 1+1 protection in high scenario: Description of demands routing. The type W means that it is working path and type P protection path.

4.6.3 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 4.186.

	Low Traffic	Medium Traffic	High Traffic
CAPEX without survivability	7 531 590 €	43 427 900 €	85 988 800 €
CAPEX/Gbit/s without survivability	15 063 €/Gbit/s	8 686 €/Gbit/s	8 599 €/Gbit/s
Traffic (Gbit/s)	500	5 000	10 000
Number of Add ports	18	132	x
Number of Line ports	20	164	x
Number of Tributary ports	136	1 360	2 720
Number of Transceivers	20	164	x
Number of Transponders	18	132	x
Link Cost	10 490 000 €	82 520 000 €	x x x €
Node Cost	2 077 590 €	14 145 900 €	x x x €
CAPEX	**12 567 590 €**	**96 665 900 €**	**x x x €**
CAPEX/Gbit/s	**25 135 €/Gbit/s**	**19 333 €/Gbit/s**	**x x €/Gbit/s**

Table 4.186: Translucent with 1+1 protection: Table with the various CAPEX values obtained in the different traffic scenarios.

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

- Comparing the low traffic 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 higher the traffic, the lower CAPEX/Gbit/s will be. We can see that in medium and high traffic the results tend to be one closer and lower value.

- Comparing this cost with the without survivability cost we can conclude that protection is significantly more expensive. As can be seen in the table this increase is approximately double as with 1+1 protection we have a cost more than twice than the cost without survivability.

CHAPTER 5

Analytical Models

The focus of the current section is to propose and describe the analytical computation of the network CAPEX, based on the various modes of transport without survivability and protection. In the following sections, all calculations for opaque and transparent modes of transport are presented in detail, without survivability and with 1+1 protection.

5.1 Opaque without Survivability

In this case the survivability coefficient is zero because it is without survivability.
We already have all the necessary formulas to obtain the CAPEX value for the reference network 2.4. As described in the subsection of network traffic 2.5, 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 2.5.1.

Using equation 3.23:

$D = \frac{1}{2} * (1 + 1) * (\frac{1000}{100})$ $\qquad D = 10$

Replacing in equation 3.22:

$< w > = (\frac{10*1.533}{16}) * (1 + 0)$ $\qquad < w > = 1$

Using equation 3.21:

$N^R = (\frac{460}{100}-1) + (\frac{640}{100}-1) + (\frac{75}{100}-1) + (\frac{684}{100} -1) + (\frac{890}{100}-1) + (\frac{103}{100}-1) + (\frac{761}{100}-1) + (\frac{361}{100}-1)$

$N^R = 35$

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 1) + (2 * 35 * 4 000) = **8 520 000 €**

In relation to the cost of the nodes we first use the equation 3.29:

$< d > = \frac{10}{6}$ $\qquad < d > = 1.6667$

Replacing in equation 3.28:

$< P_{exc} > = 1.6667 * 1.533 * (1 + 0)$ $\qquad < P_{exc} > = 2.5550$

Finally, replacing all in equation 3.25 the Node Cost is:

$C_N = C_{exc}$ = 6 * (10 000 + (1 000 * 100 * 2.5550)) + (20 * 136) = **1 595 720 €**

The CAPEX is:

$CAPEX$ = 8 520 000 + 1 595 720 $CAPEX$ = **10 115 720 €**

Medium Traffic Scenario

In this scenario we have to take into account the traffic calculated in 2.5.2.

Using equation 3.23:

$D = \frac{1}{2} * (1 + 1) * (\frac{10000}{100})$ $D = 100$

replacing in equation 3.22:

$< w > = (\frac{100*1.533}{16}) * (1 + 0)$ $< w > = 9.625$

Using equation 3.21:

$N^R = (\frac{460}{100}\text{-}1) + (\frac{640}{100}\text{-}1) + (\frac{75}{100}\text{-}1) + (\frac{684}{100} \text{-}1) + (\frac{890}{100}\text{-}1) + (\frac{103}{100}\text{-}1) + (\frac{761}{100}\text{-}1) + (\frac{361}{100}\text{-}1)$

$N^R = 35$

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 9.625) + (2 * 35 * 4 000) = **77 520 000 €**

In relation to the cost of the nodes we first use the equation 3.29:

$< d > = \frac{100}{6}$ $< d > = 16.6667$

Replacing in equation 3.28:

$< P_{exc} >$ = 16.6667 * 1.533 * (1 + 0) $< P_{exc} >$ = 25.5501

Finally, replacing all in equation 3.25 the Node Cost is:

$C_N = C_{exc}$ = 6 * (10 000 + (1 000 * 100 * 25.5501)) + (20 * 1 360) = **15 417 260 €**

The CAPEX is:

$CAPEX$ = 77 520 000 + 15 417 260 $CAPEX$ = **92 937 260 €**

High Traffic Scenario

In this scenario we have to take into account the traffic calculated in 2.5.3.

Using equation 3.23:

$D = \frac{1}{2}$ * (1 + 1) * ($\frac{20000}{100}$) D = 200

replacing in equation 3.22:

$< w >$ = ($\frac{200*1.533}{16}$) * (1 + 0) $< w >$ = 19.1875

Using equation 3.21:

N^R = ($\frac{460}{100}$-1) + ($\frac{640}{100}$-1) + ($\frac{75}{100}$-1) + ($\frac{684}{100}$ -1) + ($\frac{890}{100}$-1) + ($\frac{103}{100}$-1) + ($\frac{761}{100}$-1) + ($\frac{361}{100}$-1)

N^R = 35

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 19.1875) + (2 * 35 * 4 000) = **154 020 000 €**

In relation to the cost of the nodes we first use the equation 3.29:

$< d >$ = $\frac{200}{6}$ $< d >$ = 33.3333

Replacing in equation 3.28:

$< P_{exc} >$ = 33.3333 * 1.533 * (1 + 0) $< P_{exc} >$ = 51.0999

Finally, replacing all in equation 3.25 the Node Cost is:

$C_N = C_{exc}$ = 6 * (10 000 + (1 000 * 100 * 51.0999)) + (20 * 2 720) = **30 774 340 €**

The CAPEX is:

$CAPEX$ = 154 020 000 + 30 774 340 $CAPEX$ = **184 794 340 €**

5.2 Opaque with 1+1 Protection

In this case the survivability coefficient is $< kp >$ because it is with 1+1 protection where

$$< kp >= \frac{2.467}{1.533} = 1.609$$

We already have all the necessary formulas to obtain the CAPEX value for the reference network 2.4. As described in the subsection of network traffic 2.5, 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 2.5.1.

Using equation 3.23:

$D = \frac{1}{2} * (1 + 1) * (\frac{1000}{100})$ $D = 10$

Replacing in equation 3.22:

$< w >$ = ($\frac{10*1.533}{16}$) * (1 + 1.609) $< w >$ = 2.609

Using equation 3.21:

N^R = ($\frac{460}{100}$-1) + ($\frac{640}{100}$-1) + ($\frac{75}{100}$-1) + ($\frac{684}{100}$ -1) + ($\frac{890}{100}$-1) + ($\frac{103}{100}$-1) + ($\frac{761}{100}$-1) + ($\frac{361}{100}$-1)

N^R = 35

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 2.609) + (2 * 35 * 4 000) = **21 392 000 €**

In relation to the cost of the nodes we first use the equation 3.29:

$< d >$ = $\frac{10}{6}$ $< d >$ = 1.6667

Replacing in equation 3.28:

$< P_{exc} >$ = 1.6667 * 1.533 * (1 + 1.609) $< P_{exc} >$ = 6.6661

Finally, replacing all in equation 3.25 the Node Cost is:

$C_N = C_{exc}$ = 6 * (10 000 + (1 000 * 100 * 6.6661)) + (20 * 136) = **4 062 380 €**

The CAPEX is:

$CAPEX$ = 21 392 000 + 4 062 380 $CAPEX$ = **25 454 380 €**

Medium Traffic Scenario

In this scenario we have to take into account the traffic calculated in 2.5.2.

Using equation 3.23:

$D = \frac{1}{2}$ * (1 + 1) * ($\frac{10000}{100}$) D = 100

Replacing in equation 3.22:

$< w >$ = ($\frac{100*1.533}{16}$) * (1 + 1.609) $< w >$ = 25.11

Using equation 3.21:

N^R = ($\frac{460}{100}$-1) + ($\frac{640}{100}$-1) + ($\frac{75}{100}$-1) + ($\frac{684}{100}$ -1) + ($\frac{890}{100}$-1) + ($\frac{103}{100}$-1) + ($\frac{761}{100}$-1) + ($\frac{361}{100}$-1)

N^R = 35

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 25.11) + (2 * 35 * 4 000) = **201 400 000 €**

In relation to the cost of the nodes we first use the equation 3.29:

$< d > = \frac{100}{6}$ $< d >$ = 16.6667

Replacing in equation 3.28:

$< P_{exc} >$ = 16.6667 * 1.533 * (1 + 1.609) $< P_{exc} >$ = 66.6601

Finally, replacing all in equation 3.25 the Node Cost is:

$C_N = C_{exc}$ = 6 * (10 000 + (1 000 * 100 * 66.6601)) + (20 * 1 360) = **40 083 260 €**

The CAPEX is:

$CAPEX$ = 201 400 000 + 40 083 260 $CAPEX$ = **241 483 260 €**

High Traffic Scenario

In this scenario we have to take into account the traffic calculated in 2.5.3.

Using equation 3.23:

$D = \frac{1}{2}$ * (1 + 1) * ($\frac{20000}{100}$) D = 200

Replacing in equation 3.22:

$< w >$ = ($\frac{200*1.533}{16}$) * (1 + 1.609) $< w >$ = 50.060

Using equation 3.21:

N^R = ($\frac{460}{100}$-1) + ($\frac{640}{100}$-1) + ($\frac{75}{100}$-1) + ($\frac{684}{100}$ -1) + ($\frac{890}{100}$-1) + ($\frac{103}{100}$-1) + ($\frac{761}{100}$-1) + ($\frac{361}{100}$-1)

N^R = 35

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 50.060) + (2 * 35 * 4 000) = **401 001 500 €**

In relation to the cost of the nodes we first use the equation 3.29:

$< d > = \frac{200}{6}$ $< d >$ = 33.3333

Replacing in equation 3.28:

$< P_{exc} >$ = 33.3333 * 1.533 * (1 + 1.609) $< P_{exc} >$ = 133.3198

Finally, replacing all in equation 3.25 the Node Cost is:

$C_N = C_{exc}$ = 6 * (10 000 + (1 000 * 100 * 133.3198)) + (20 * 2 720) = **80 106 280 €**

The CAPEX is:

$CAPEX$ = 401 001 500 + 80 106 280 $CAPEX$ = **481 107 780 €**

5.3 Transparent without Survivability

In this case the survivability coefficient is zero because it is without survivability.
We already have all the necessary formulas to obtain the CAPEX value for the reference network 2.4. As described in the subsection of network traffic 2.5, 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 2.5.1.

Using equation 3.23:

$D = \frac{1}{2}$ * (1 + 1.25) * ($\frac{1000}{100}$) D = 11.25

Replacing in equation 3.22:

$< w >$ = ($\frac{11.25*1.533}{16}$) * (1 + 0) $< w >$ = 1.125

Using equation 3.21:

N^R = 35

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 1.125) + (2 * 35 * 4 000) = **9 520 000 €**

In relation to the cost of the nodes we first use the equation 3.29:

$< d >$ = $\frac{11.25}{6}$ $< d >$ = 1.875

Replacing in equation 3.31 and 3.32:

$< P_{exc} >$ = 1.875

$< P_{oxc} >$ = 1.875 * [1 + (1 + 0) * 1.533] $< P_{oxc} >$ = 4.7494

Finally, replacing all in equation 3.25 and 3.26 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 €**

$CAPEX$ = 9 520 000 + 1 307 792 $CAPEX$ = **10 827 792 €**

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.2.

Using equation 3.23:

D = $\frac{1}{2}$ * (1 + 1.25) * ($\frac{10000}{100}$) D = 112.5

Replacing in equation 3.22:

$< w >$ = ($\frac{112.5*1.533}{16}$) * (1 + 0) $< w >$ = 10.8125

Using equation 3.21:

N^R = 35

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 10.8125) + (2 * 35 * 4 000) = **87 020 000 €**

In relation to the cost of the nodes we first use the equation 3.29:

$< d >$ = $\frac{112.5}{6}$ $< d >$ = 18.75

Replacing in equation 3.31 and 3.32:

$< P_{exc} >$ = 18.75

$< P_{oxc} >$ = 18.75 * [1 + (1 + 0) * 1.533] $< P_{oxc} >$ = 47.4938

Finally, replacing all in equation 3.25 and 3.26 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 €**

$CAPEX$ = 87 020 000 + 12 169 607 $CAPEX$ = **99 189 607 €**

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.3.

Using equation 3.23:

$D = \frac{1}{2} * (1 + 1.25) * (\frac{20000}{100})$ $D = 225$

Replacing in equation 3.22:

$< w > = (\frac{225*1.533}{16}) * (1 + 0)$ $< w > = 21.5625$

Using equation 3.21:

$N^R = 35$

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 21.5625) + (2 * 35 * 4 000) = **173 020 000 €**

In relation to the cost of the nodes we first use the equation 3.29:

$< d > = \frac{225}{6}$ $< d > = 37.5$

Replacing in equation 3.31 and 3.32:

$< P_{exc} > = 37.5$

$< P_{oxc} >$ = 37.5 * [1 + (1 + 0) * 1.533] $< P_{oxc} > = 94.9875$

Finally, replacing all in equation 3.25 and 3.26 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 €**

$CAPEX$ = 173 020 000 + 24 159 213 $CAPEX$ = **197 179 213 €**

5.4 Transparent with 1+1 Protection

In this case the survivability coefficient is $< kp >$ because it is with protection 1+1 where

$$< kp >= \frac{2.467}{1.533} = 1.609$$

We already have all the necessary formulas to obtain the CAPEX value for the reference network 2.4. As described in the subsection of network traffic 2.5, 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 2.5.1.

Using equation 3.23:

D = $\frac{1}{2}$ * (1 + 1.25) * ($\frac{1000}{100}$) D = 11.25

Replacing in equation 3.22:

$< w >$ = ($\frac{11.25*1.533}{16}$) * (1 + 1.609) $< w >$ = 2.9351

Using equation 3.21:

N^R = 35

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 2.9351) + (2 * 35 * 4 000) = **24 000 800 €**

In relation to the cost of the nodes we first use the equation 3.29:

$< d >$ = $\frac{11.25}{6}$ $< d >$ = 1.875

Replacing in equation 3.31 and 3.32:

$< P_{exc} >$ = 1.875

$< P_{oxc} >$ = 1.875 * [1 + (1 + 1.609) * 1.533] $< P_{oxc} >$ = 9.3742

Finally, replacing all in equation 3.25 and 3.26 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 €**

$CAPEX$ = 24 000 800 + 1 448 333 $CAPEX$ = **25 449 133 €**

Medium Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.2.

Using equation 3.23:

D = $\frac{1}{2}$ * (1 + 1.25) * ($\frac{10000}{100}$) D = 112.5

Replacing in equation 3.22:

$< w >$ = ($\frac{112.5*1.533}{16}$) * (1 + 1.609) $< w >$ = 28.2098

Using equation 3.21:

N^R = 35

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 28.2098) + (2 * 35 * 4 000) = **226 198 400 €**

In relation to the cost of the nodes we first use the equation 3.29:

$< d >$ = $\frac{112.5}{6}$ $< d >$ = 18.75

Replacing in equation 3.31 and 3.32:

$< P_{exc} >$ = 18.75

$< P_{oxc} >$ = 18.75 * [1 + (1 + 1.609) * 1.533] $< P_{oxc} >$ = 93.7424

Finally, replacing all in equation 3.25 and 3.26 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 = **12 863 336 €**

$CAPEX$ = 226 198 400 + 12 863 336 $CAPEX$ = **239 061 736 €**

High Traffic Scenario:

In this scenario we have to take into account the traffic calculated in 2.5.3.

Using equation 3.23:

$D = \frac{1}{2}$ * (1 + 1.25) * ($\frac{20000}{100}$) D = 225

Replacing in equation 3.22:

$<w>$ = ($\frac{225*1.533}{16}$) * (1 + 1.609) $<w>$ = 56.2566

Using equation 3.21:

N^R = 35

Finally, replacing all in equation 3.20 the Link Cost is:

C_L = (2 * 8 * 15 000) + (2 * 8 * 5 000 * 100 * 56.2566) + (2 * 35 * 4 000) = **450 572 800 €**

In relation to the cost of the nodes we first use the equation 3.29:

$<d> = \frac{225}{6}$ $<d>$ = 37.5

Replacing in equation 3.31 and 3.32:

$<P_{exc}>$ = 37.5

$<P_{oxc}>$ = 37.5 * [1 + (1 + 1.609) * 1.533] $<P_{oxc}>$ = 187.4849

Finally, replacing all in equation 3.25 and 3.26 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 €**

$CAPEX$ = 450 572 800 + 25 546 673 $CAPEX$ = **476 119 473 €**

CHAPTER 6

Comparative Analysis

6.1 Opaque without Survivability

In this section, we will compare the CAPEX values obtained for the three scenarios in the three types of design. The first is the dimensioning using ILPs 4.1, the second through analytical models 5.1 and finally using heuristic algorithms following a guide document [?]. It is possible to see these results in detail in the appendices.
For a better analysis of the results, table 6.1 was created, with all the scenarios used where it is possible to see values obtained and their margin of error for the ILP model.

		ILP	Analytical	Heuristic
Low Traffic	Link Cost	9 404 000 €	8 520 000 €	12 020 000 €
	Node Cost	1 862 590 €	1 595 720 €	2 362 590 €
	CAPEX	**11 266 590 €**	**10 115 720 €**	**14 382 590 €**
Medium Traffic	Link Cost	75 520 000 €	77 520 000 €	77 020 000 €
	Node Cost	15 085 900 €	15 417 260 €	15 385 900 €
	CAPEX	**90 605 900 €**	**92 937 260 €**	**92 405 900 €**
High Traffic	Link Cost	148 520 000 €	154 020 000 €	149 020 000 €
	Node Cost	29 711 800 €	30 774 340 €	29 814 200 €
	CAPEX	**178 231 800 €**	**184 794 340 €**	**178 834 200 €**

Table 6.1: 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 higher 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.

6.2 Opaque with 1+1 Protection

In this section, we will compare the CAPEX values obtained for the three scenarios in the three types of design. The first is the dimensioning using ILPs 4.2, the second through analytical models 5.2 and finally using heuristic algorithms following a guide document [**?**]. It is possible to see these results in detail in the appendices.
For a better analysis of the results, table 6.2 was created, with all the scenarios used where it is possible to see values obtained and their margin of error for the ILP model.

		ILP	Analytical	Heuristic
Low Traffic	Link Cost	22 520 000 €	21 392 000 €	23 520 000 €
	Node Cost	4 462 590 €	4 062 380 €	4 662 590 €
	CAPEX	**26 982 590 €**	**25 454 380 €**	**28 182 590 €**
Medium Traffic	Link Cost	199 520 000 €	201 400 000 €	199 520 000 €
	Node Cost	39 885 900 €	40 083 260 €	39 885 900 €
	CAPEX	**239 405 900 €**	**241 483 260 €**	**239 405 900 €**
High Traffic	Link Cost	397 520 000 €	401 001 500 €	397 520 000 €
	Node Cost	79 511 800 €	80 106 280 €	79 514 200 €
	CAPEX	**477 031 800 €**	**481 107 780 €**	**477 034 200 €**

Table 6.2: 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.

6.3 Transparent without Survivability

In this section, we will compare the CAPEX values obtained for the three scenarios in the three types of design. The first is the dimensioning using ILPs 4.3, the second through analytical models 5.3 and finally using heuristic algorithms following a guide document [?]. It is possible to see these results in detail in the appendices.
For a better analysis of the results, table 6.3 was created, with all the scenarios used where it is possible to see values obtained and their margin of error for the ILP model.

		ILP	Analytical	Heuristic
Low Traffic	Link Cost	26 520 000 €	9 520 000 €	26 520 000 €
	Node Cost	3 797 590 €	1 307 792 €	3 797 590 €
	CAPEX	**30 317 590 €**	**10 827 792 €**	**30 317 590 €**
Medium Traffic	Link Cost	84 520 000 €	87 020 000 €	84 520 000 €
	Node Cost	12 310 900 €	12 169 607 €	15 180 900 €
	CAPEX	**96 830 900 €**	**99 189 607 €**	**99 700 900 €**
High Traffic	Link Cost	157 520 000 €	173 020 000 €	157 520 000 €
	Node Cost	22 951 800 €	24 159 213 €	28 486 800 €
	CAPEX	**180 471 800 €**	**197 179 213 €**	**186 006 800 €**

Table 6.3: 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 this 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.

6.4 Transparent with 1+1 Protection

In this section, we will compare the CAPEX values obtained for the three scenarios in the three types of design. The first is the dimensioning using ILPs 4.4, the second through analytical models 5.4 and finally using heuristic algorithms following a guide document [**?**]. It is possible to see these results in detail in the appendices.
For a better analysis of the results, table 6.4 was created, with all the scenarios used where it is possible to see values obtained and their margin of error for the ILP model.

		ILP	Analytical	Heuristic
Low Traffic	Link Cost	68 520 000 €	24 000 800 €	68 520 000 €
	Node Cost	3 947 590 €	1 448 333 €	4 007 590 €
	CAPEX	**72 467 590 €**	**25 449 133 €**	**72 527 590 €**
Medium Traffic	Link Cost	226 520 000 €	226 198 400 €	226 520 000 €
	Node Cost	13 020 900 €	12 863 336 €	15 890 900 €
	CAPEX	**239 540 900 €***	**239 061 736 €**	**242 410 900 €**
High Traffic	Link Cost	424 520 000 €	450 572 800 €	424 520 000 €
	Node Cost	24 286 800 €	25 546 673 €	29 821 800 €
	CAPEX	**448 806 800 €***	**476 119 473 €**	**454 341 800 €**

Table 6.4: 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.

6.5 Translucent without Survivability

In this section, we will compare the CAPEX values obtained for the three scenarios in the two types of design. The first is the dimensioning using ILPs 4.5 and the second using heuristic algorithms following a guide document [**?**]. It is possible to see these results in detail in the appendices. For this case it was not possible to obtain analytical values for comparison.
For a better analysis of the results, table 6.5 was created, with all the scenarios used where it is possible to see values obtained and their margin of error for the ILP model.

		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 €**

Table 6.5: Translucent without survivability: Table with different value of CAPEX for all scenarios.

As already mentioned it is not possible to make comparisons between ILP and analytical calculations. As expected, the results obtained by the ILP model are always better than the values obtained through the heuristic. Comparing the ILP model with the heuristic model for this particular case, we note that, for the low scenario, there is a larger margin of error, approximately 53%, than for the medium and high scenarios. In the case of the medium scenario, the heuristic already approaches the optimal cost where the margin of error is lowest, approximately 13%, which is a big difference compared to the low scenario. For the high scenario, the heuristic is closer to the ILP model. The value is larger than the ILP model as expected, but with a low margin of error, approximately 9%.

6.6 Translucent with 1+1 Protection

In this section, we will compare the CAPEX values obtained for the three scenarios in the two types of design. The first is the dimensioning using ILPs 4.6 and the second using heuristic algorithms following a guide document [?]. It is possible to see these results in detail in the appendices. For this case it was not possible to obtain analytical values for comparison.
For a better analysis of the results, table 6.6 was created, with all the scenarios used where it is possible to see values obtained and their margin of error for the ILP model.

		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	xxxxxx €	16 861 800 €
	CAPEX	**xxxxxx €**	**186 381 800 €**

Table 6.6: Translucent with 1+1 protection: Table with different value of CAPEX for all scenarios.

Again, as already mentioned, it is not possible to make comparisons between the ILP and the analytical calculations. Comparing the ILP model with the heuristic model, it is possible to observe that the result obtained by the ILP model is always better (smaller) than the value obtained by the heuristic. For the low scenario there is a very high margin of error, approximately 136%. For the medium scenario, the margin of error is already greatly reduced by being approximately 3%, so it is a value closer to the optimal cost than to the low scenario.

CHAPTER 7

Conclusions and future directions

7.1 Conclusions

After realizing the ILP models for the three transport modes we will focus on these results obtained and draw as many conclusions as possible from these results. For this, the figure 7.1 is created with the information obtained previously.

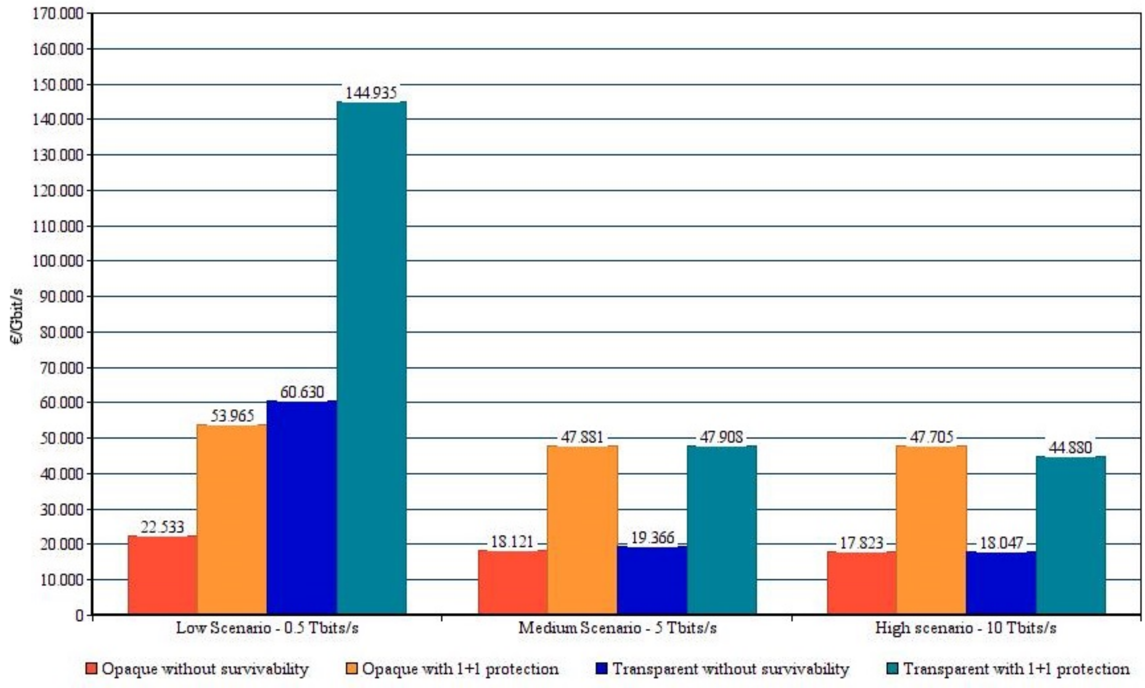

Figure 7.1: Graphic with the cost in Euros per Gbit/s of the three modes of transport without survivability and with 1+1 protection for all scenarios referred initially.

Through the previous figure we can draw several conclusions such as: Regardless of the transport mode and the type of survivability, it is clear that the higher the network traffic, the lower the cost per Gbit/s. The cost with 1+1 protection is always more than twice the cost without protection regardless of the mode of transport used. It is possible to state that the translucent transport mode has a cheaper cost compared to the other two modes of transport, regardless of network traffic and type of survival. Regarding the low scenario it is possible to state that the transparent mode has a much higher cost than other modes of transport. In relation to the other two scenarios it is possible to state that the opaque and transparent mode have a similar cost regardless of the mode of survivability. In the last scenario transparent mode with protection has a cost per bit lower than opaque transport mode.

The transparent mode has a very high cost per Gbit/s in the low scenario because this model, despite having little traffic, always defines at least one optical channel for each pair (o, d) thus making the CAPEX of this network become very expensive.

The translucent mode has a much lower cost per Gbit/s than the other modes because this mode allows different pair (o, d) to use the same optical channel thus decreasing the value of optical channels used and consequently decreases the CAPEX of the network.

7.2 Future directions

Throughout this dissertation specific situations were analyzed and some open uses were discovered. Future work suggests the following important topics:

Opaque transport mode

- Allow blocking because the presented model assume that the solution is possible or impossible, does not support a partial solution where some demands are not routed.
- Assume a multiple transmission system, that is, for each link there is more than one transmission system.
- Allowing multi-path routing, so that not all demands that sharing the same end nodes have to follow the same path.

Transparent transport mode

- Allow blocking because the presented model assume that the solution is possible or impossible, does not support a partial solution where some demands are not routed.
- Assume a multiple transmission system, that is, for each link there is more than one transmission system.

Translucent transport mode

- Allow blocking because the presented model assume that the solution is possible or impossible, does not support a partial solution where some demands are not routed.
- Assume a multiple transmission system, that is, for each link there is more than one transmission system.
- Consent to a Maximum Reach.
- Define the variable N_{oxc} as not being fixed allowing only certain nodes instead of all.

Analytical model

- It's necessary to focus on the calculation of the CAPEX for translucent mode.
- Include the LR transponders in the node instead of being calculated on the link.

Reference

[1] Alcatel-Lucent (2010). "Understanding OTN Optical Transport Network (G.709), March 9, 2010" [Online]. Available: http://www.cvt-dallas.org/March2010.pdf

[2] L. Gyarmati, T. Cinkler, and G. Sallai, "Srlg-disjoint multi-path protection: When lp meets ILP," in *Proc. Networks 2008 - The 13th Int. Telecommunications Network Strategy and Planning Symp*, vol. Supplement, pp. 1-10, September 2008.

[3] Wikipedia "CAPEX" [Online]. Available: https://pt.wikipedia.org/wiki/CAPEX

[4] Wikipedia "OPEX" [Online]. Available: https://pt.wikipedia.org/wiki/OPEX

[5] A. N. Pinto, "Design of Optical Transport Networks," in *Aulas de redes opticas 2016-2017.*

[6] R. Ramaswami, K. N. Sivarajan, and G. H. Sasaki, *Optical Networks: A Practical Perspective*, Morgan Kaufmann, 2010.

[7] R. M. D. Morais, "Planning and Dimensioning of Multilayer Optical Transport Networks." PhD thesis, Universidade de Aveiro, 2015.

[8] V. R. B. S. Braz, "Dimensioning and Optimization of Node Architecture in Optical Transport Networks." Master's thesis, Universidade de Aveiro, 2016.

[9] C. Pavan, R. M. Morais, and A. N. Pinto, "Quantifying the restoration capacity in optical mesh networks," in *Proc. Next Generation Internet Networks - NGI*, pp. 1–5, July 2009.

[10] C. Pavan, R. M. Morais, A. R. Correia, and A. N. Pinto, "Dimensioning of optical networks with incomplete information," in *Proc. Fourth Advanced International Conference Telecommunications - AICT*, pp. 261–264, June 2008.

[11] A. Gladisch, R.-P. Braun, D. Breuer, A. Ehrhardt, H.-M. Foisel, M. Jaeger, R. Leppla, M. Schneiders, S. Vorbeck, W. Weiershausen, and F. Westphal, "Evolution of terrestrial optical system and core network architecture," *Proceedings of the IEEE*, vol. 94, no. 5, pp. 869–891, June 2006.

[12] P. Babarczi, "Survivable Optical Network Design with Unambiguous Shared Risk Link Group Failure Localization," Ph.D. thesis, Budapest University of Technology and Economics, 2011.

[13] H. Kerivin and A. R. Mahjoub, "Design of survivable networks: A survey," *Networks*, vol. 46, pp. 1–21, August 2005.

[14] R. M. Morais, "Desenho Topológico de Redes Ópticas," Master's thesis, University of Aveiro, Aveiro, Portugal, 2008.

[15] O. Klopfenstein, "Access network dimensioning with uncertain traffic forecasts," in *Proc International Telecommunications Network Strategy and Planning Symposium - NETWORKS*, pp. 1–52, October 2008.

[16] S. Yang and F. Kuipers, "Traffic uncertainty models in network planning," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 172–177, February 2014.

[17] D. Cieslik, *Network Design Problems*, Wiley, 2009.

[18] S. Ramamurthy, L. Sahasrabuddhe, and B. Mukherjee, "Survivable WDM mesh networks," *IEEE/OSA Journal of Lightwave Technology*, vol. 21, no. 4, pp. 870–883, April 2003.

[19] D. Jungnickel, *Graphs, Networks and Algorithms*, Springer Publishing Company, 2007.

[20] M. R. Garey and D. S. Johnson, *Computers and Intractability: A Guide to the Theory of NP-Completeness*, W. H. Freeman & Co., 1990.

[21] S. Routray, R. M. Morais, J. da Rocha, and A. N. Pinto, "Statistical model for link lengths in optical transport networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 5, no. 7, pp. 762–773, July 2013.

[22] S. Soni and H. Pirkul, "Design of survivable networks with connectivity requirements," *Telecommunication Systems*, vol. 20, no. 1-2, pp. 133–149, May 2002.

[23] A. Balakrishnan, T. L. Magnanti, and P. Mirchandani, "Connectivity-splitting models for survivable network design," *Networks*, vol. 43, no. 1, pp. 10–27, January 2004.

[24] A. Balakrishnan, P. Mirchandani, and H. P. Natarajan, "Connectivity upgrade models for survivable network design," *Operations Research*, vol. 57, no. 1, pp. 170–186, February 2009.

[25] S. Soni, R. Gupta, and H. Pirkul, "Survivable network design: The state of the art," *Information Systems Frontiers*, vol. 1, no. 3, pp. 303–315, October 1999.

[26] C. Pavan, R. M. Morais, J. da Rocha, and A. N. Pinto, "Generating realistic optical transport network topologies," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 2, no. 1, pp. 80–90, January 2010.

[27] Fico Xpress optimization suite (2010). [Online]. Available: http://www.fico.com/en/products/fico-xpress-optimization-suite/

[28] R. Huelsermann, M. Gunkel, C. Meusburger, and D. A. Schupke, "Cost modeling and evaluation of capital expenditures in optical multilayer networks," *Journal of Optical Networking*, vol. 7, pp. 814–833, September 2008.

Opaque without Survivability

CAPEX of the Network - Low Traffic Scenario						
			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 €

Table 7.1: Table with detailed description of CAPEX of Vasco's 2016 results.

CAPEX of the Network - Medium Traffic Scenario						
			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 €

Table 7.2: Table with detailed description of CAPEX of Vasco's 2016 results.

CAPEX of the Network - High Traffic Scenario						
			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 €	29 814 200 €
		ODU0 Ports	1 200	10 €/port	12 000 €	
		ODU1 Ports	1 000	15 €/port	15 000 €	
		ODU2 Ports	320	30 €/port	9 600 €	
		ODU3 Ports	120	60 €/port	7 200 €	
		ODU4 Ports	80	100 €/port	8 000 €	
		Line Ports	297	100 000 €/port	29 700 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						178 834 200 €

Table 7.3: Table with detailed description of CAPEX of Vasco's 2016 results.

Opaque with 1+1 Protection

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

Table 7.4: Table with detailed description of CAPEX of Vasco's 2016 results.

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

Table 7.5: Table with detailed description of CAPEX of Vasco's 2016 results.

CAPEX of the Network - High Traffic Scenario						
			Quantity	Unit Price	Cost	Total
Link Cost	OLTs		16	15 000 €	240 000 €	397 520 000 €
	100 Gbits/s Transceivers		794	5 000 €/Gbit/s	397 000 000 €	
	Amplifiers		70	4 000 €	280 000 €	
Node Cost	Electrical	EXCs	6	10 000 €	60 000 €	79 514 200 €
		ODU0 Ports	1 200	10 €/port	12 000 €	
		ODU1 Ports	1 000	15 €/port	15 000 €	
		ODU2 Ports	320	30 €/port	9 600 €	
		ODU3 Ports	120	60 €/port	7 200 €	
		ODU4 Ports	80	100 €/port	8 000 €	
		Line Ports	794	100 000 €/port	99 400 000 €	
	Optical	OXCs	0	20 000 €	0 €	
		Ports	0	2 500 €/port	0 €	
Total Network Cost						477 034 200 €

Table 7.6: Table with detailed description of CAPEX of Vasco's 2016 results.

Transparent without Survivability

CAPEX of the Network - Low Traffic Scenario						
			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 €

Table 7.7: Table with detailed description of CAPEX of Vasco's 2016 results.

CAPEX of the Network - Medium Traffic Scenario						
			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 €

Table 7.8: Table with detailed description of CAPEX of Vasco's 2016 results.

CAPEX of the Network - High Traffic Scenario						
			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 €

Table 7.9: Table with detailed description of CAPEX of Vasco's 2016 results.

Transparent with 1+1 Protection

CAPEX of the Network - Low Traffic Scenario						
			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 €

Table 7.10: Table with detailed description of CAPEX of Vasco's 2016 results.

CAPEX of the Network - Medium Traffic Scenario						
			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 €

Table 7.11: Table with detailed description of CAPEX of Vasco's 2016 results.

CAPEX of the Network - High Traffic Scenario						
			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 €

Table 7.12: Table with detailed description of CAPEX of Vasco's 2016 results.

Translucent without Survivability

CAPEX of the Network - Low Traffic Scenario						
			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 €

Table 7.13: Table with detailed description of CAPEX.

CAPEX of the Network - Medium Traffic Scenario						
			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 €

Table 7.14: Table with detailed description of CAPEX.

CAPEX of the Network - High Traffic Scenario						
			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 €

Table 7.15: Table with detailed description of CAPEX.

Translucent with 1+1 Protection

CAPEX of the Network - Low Traffic Scenario						
			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 €

Table 7.16: Table with detailed description of CAPEX.

CAPEX of the Network - Medium Traffic Scenario						
			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 €

Table 7.17: Table with detailed description of CAPEX.

CAPEX of the Network - High Traffic Scenario						
			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 €

Table 7.18: Table with detailed description of CAPEX.