

NetXPTO - NetPlanner

19 de Fevereiro de 2019

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Heuristic algorithms are used in this report with an objective to minimize the total CAPEX of the network. It is important to have these comparison results with the linear programming ones, because these formulations are faster than the optimal methods and can generate also a near optimal solution. Another advantage of the heuristic approach is that heuristic solutions leads to good performances in practical network scenarios when we present a sufficiently feasible solution, instead of an optimal solution.

In order to get the total network cost for the reference network, the CAPEX is calculated by routing and grooming heuristic algorithms implemented in Java and it is considered that all network equipment is bidirectional. These algorithms are tested in a network design software called Net2Plan.

This chapter consists in demonstrating how the matrices are created, how the heuristic algorithms work and analyzing the results. It is divided in six subsections and the results differ into three different transport modes: opaque (link-by-link grooming method), transparent (single-hop grooming method) and translucent (multi-hop grooming method). Each one of these transport methods are also distinguished and compared by the possibility of being without survivability or with 1+1 protection and for the cases of low, medium and high traffic in the network.

1.1 CAPEX

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

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

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

To calculate the total network cost it has to be considered the links cost and the nodes cost. The CAPEX value of a network, C_C , in monetary units (e.g. euros, or dollars), is calculated by the equation 1.1

$$C_C = C_L + C_N \quad (1.1)$$

where

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

On the first hand, the links' cost, C_L , in monetary units (e.g. euros, or dollars), is calculated by the equation 1.2. If the length of the link is longer, the resulting costs will be higher due to of the necessity of having more components which carry all the traffic from all origin nodes to all destination nodes

$$C_L = \sum_{i=1}^N \sum_{j=i+1}^N L_{ij} (2\gamma_0^{OLT} + 2\gamma_1^{OLT} \tau W_{ij} + N_{ij}^R c^R) \quad (1.2)$$

where

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

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

The line bit-rate that is used in this report has the value of 100. It represents the separation between regeneration stages in km. On the other hand, the nodes' cost, C_N , in monetary units (e.g. euros, or dollars), is calculated by the equation 1.3

$$C_N = C_{EXC} + C_{OXC} \quad (1.3)$$

where

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

As all the nodes have an electrical part and an optical part, it is necessary to calculate both with their respective formulas and sum the results. The constitution of the electrical node part can be seen in the Integer Linear Programming section ???. The electrical nodes' cost, C_{EXC} , in monetary units (e.g. euros, or dollars), is given by the equation 1.4

$$C_{EXC} = \sum_{n=1}^N N_{exc,n} \left(\gamma_{e0} + \sum_{c=-1}^B \gamma_{e1,c} P_{exc,c,n} \right) \quad (1.4)$$

where

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

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

Tabela 1.1: Table with index and your corresponding bit rate

The constitution of the optical node part can be seen in the Integer Linear Programming section ?? . Finally, the optical nodes' cost, C_{OXC} , in monetary units (e.g. euros, or dollars), is given by the equation 1.5

$$C_{OXC} = \sum_{n=1}^N N_{oxc,n} (\gamma_{o0} + \gamma_{o1} P_{oxc,n}) \quad (1.5)$$

where

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

After all the formulas needed to calculate the CAPEX of a network are demonstrated above, it is also essential to have pre-defined the costs of the network equipments. In the table 1.2 it is shown the cost, in euros, of all the equipments with their symbols used in the respective formulas.

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

Tabela 1.2: Table with costs

1.1.1 Opaque without Survivability

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

In the opaque transport mode (link-by-link approach), the lightpath entering any intermediate node is necessarily terminated, i.e., there are performed OEO (optical-electrical-optical) conversions at every intermediate node since the origin to the destination node. These conversions are used for every wavelength at every node.

Contrary to the opaque with dedicated 1+1 protection technique, the opaque without survivability technique does not have a backup path, so if there is a network failure it is more likely to suffer large data losses, which consequently leads to higher network costs. However, the CAPEX will be significantly lower, because that not includes a secondary path that will increase several network elements.

After the creation of the matrices and the network topology, it is necessary to apply the routing and grooming algorithms created. In the end, a cost report algorithm will be applied to visualize the network CAPEX results for the network in question.

Firstly, in the opaque transport mode, the optical node cost is 0 because all the ports in the network are electrical. Consequently, to calculate the nodes' cost in this transport mode it only has to be considered the electrical nodes' cost:

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

As previously mentioned, equation 1.6 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n , $P_{exc,-1,n}$, i.e., the number of line ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^N w_{nj} \quad (1.6)$$

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

As previously mentioned, equation 1.7 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n , $P_{exc,c,n}$, i.e., the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^N D_{nd,c} \quad (1.7)$$

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

In this case there is the following particularity:

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

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

In the next pages it will be described all the steps performed to obtain the final results in the opaque transport mode without survivability. In the figure below 1.1 it is shown a fluxogram with the description of this transport mode approach.



Figura 1.1: Fluxogram with the steps performed in the opaque without survivability transport mode approach.

Creation and join the traffic matrices

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

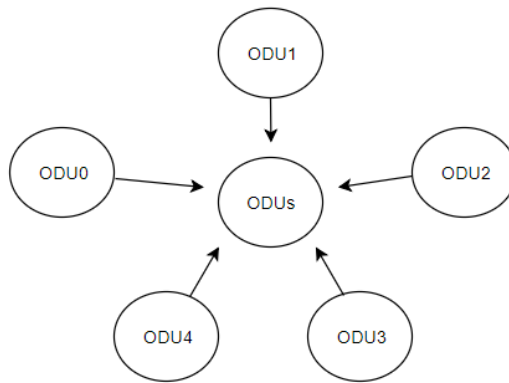


Figura 1.2: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.



Figura 1.3: Load of the join traffic matrices algorithm for the opaque transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

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



Figura 1.4: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. In the opaque transport mode the physical and logical topologies are the same, so it is needed to add a new layer from the lower layer (default layer). The lower layer is the physical layer of the network and it is now created a new upper layer which is the logical layer of the network and represents the logical topology of the opaque transport mode. The allowed physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 1.1.1 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the opaque transport mode without survivability.

```

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

```

Figura 1.5: Java code of the logical topology approach for the opaque transport mode. The logical layer is created from the physical layer, as in this transport mode they are the same. The new layer is now the opaque logical topology of the network.



Figura 1.6: Load of the logical topology algorithm for the opaque transport mode.



Figura 1.7: Allowed optical topology. It is assumed that each transmission system supports up to 100 optical channels.

Creation of routes and aggregation of traffic

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

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

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

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

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

Figura 1.8: Creation of routes and aggregation of traffic for the opaque without survivability transport mode. The candidate routes are searched by the shortest path type method and the offered traffic demands are set into these routes.

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

Tabela 1.3: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

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

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

Figura 1.9: Calculation of the number of wavelengths per link for the opaque transport mode. The link capacity is based on the traffic per demand.

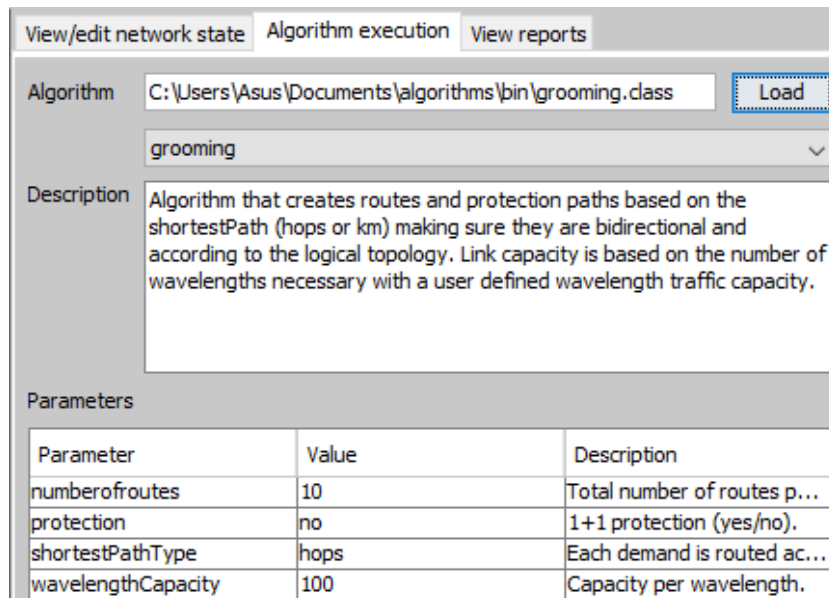


Figura 1.10: Load of the grooming algorithm for the opaque without survivability transport mode. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 1.1.1 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details. In the opaque transport mode the optical node cost is 0 because all the network ports are electrical, so it only has to be considered the electrical nodes' costs and the electrical links' costs.



Figura 1.11: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

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

Low Traffic Scenario:

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



Figura 1.12: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 1.13: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.



Figura 1.14: ODU0 logical topology defined by the ODU0 traffic matrix.

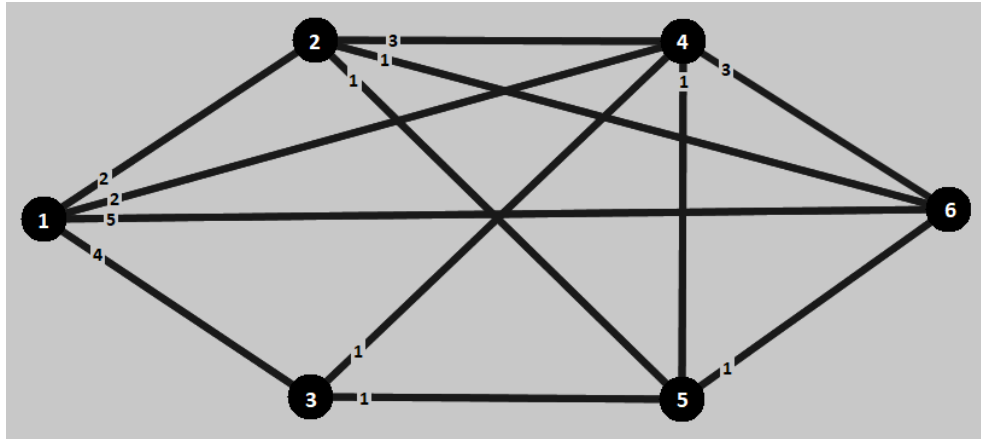


Figura 1.15: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.16: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 1.17: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.18: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.19: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.4.

All the values calculated in the previous table were obtained through the equations 1.2 and 1.3 referred to in section 1.1, but for a more detailed analysis we created table 1.5 where we can see how all the parameters are calculated individually.

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

Tabela 1.4: Table with detailed description of CAPEX of Vasco's 2016 results.

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

Tabela 1.5: Table with description of calculation

Medium Traffic Scenario:

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

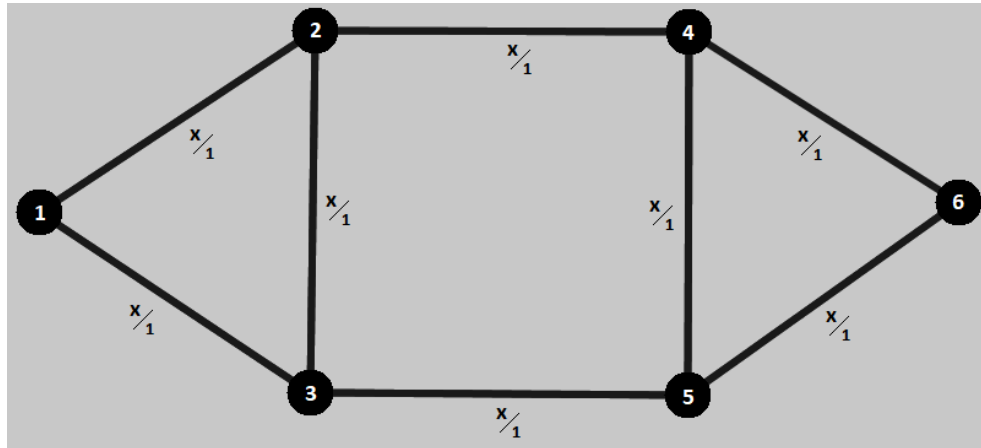


Figura 1.20: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

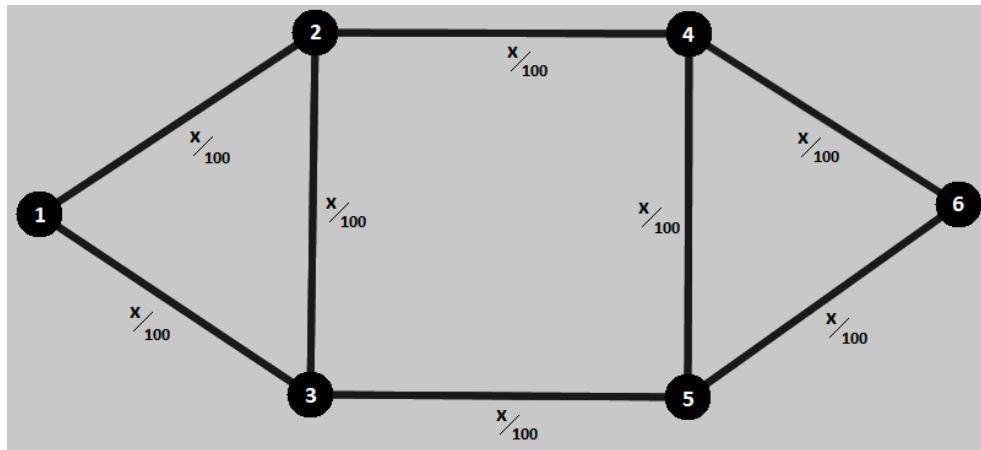


Figura 1.21: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.



Figura 1.22: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.23: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.24: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 1.25: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.26: ODU4 logical topology defined by the ODU4 traffic matrix.

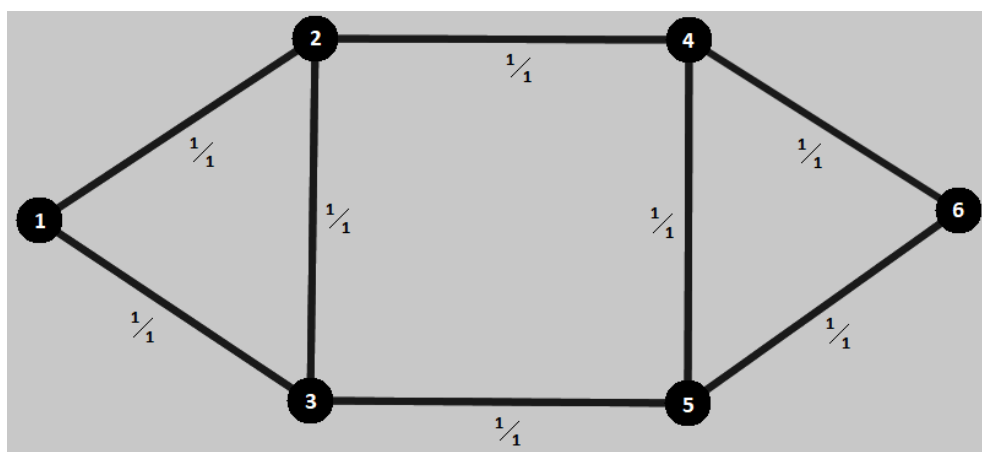


Figura 1.27: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.6. In table 1.5 mentioned in previous scenario we can see how all the values were calculated.

| CAPEX of the Network | | | | | |
|----------------------|--------------------------|------------|------------|----------------|--------------|
| | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € |
| | 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 € |
| | | ODU0 Ports | 600 | 10 €/port | 6 000 € |
| | | ODU1 Ports | 500 | 15 €/port | 7 500 € |
| | | ODU2 Ports | 160 | 30 €/port | 4 800 € |
| | | ODU3 Ports | 60 | 60 €/port | 3 600 € |
| | | ODU4 Ports | 40 | 100 €/port | 4 000 € |
| | | Line Ports | 153 | 100 000 €/port | 15 300 000 € |
| | Optical | OXCs | 0 | 20 000 € | 0 € |
| | | Ports | 0 | 2 500 €/port | 0 € |
| Total Network Cost | | | | | 92 405 900 € |

Tabela 1.6: Table with detailed description of CAPEX of Vasco's 2016 results.

High Traffic Scenario:

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



Figura 1.28: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

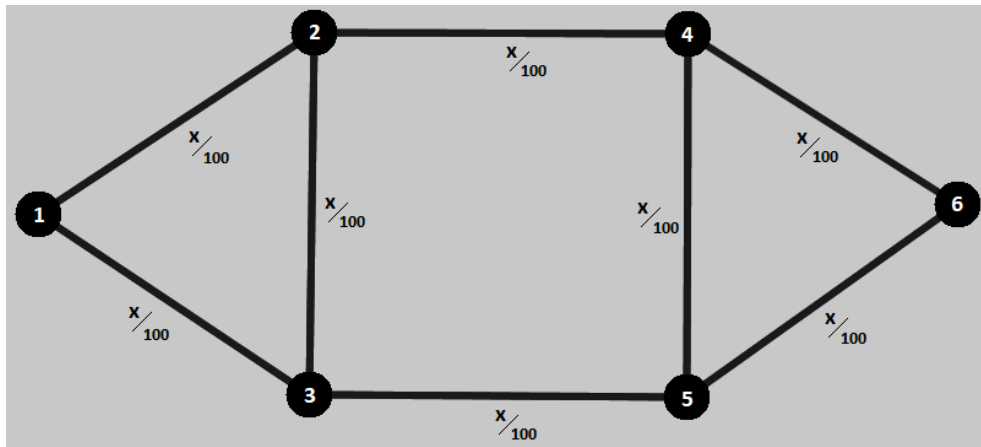


Figura 1.29: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

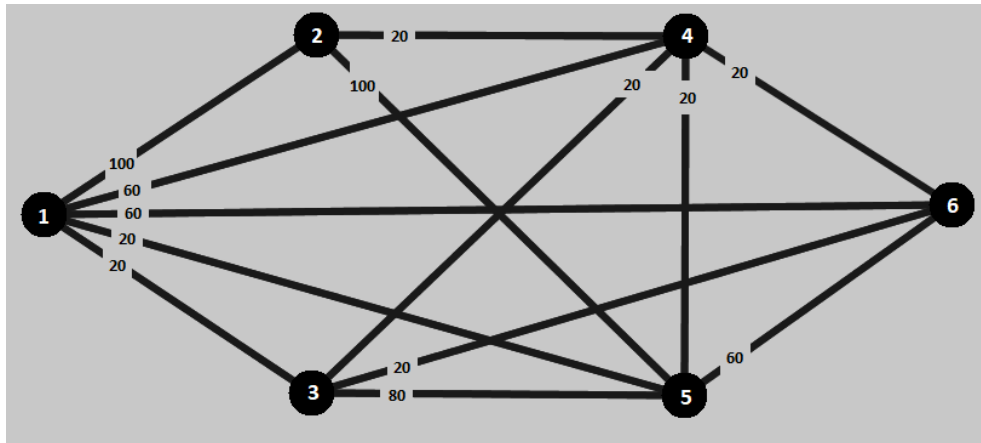


Figura 1.30: ODU0 logical topology defined by the ODU0 traffic matrix.

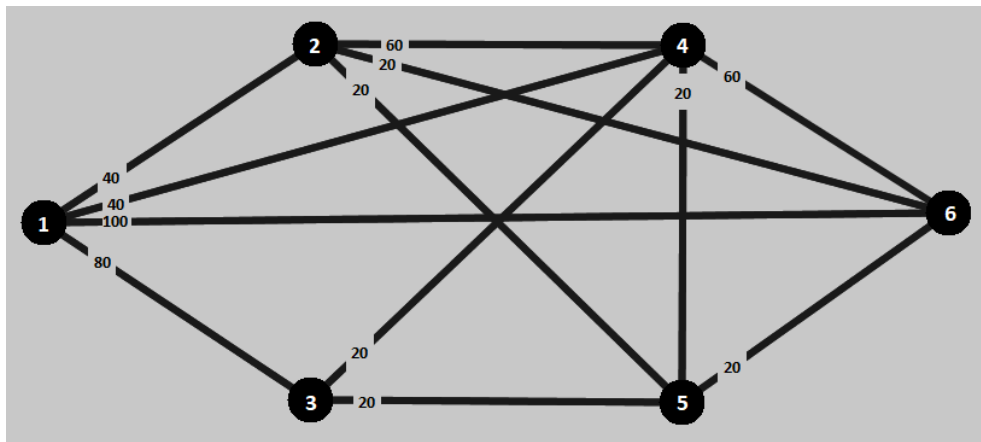


Figura 1.31: ODU1 logical topology defined by the ODU1 traffic matrix.

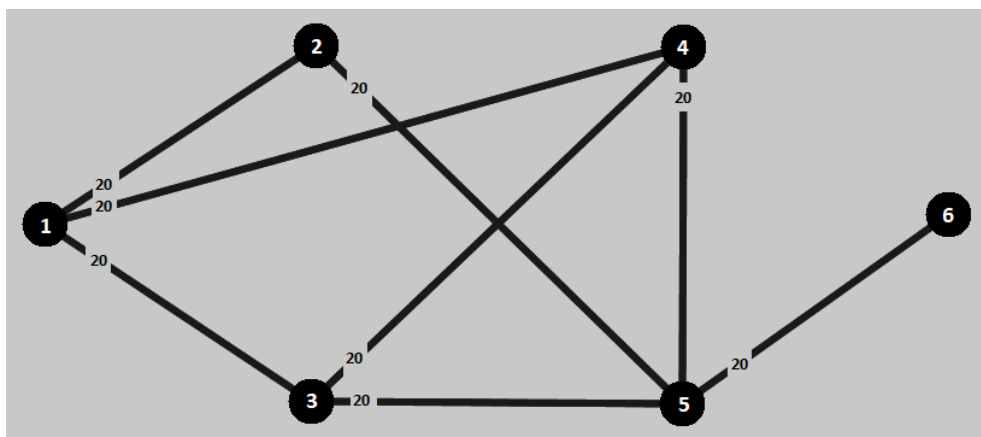


Figura 1.32: ODU2 logical topology defined by the ODU2 traffic matrix.

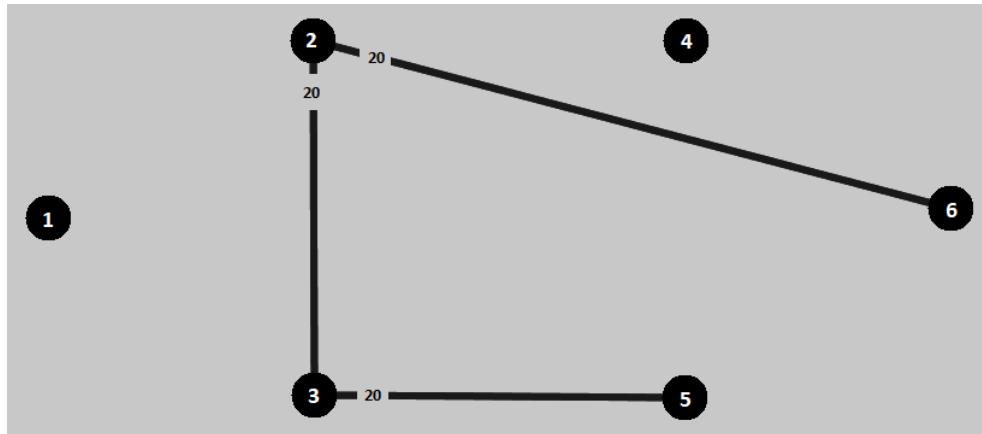


Figura 1.33: ODU3 logical topology defined by the ODU3 traffic matrix.

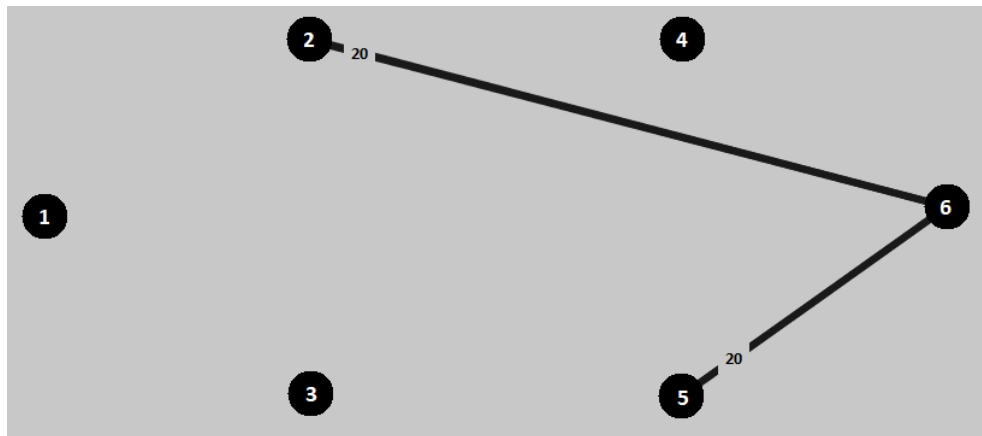


Figura 1.34: ODU4 logical topology defined by the ODU4 traffic matrix.

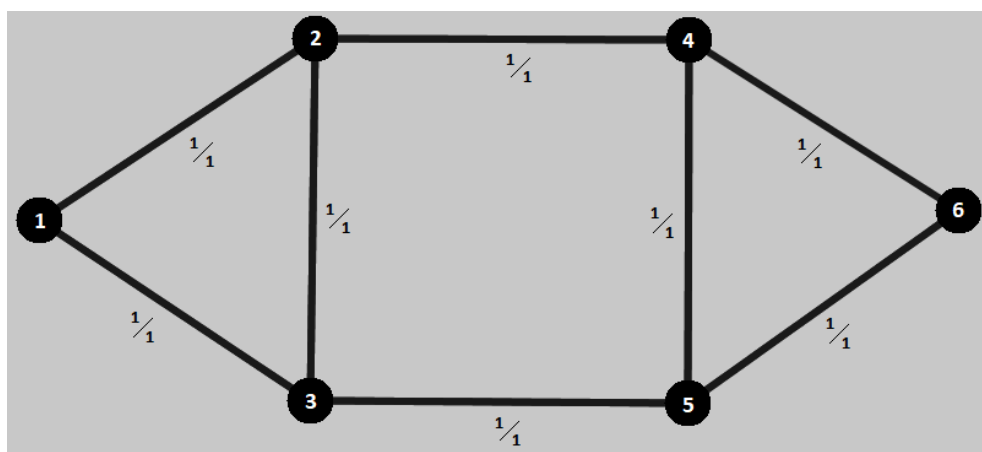


Figura 1.35: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.7. In table 1.5 mentioned in previous scenario we can see how all the values were calculated.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|------------|----------|----------------|---------------|---------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 149 020 000 € |
| | 100 Gbits/s Transceivers | | 297 | 5 000 €/Gbit/s | 148 500 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 29 811 800 € |
| | | ODU0 Ports | 1 200 | 10 €/port | 12 000 € | |
| | | ODU1 Ports | 1 000 | 15 €/port | 15 000 € | |
| | | ODU2 Ports | 320 | 30 €/port | 9 600 € | |
| | | ODU3 Ports | 120 | 60 €/port | 7 200 € | |
| | | ODU4 Ports | 80 | 100 €/port | 8 000 € | |
| | Optical | Line Ports | 297 | 100 000 €/port | 29 700 000 € | |
| | | OXCs | 0 | 20 000 € | 0 € | |
| | | Ports | 0 | 2 500 €/port | 0 € | |
| Total Network Cost | | | | | | 178 831 800 € |

Tabela 1.7: Table with detailed description of CAPEX of Vasco's 2016 results.

Conclusions

Once we have obtained the results for all the scenarios we will now draw some conclusions about these results. For a better analysis of the results will be created the table 1.8 with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

| | Low Traffic | Medium Traffic | High Traffic |
|---------------------------|------------------------|------------------------|------------------------|
| Traffic (Gbit/s) | 500 | 5 000 | 10 000 |
| Bidirectional Links used | 8 | 8 | 8 |
| Number of Line ports | 23 | 153 | 297 |
| Number of Tributary ports | 136 | 1 360 | 2 720 |
| Number of Transceivers | 23 | 153 | 297 |
| Link Cost | 12 020 000 € | 77 020 000 € | 149 020 000 € |
| Node Cost | 2 362 590 € | 15 385 900 € | 29 811 800 € |
| CAPEX | 14 382 590 € | 92 405 900 € | 178 831 800 € |
| CAPEX/Gbit/s | 28 765 €/Gbit/s | 18 481 €/Gbit/s | 17 883 €/Gbit/s |

Tabela 1.8: Table with different value of CAPEX for this case.

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

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

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

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

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

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

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

Opens Issues

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

- Allow blocking.

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

- Allow multiple transmission system.

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

- Allowing multi-path routing.

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

Allow Blocking

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

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

In the figure below it is shown a fluxogram with the description of the opaque transport mode approach.

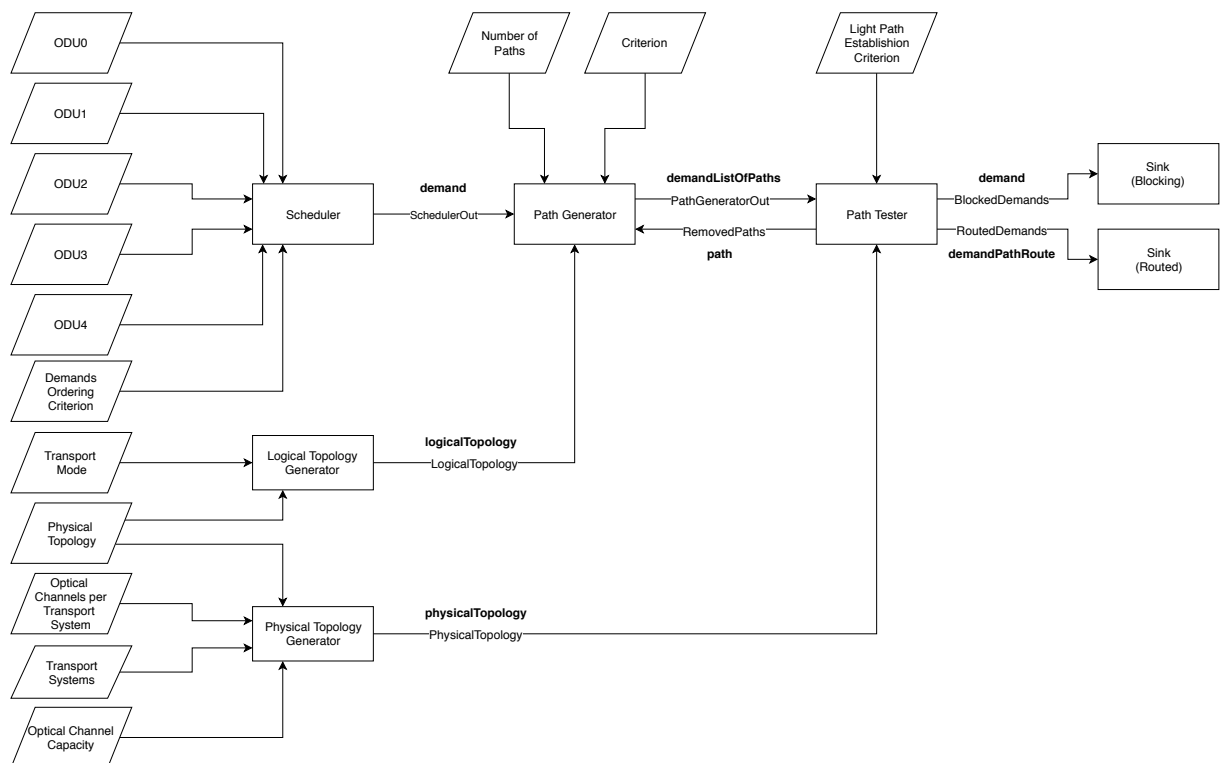


Figura 1.36: Fluxogram with the steps performed in the opaque transport mode approach.

| Parameter | Default value | Description |
|------------------------------------|---------------|---|
| ODU0 | Null | ODU0 demands |
| ODU1 | Null | ODU1 demands |
| ODU2 | Null | ODU2 demands |
| ODU3 | Null | ODU3 demands |
| ODU4 | Null | ODU4 demands |
| Demands Ordering Criterion | ODU4...ODU0 | Order by which demands will be sorted |
| Number of Paths | 3 | Number of paths created between a pair of nodes |
| Criterion | Hops | Shortest path type |
| Transport Mode | Null | Opaque, transparent or translucent modes |
| Physical Topology | Null | Physical connections of the network |
| Optical Channels | 100 | Optical channels per transport system |
| Transport Systems | 1 | Number of transport systems connecting each pair of nodes |
| Optical Channel Capacity | 100 Gbps | Physical capacity of each channel |
| Light Path Establishment Criterion | to define | to define |

Tabela 1.9: System input parameters.

| Block | Input Parameters | Input Signals |
|-----------------------------|--|------------------------------------|
| Scheduler | ODU0, ODU1, ODU2, ODU3, ODU4, Demands Odering Criterion | None |
| Logical Topology Generator | Transport Mode, Physical Topology | None |
| Physical Topology Generator | Physical Topology, Optical Channels, Transport Systems, Optical Channel Capacity | None |
| Path Generator | Number of Paths, Criterion | LogicalTopology, RemovedPaths |
| Path Tester | Ligh Path Establishment Criterion | PathGeneratorOut, PhysicalTopology |
| Sink (Blocking) | None | BlockedDemands |
| Sink (Routed) | None | RoutedDemands |

Tabela 1.10: Blocks input parameters and signals.

| Block | State Variables |
|-----------------------------|---|
| Scheduler | ODU0, ODU1, ODU2, ODU3, ODU4 |
| Logical Topology Generator | Logical Topology Matrix |
| Physical Topology Generator | Physical Topology Matrix |
| Path Generator | Logical Topology Matrix, Logical Link, Light Path |
| Path Tester | Physical Topology Matrix, Link, Optical Channel |
| Sink (Blocking) | None |
| Sink (Routed) | None |

Tabela 1.11: Blocks state variables.

| Signal Name | Signal Type |
|------------------|-------------------|
| SchedulerOut | demand |
| LogicalTopology | logicalTopology |
| PhysicalTopology | physicalTopology |
| PathGeneratorOut | demandListOfPaths |
| RemovedPaths | path |
| BlockedDemands | demand |
| RoutedDemands | demandPathRoute |

Tabela 1.12: System Signals.

Signal Types

demand

| Demand Index | Source Node | Destination Node | ODU Type | Restoration Method |
|---------------|-------------|------------------|----------|---|
| 1... ∞ | 1...N | 1...N | 0...4 | 0 - None 1 - Protection 1+1 2 - Restoration |

Tabela 1.13: Constitution of a demand.

N represents the number of nodes present in the network.

logicalTopology

This is the output signal of the Logical topology generator block, it has a matrix NxN where every logical connection existent between nodes in the network is displayed. In this particular case we are studying the opaque transport node so our logical topology will be the one presented in table 1.13. In addition here will occur the creation structures corresponding

to our network logical links and light paths.

| Nodes | 1 | 2 | 3 | 4 | 5 | 6 |
|-------|----------|----------|----------|----------|----------|----------|
| 1 | 0 | 0/1 | 0/1 | 0/1 | 0/1 | 0/1 |
| 2 | 0/1 | 0 | 0/1 | 0/1 | 0/1 | 0/1 |
| 3 | 0/1 | 0/1 | 0 | 0/1 | 0/1 | 0/1 |
| 4 | 0/1 | 0/1 | 0/1 | 0 | 0/1 | 0/1 |
| 5 | 0/1 | 0/1 | 0/1 | 0/1 | 0 | 0/1 |
| 6 | 0/1 | 0/1 | 0/1 | 0/1 | 0/1 | 0 |

Tabela 1.14: Logical Topology Matrix.

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

Tabela 1.15: Opaque Topology Matrix.

| Index | Link Source Node | Link Destination Node | Number of Light Paths |
|-------|------------------|-----------------------|-----------------------|
| 1 | 1...N | 1...N | -1 |
| ... | ... | ... | ... |
| LO | 1...N | 1...N | -1 |

Tabela 1.16: Logical link variable.

LO represents the number of logical links present in the network.

| Link Index | Light Path Number | Physical Links | Wavelength | Capacity (ODU0s) |
|------------|-------------------|----------------|------------|------------------|
| 1 | 1 | [0/1...0/1] | 1...OC | |
| ... | ... | ... | ... | |
| LO | LP | [0/1...0/1] | 1...OC | |

Tabela 1.17: Light path variable.

LP represents the number of light paths established in the network.
 OC represents the number optical channels existent in each physical link.

The Physical Links variable inside of the light paths represents the links existent in our network, in this case they can assume two different values, 0 or 1, depending on whether they are used or not to route a demand through a certain light path.

physicalTopology

Here the information about every physical connection existent between nodes and their capacity initially existent is sent to the Path tester block where later on will be updated.

| Index | Link Source Node | Link Destination Node | Number of Optical Channels |
|-------|------------------|-----------------------|----------------------------|
| 1 | 1...N | 1...N | OC |
| ... | ... | ... | ... |
| L | 1...N | 1...N | OC |

Tabela 1.18: Link variable.

| Link Index | Optical Channel Number | Capacity (ODU0s) | Wavelength | Source Node | Destination Node |
|------------|------------------------|------------------|------------|-------------|------------------|
| 1...L | 1...OC | | 1...OC | 1...N | 1...N |

Tabela 1.19: Optical channel variable.

path

| Path Index | Source Node | Destination Node | Logical links | Hops |
|------------|-------------|------------------|---------------|------|
| | 1...N | 1...N | [0/1...0/1] | |

Tabela 1.20: Path type signal.

The Logical links variable represents the logical links existent in our network, in this case they can assume two different values, 0 or 1, depending on whether they are used or not to route a demand through a certain path.

demandListOfPaths

Inside of the Path Generator block a list of logical paths associated to a pair of source and destination nodes will be created. This paths will depend directly on the logical topology of the network and on the availability of the links.

| Demand index | Path index |
|---------------|------------|
| 1... ∞ | x |
| | x+1 |
| | x+2 |

Tabela 1.21: demandListOfPaths signal.

demandPathRoute

| Demand Index | Path Index | Physical Link Index | 1...L |
|--------------|------------|---------------------|--------|
| 1...N | 1...N | Optical Channel | 1...OC |

Tabela 1.22: demandPathRoute signal.

1.1.2 Opaque with 1+1 Protection

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

The impact of failure in WDM (Wavelength Division Multiplexing) networks is caused by extremely high volume of traffic carried. In a high speed network like the WDM, a failure of a network element may cause failure of various optical channels that leads to large data and revenue losses, which can interrupt communication services.

In this protection scheme, the primary and backup path carry the traffic end-to-end, i.e., there is a need to have a backup path (the unaffected path) in case of a network failure. Then, the receiver will decide which one of the two incoming traffic it is going to pick, if the primary or the backup path.

Although it is the fastest protection scheme, it is also the most expensive, because it normally uses more than the double of the capacity of the primary path. This happens because the backup path is typically longer than the primary.

After the creation of the matrices and the network topology, it is necessary to apply the routing and grooming algorithms created. In the end, a report algorithm will be applied to obtain the best CAPEX result for the network in question.

Firstly, in the opaque transport mode, the optical node cost is 0 because all the ports in the network are electrical. Consequently, to calculate the nodes' cost in this transport mode it only has to be considered the electrical nodes' cost:

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

As previously mentioned, equation 1.8 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n , $P_{exc,-1,n}$, i.e., the number of line ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^N w_{nj} \quad (1.8)$$

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

As previously mentioned, equation 1.9 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n , $P_{exc,c,n}$, i.e., the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^N D_{nd,c} \quad (1.9)$$

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

In this case there is the following particularity:

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

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

In the next pages it will be described all the steps performed to obtain the final results in the opaque transport mode with 1+1 protection. In the figure below 1.37 it is shown a fluxogram with the description of this transport mode approach.

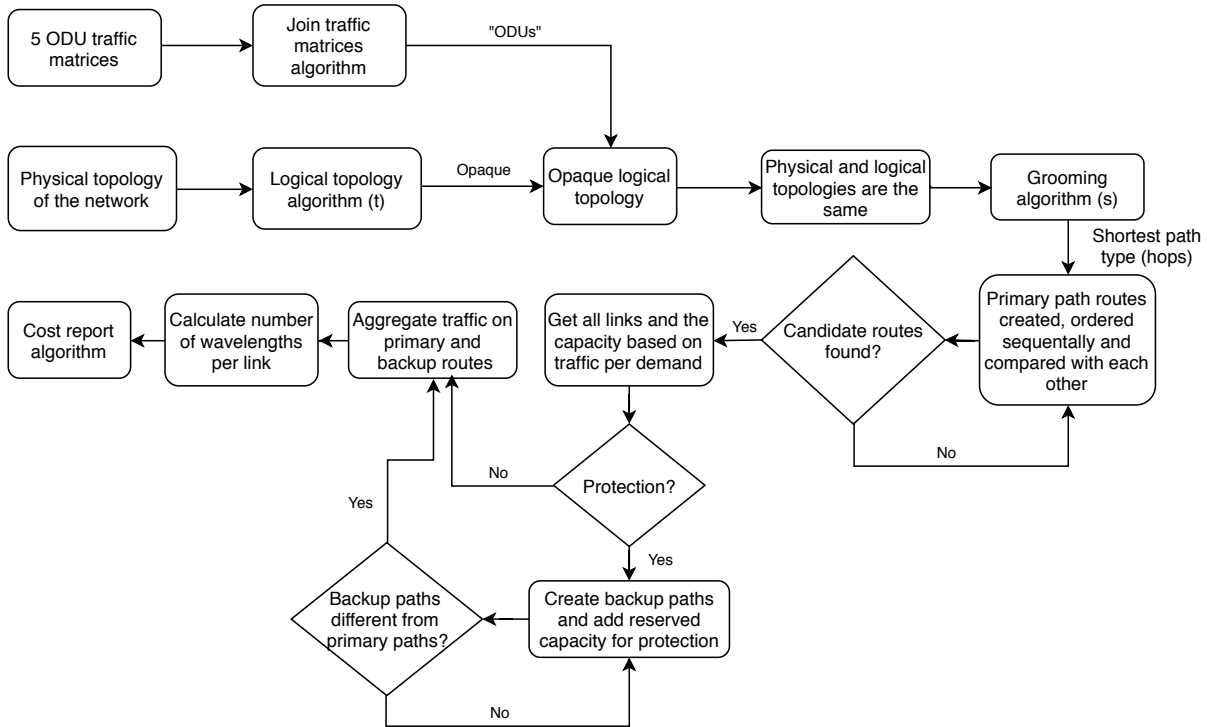


Figura 1.37: Fluxogram with the steps performed in the opaque with 1+1 protection transport mode approach.

Creation and join the traffic matrices

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

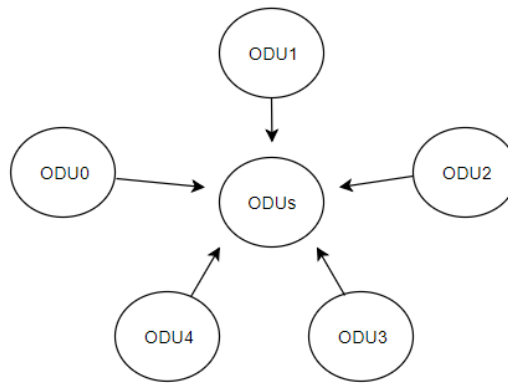


Figura 1.38: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.

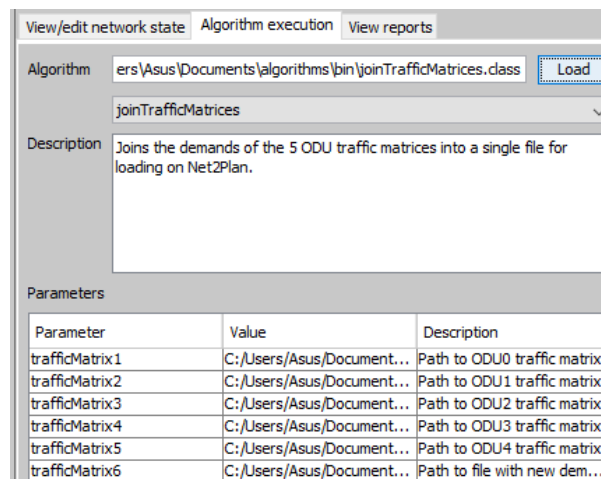


Figura 1.39: Load of the join traffic matrices algorithm for the opaque transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

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



Figura 1.40: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. In the opaque transport mode the physical and logical topologies are the same, so it is needed to add a new layer from the lower layer (default layer). The lower layer is the physical layer of the network and it is now created a new upper layer which is the logical layer of the network and represents the logical topology of the opaque transport mode. The allowed physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 1.1.2 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the opaque transport mode with 1+1 protection.


```

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

```

Figura 1.41: Java code of the logical topology approach for the opaque transport mode. The logical layer is created from the physical layer, as in this transport mode they are the same. The new layer is now the opaque logical topology of the network.

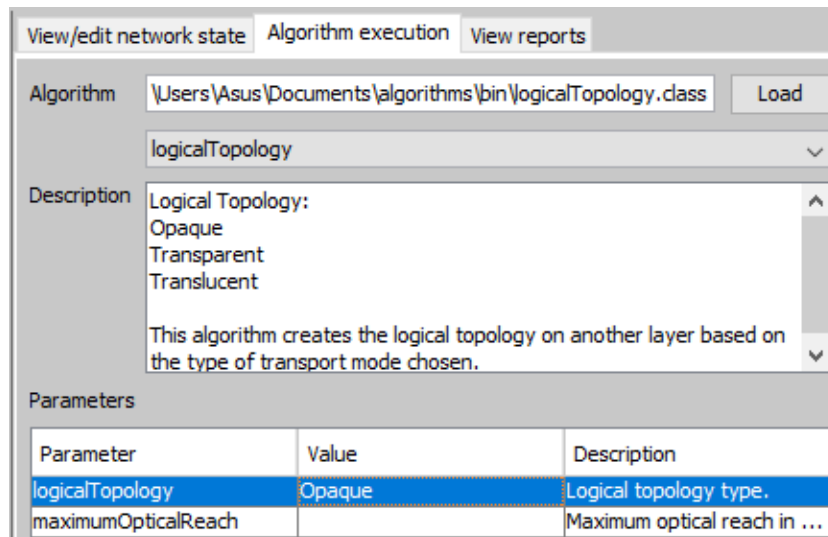


Figura 1.42: Load of the logical topology algorithm for the opaque transport mode.

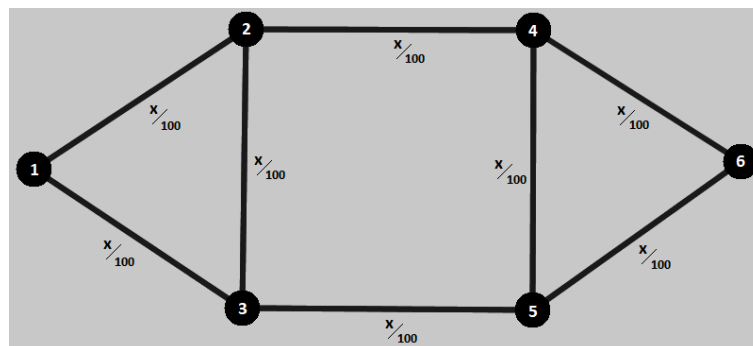


Figura 1.43: Allowed optical topology. It is assumed that each transmission system supports up to 100 optical channels.

Creation of routes and aggregation of traffic

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

```

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

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

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

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

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

```

Figura 1.44: Creation of routes and aggregation of traffic for the opaque with 1+1 protection transport mode. The candidate routes are searched by the shortest path type and the offered traffic demands are set into these routes.

```

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

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

```

Figura 1.45: Creation of routes and aggregation of traffic for the opaque with 1+1 protection transport mode. The protection segments are added to all the primary paths that were chosen by the shortest path type method.

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

Tabela 1.23: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

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

```

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

```

Figura 1.46: Calculation of the number of wavelengths per link for the opaque transport mode. The link capacity is based on the traffic per demand.

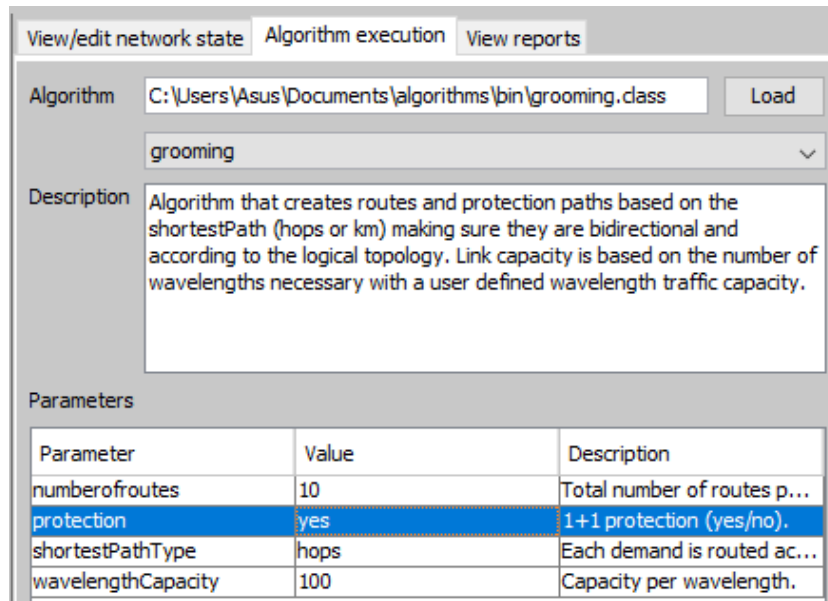


Figura 1.47: Load of the grooming algorithm for the opaque with 1+1 protection transport mode. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 1.1.2 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details. In the opaque transport mode the optical node cost is 0 because all the network ports are electrical, so it only has to be considered the electrical nodes' costs and the electrical links' costs.

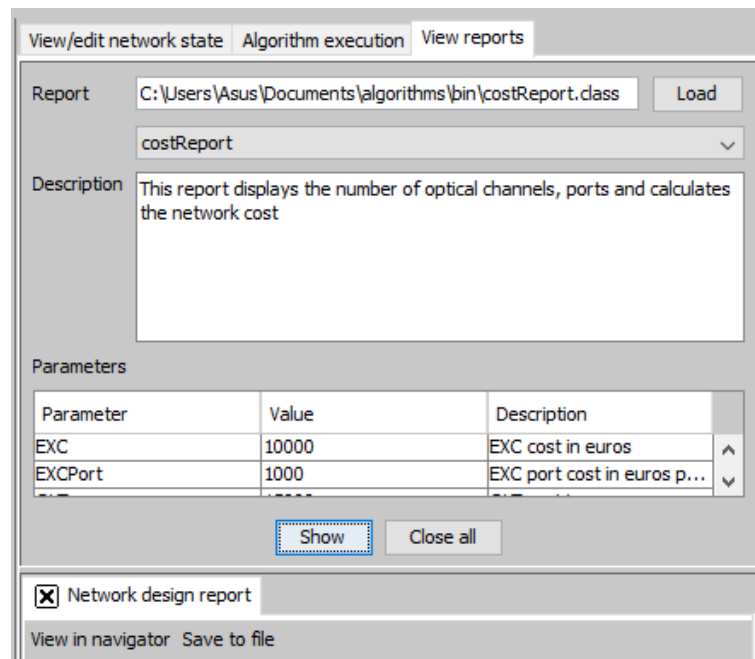


Figura 1.48: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

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

Low Traffic Scenario:

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

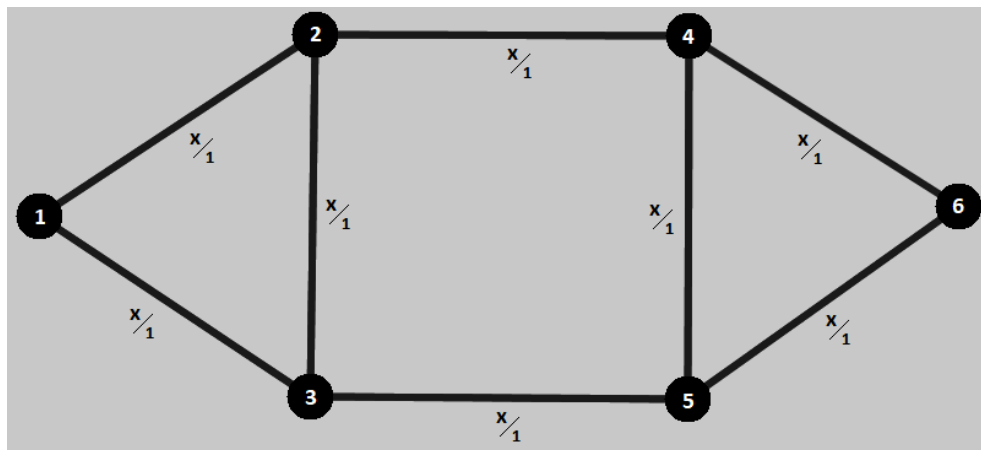


Figura 1.49: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

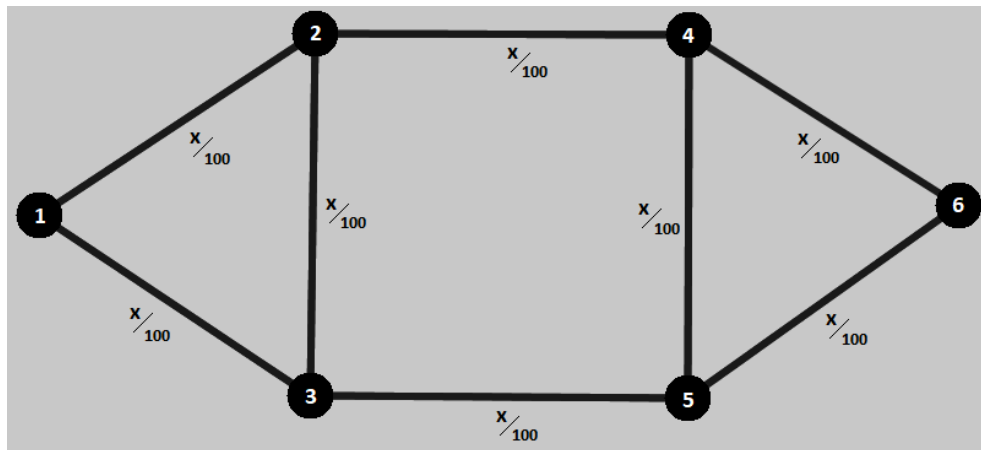


Figura 1.50: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

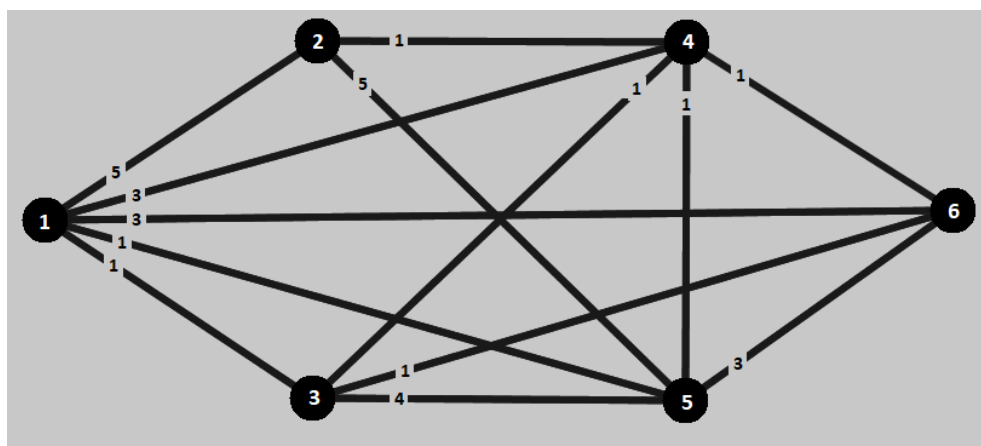


Figura 1.51: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.52: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.53: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 1.54: ODU3 logical topology defined by the ODU3 traffic matrix.

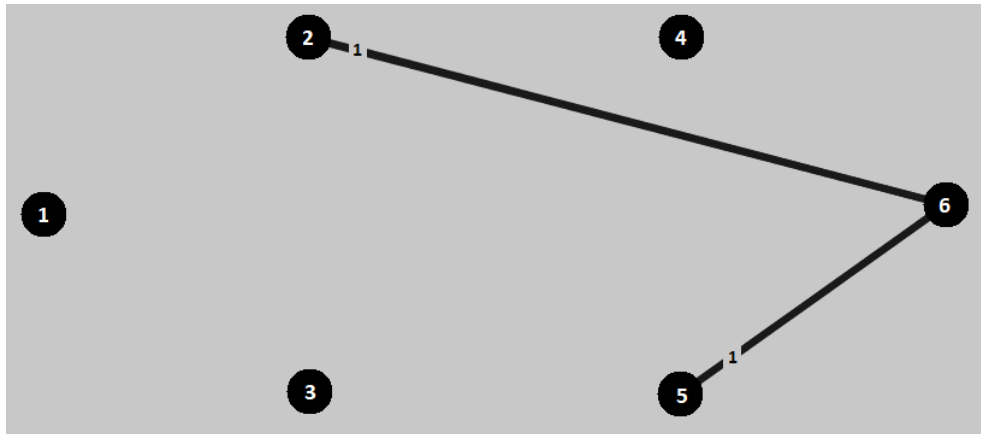


Figura 1.55: ODU4 logical topology defined by the ODU4 traffic matrix.

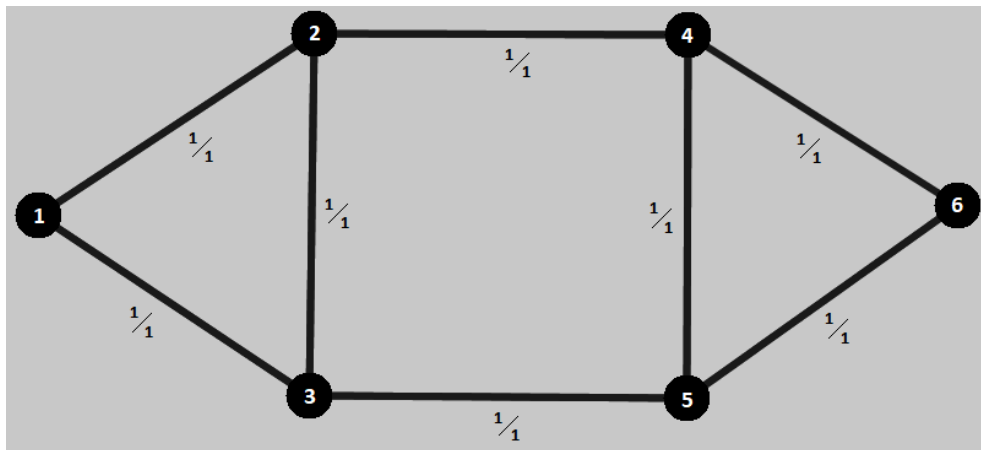


Figura 1.56: Physical topology after dimensioning.

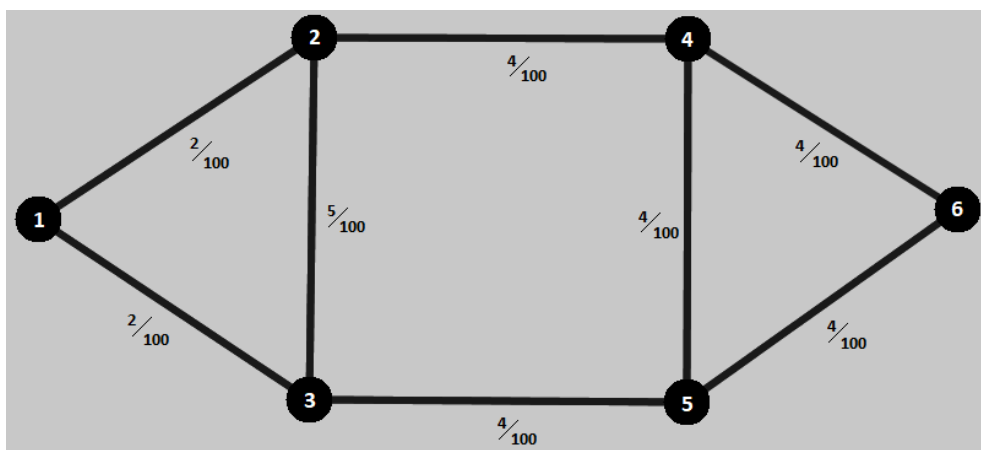


Figura 1.57: Optical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.24. In table 1.5 mentioned in previous model we can see how all the values were calculated.

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

Tabela 1.24: Table with detailed description of CAPEX of Vasco's 2016 results.

Medium Traffic Scenario:

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

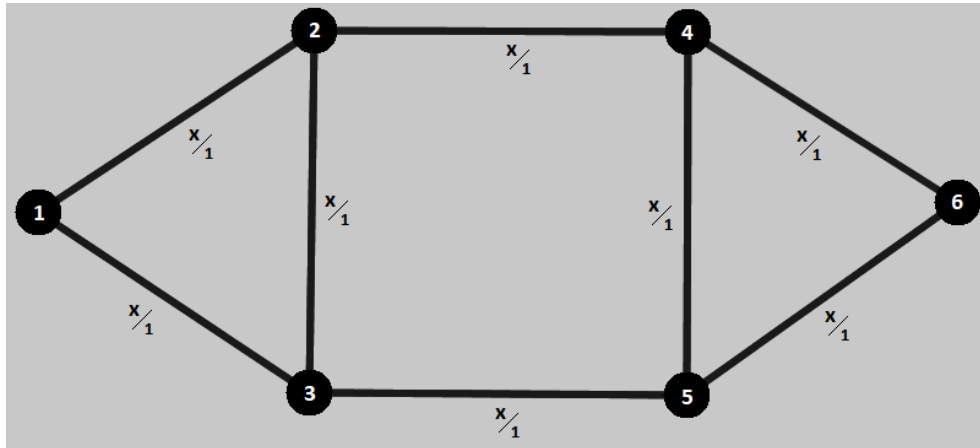


Figura 1.58: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

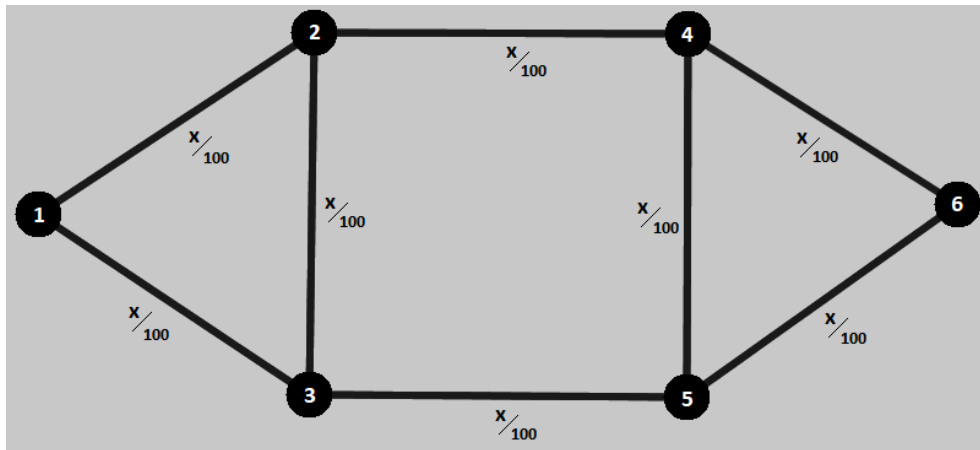


Figura 1.59: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

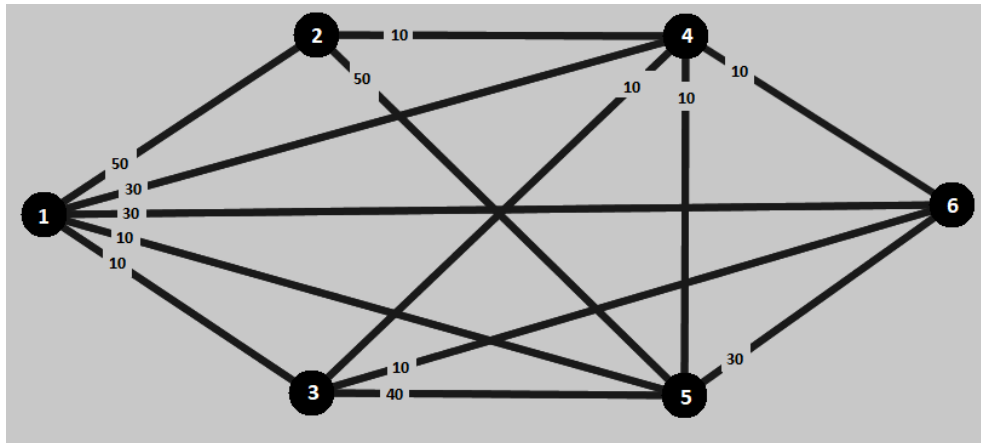


Figura 1.60: ODU0 logical topology defined by the ODU0 traffic matrix.

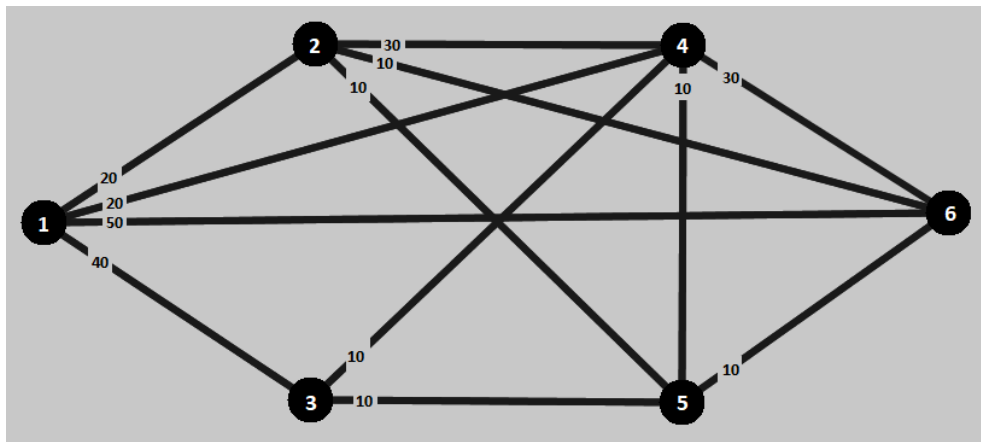


Figura 1.61: ODU1 logical topology defined by the ODU1 traffic matrix.

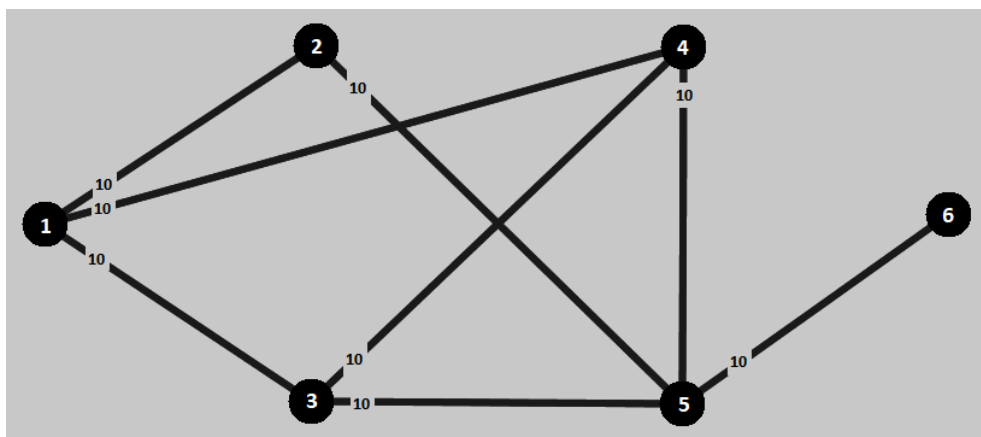


Figura 1.62: ODU2 logical topology defined by the ODU2 traffic matrix.

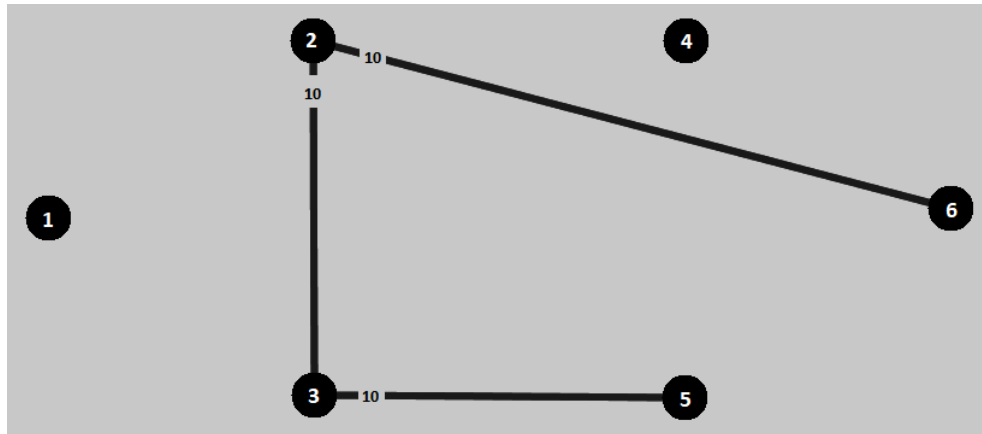


Figura 1.63: ODU3 logical topology defined by the ODU3 traffic matrix.

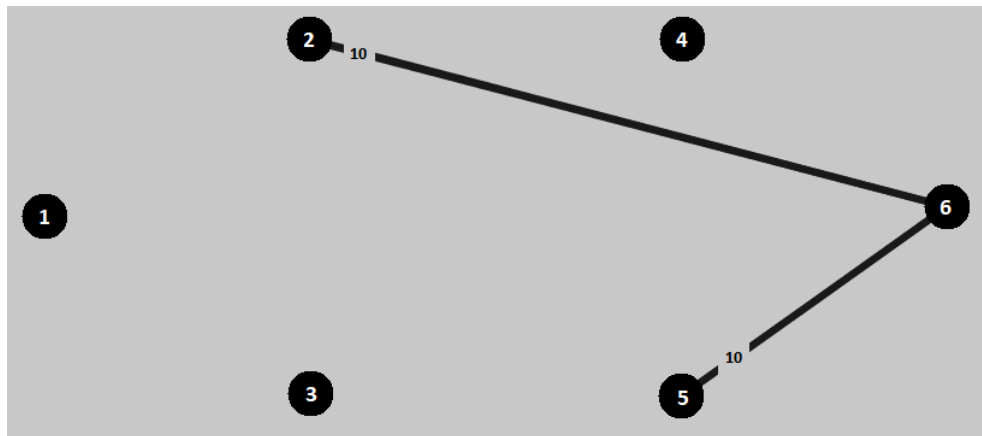


Figura 1.64: ODU4 logical topology defined by the ODU4 traffic matrix.

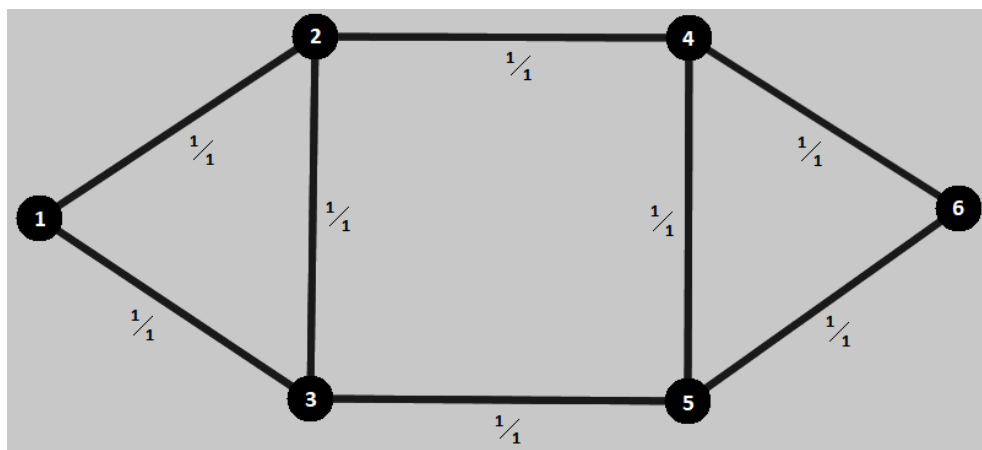


Figura 1.65: Physical topology after dimensioning.

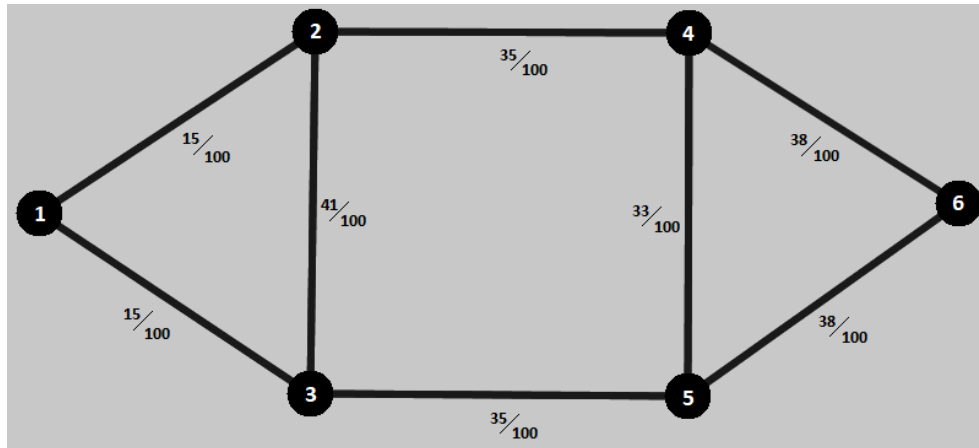


Figura 1.66: Optical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.25. In table 1.5 mentioned in previous model we can see how all the values were calculated.

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

Tabela 1.25: Table with detailed description of CAPEX of Vasco's 2016 results.

High Traffic Scenario:

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

and finally the resulting physical topology.

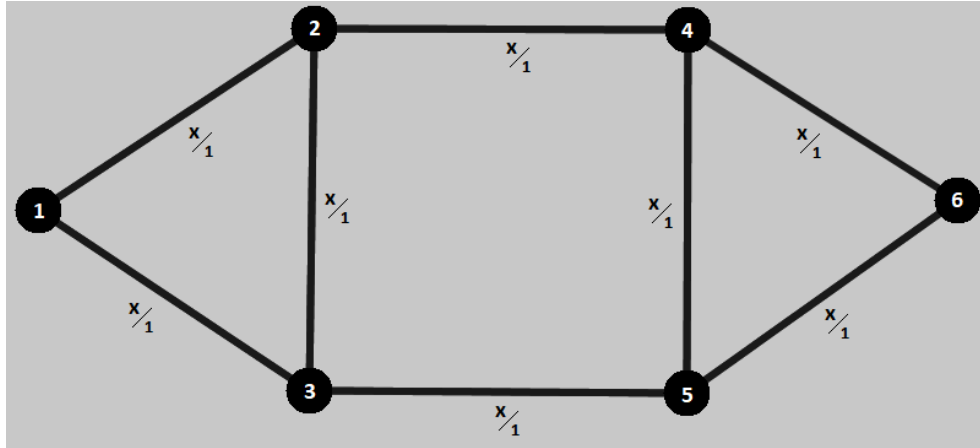


Figura 1.67: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

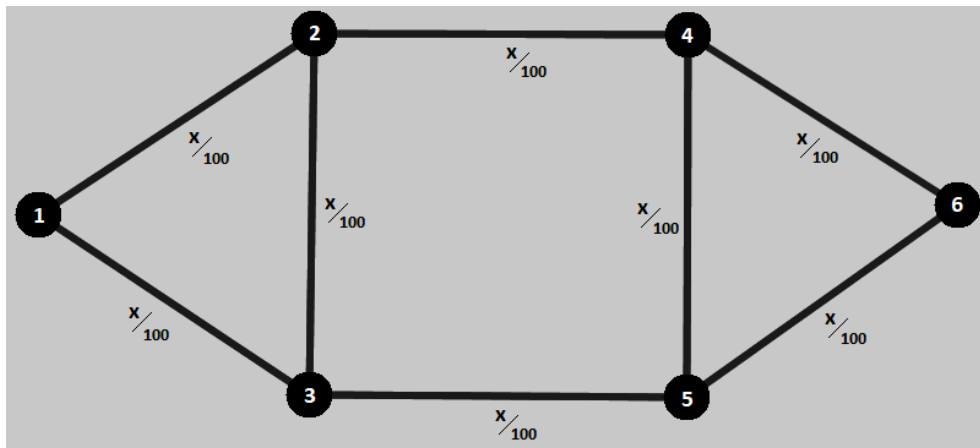


Figura 1.68: Allowed optical topology. The allowed optical topology is defined by the transport mode (opaque transport mode in this case). It is assumed that each transmission system supports up to 100 optical channels.

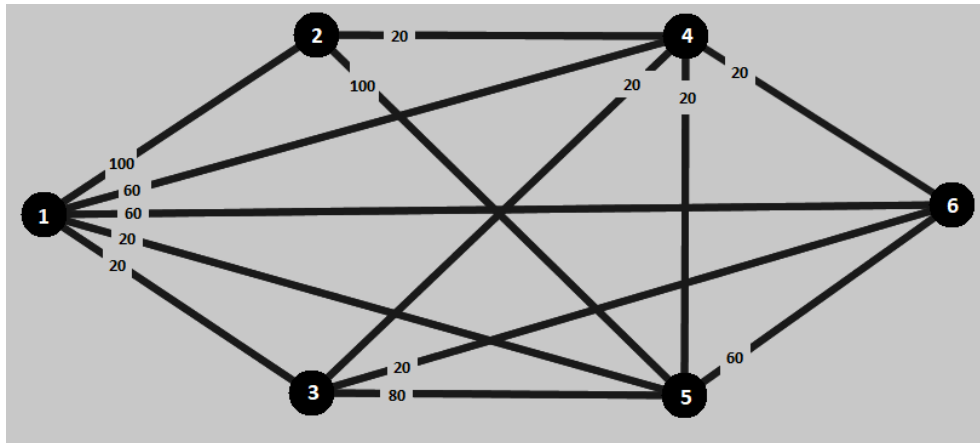


Figura 1.69: ODU0 logical topology defined by the ODU0 traffic matrix.

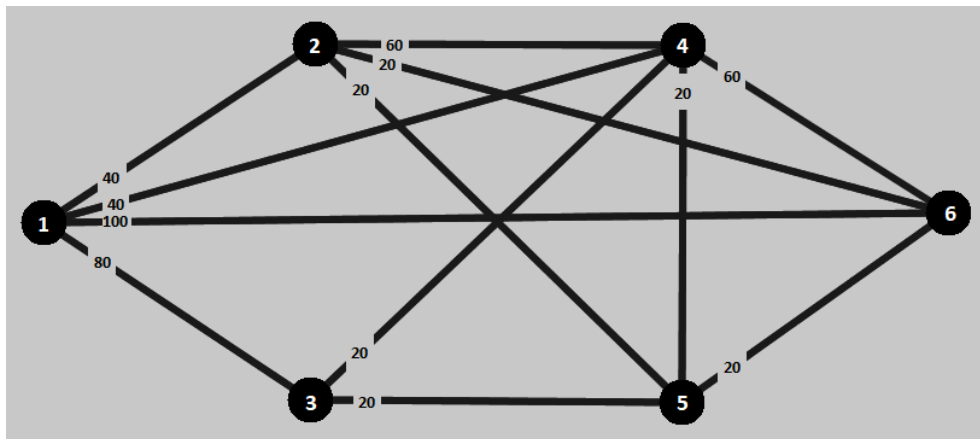


Figura 1.70: ODU1 logical topology defined by the ODU1 traffic matrix.

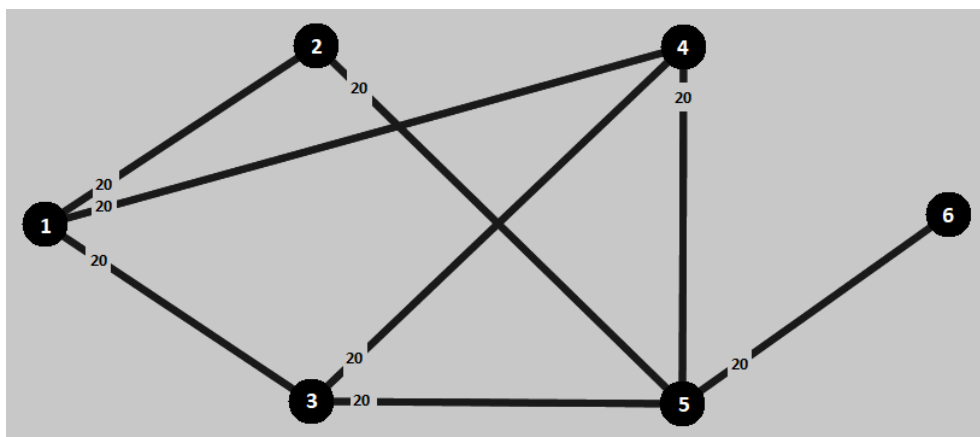


Figura 1.71: ODU2 logical topology defined by the ODU2 traffic matrix.

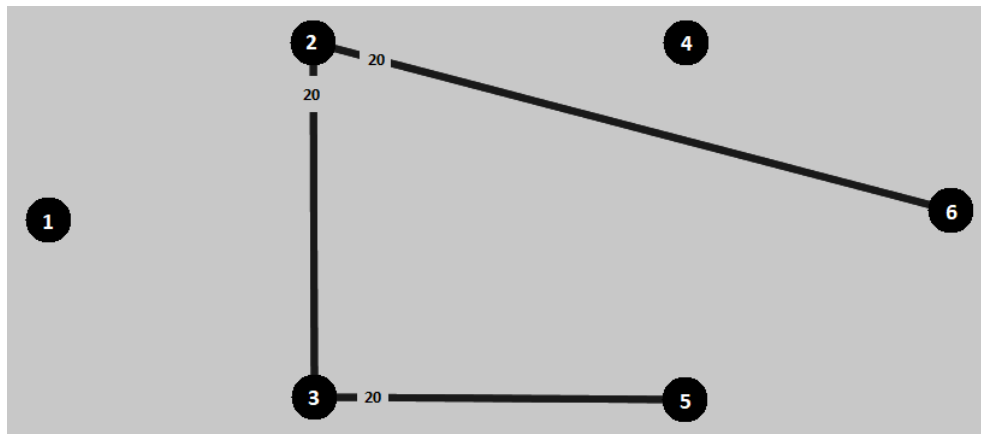


Figura 1.72: ODU3 logical topology defined by the ODU3 traffic matrix.

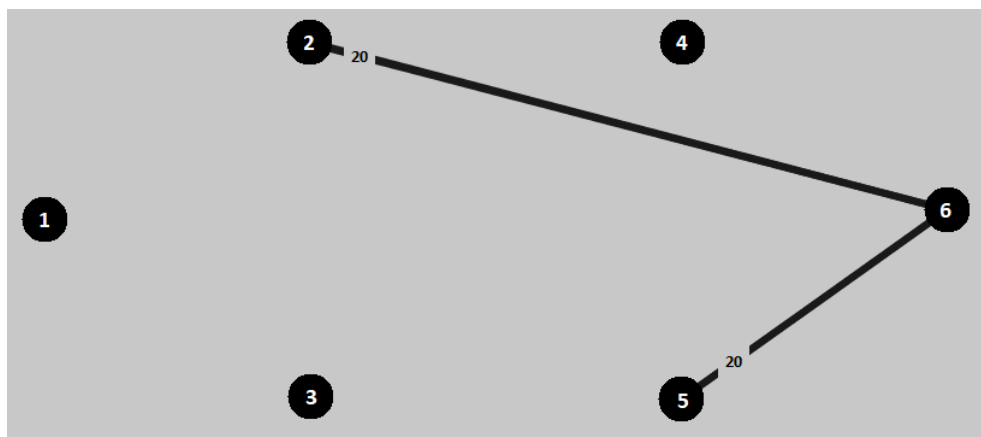


Figura 1.73: ODU4 logical topology defined by the ODU4 traffic matrix.

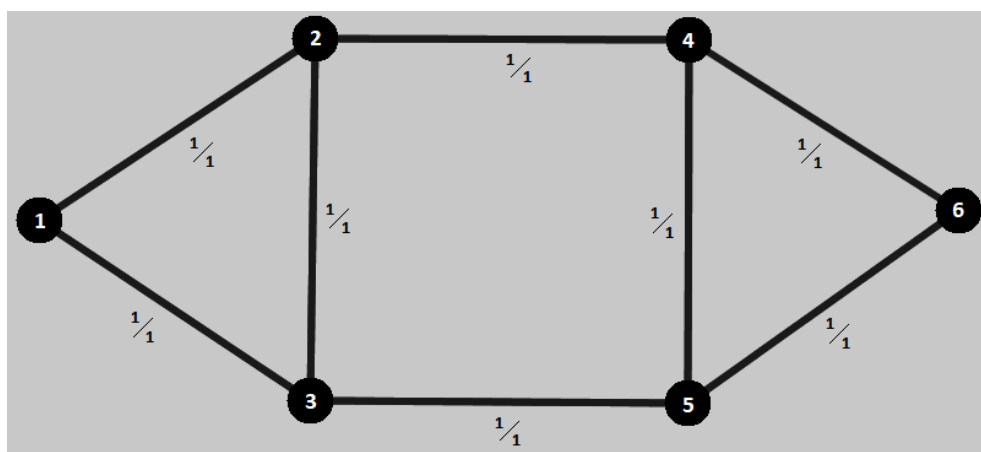


Figura 1.74: Physical topology after dimensioning.

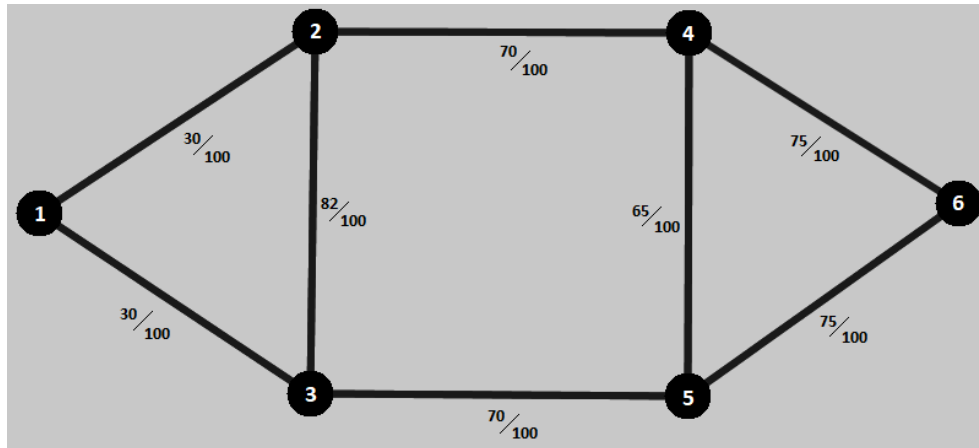


Figura 1.75: Optical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.26. In table 1.5 mentioned in previous model we can see how all the values were calculated.

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

Tabela 1.26: Table with detailed description of CAPEX of Vasco's 2016 results.

Conclusions

Once we have obtained the results for all the scenarios for opaque without survivability and opaque with 1+1 protection we will now draw some conclusions about these results. For

a better analysis of the results will be created the table 1.27 with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

| | Low Traffic | Medium Traffic | High Traffic |
|------------------------------------|------------------------|------------------------|------------------------|
| CAPEX without survivability | 14 382 590 € | 92 405 900 € | 178 831 800 € |
| CAPEX/Gbit/s without survivability | 28 765 €/Gbit/s | 18 481 €/Gbit/s | 17 883 €/Gbit/s |
| Traffic (Gbit/s) | 500 | 5 000 | 10 000 |
| Bidirectional Links used | 8 | 8 | 8 |
| Number of Line ports | 46 | 398 | 794 |
| Number of Tributary ports | 136 | 1 360 | 2 720 |
| Number of Transceivers | 46 | 398 | 794 |
| Link Cost | 23 520 000 € | 199 520 000 € | 397 520 000 € |
| Node Cost | 4 662 590 € | 39 885 900 € | 79 511 800 € |
| CAPEX | 28 182 590 € | 239 405 900 € | 477 031 800 € |
| CAPEX/Gbit/s | 56 365 €/Gbit/s | 47 881 €/Gbit/s | 47 703 €/Gbit/s |

Tabela 1.27: Table with different value of CAPEX for this case.

Looking at the previous table we can make some comparisons between the opaque with 1+1 protection scenario:

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

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

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

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

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

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

We can also make some comparisons between the opaque without survivability and opaque with 1+1 protection scenarios:

- We can see that in the opaque with 1+1 protection the CAPEX cost for all the three traffic is more than the double;

This happens because in the opaque with 1+1 protection there is a need of having a primary and a backup path, in case of a network failure, and the backup path is typically longer and normally uses more than the double of the capacity of the primary;

- The number of the network components and the CAPEX cost are directly proportional to the traffic value. The higher the traffic value, the higher the network CAPEX cost;

This happens because if the traffic value is higher, the network components have to be in more quantity to carry all the traffic end-to-end, both in the primary and backup paths;

- Comparing the CAPEX cost per bit we can see that has a similar case in both of the two scenarios. In the low traffic the cost is higher than the medium and high traffic, which in these two cases the value is very similar;

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

Opens Issues

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

- Allow blocking.

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

- Allow multiple transmission system.

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

- Allowing multi-path routing.

In the presented model all demands sharing the same end nodes have to follow the same path.

1.1.3 Transparent without Survivability

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

In the transparent transport mode (single-hop approach), the signals travel through the network in the optical domain between lightpaths. One advantage of this transport mode is that these networks require optical switching. This enables the realization of ongoing optical connections throughout several links without OEO (optical-electrical-optical) conversions. However, there are performed some conversions in some intermediate nodes.

Transparent optical connections creates lightpaths which require the assignment of a wavelength that will be used to be exchanged by wavelength converters in order to optimize the network and minimize the total CAPEX.

After the creation of the matrices and the network topology, it is necessary to apply the routing and grooming algorithms created. In the end, a report algorithm will be applied to obtain the best CAPEX result for the network in question.

We also must take into account the following particularity of this mode of transport:

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

The minimization of the network CAPEX is made through the equation 1.1 where in this case for the cost of nodes we have in consideration the electric cost 1.4 and the optical cost 1.5.

In this case the value of $P_{exc,c,n}$ is obtained by equation 1.10 for short-reach and by the equation 1.11 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 1.12.

The equation 1.10 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n , $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^N D_{nd,c} \quad (1.10)$$

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

In this case there is the following particularity:

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

As previously mentioned, the equation 1.11 refers to the number of long-reach ports of the electrical switch with bit-rate -1 in node n , $P_{exc,-1,n}$, i.e. the number of add ports of node n which can be calculated as

$$P_{exc,-1,n} = \sum_{j=1}^N f_{nj}^{od} \quad (1.11)$$

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

The equation 1.12 refers to the number of line ports and the number of adding ports of node n which can be calculated as

$$P_{oxc,n} = \sum_{j=1}^N 2f_{nj}^{od} + \sum_{j=1}^N \lambda_{nj} \quad (1.12)$$

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

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

In the next pages it will be described all the steps performed to obtain the final results in the transparent transport mode without survivability. In the figure below 1.76 it is shown a fluxogram with the description of this transport mode approach.

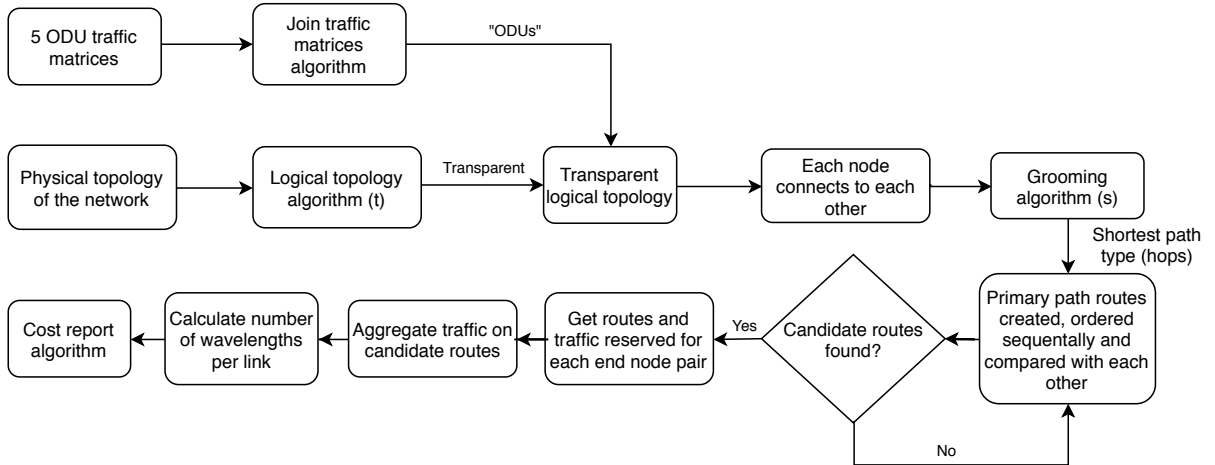


Figura 1.76: Fluxogram with the steps performed in the transparent without survivability transport mode approach.

Creation and join the traffic matrices

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

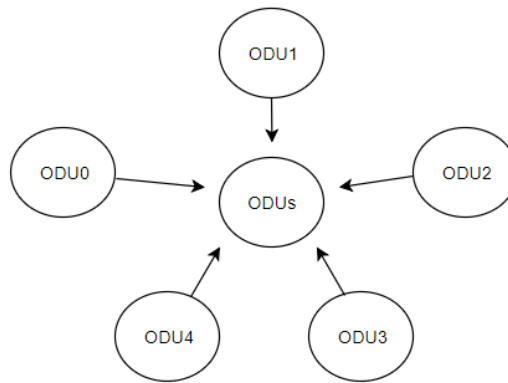


Figura 1.77: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.

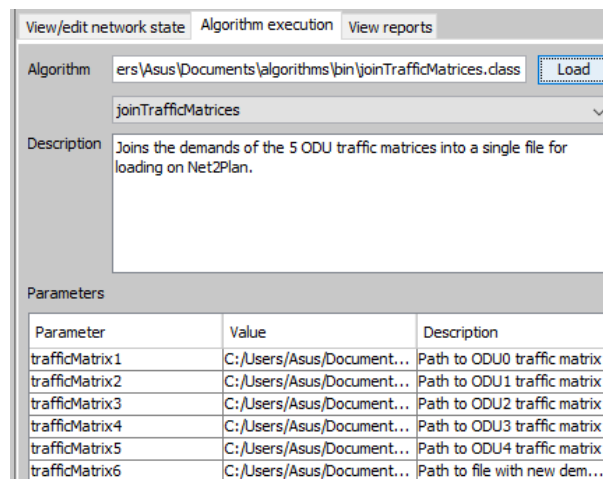


Figura 1.78: Load of the join traffic matrices algorithm for the transparent transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

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



Figura 1.79: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. In the transparent transport mode each node connects to each other creating direct links between all nodes in the network. Going through all nodes, if a node has a different index from other one, then creates a shortest and direct link between them. These additions of links between end nodes are made in the new upper layer of the network. The respective demands are saved in the new upper layer and those demands from the lower layer are then removed. The lower layer is the physical layer of the network and it is now created a new upper layer which is the logical layer of the network and represents the logical topology of the transparent transport mode. The allowed physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 1.1.3 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the transparent transport mode without survivability.

```

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

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

```

Figura 1.80: Java code of the logical topology approach for the transparent transport mode. The logical layer is created by adding direct links between all end nodes. The new layer is now the transparent logical topology of the network.

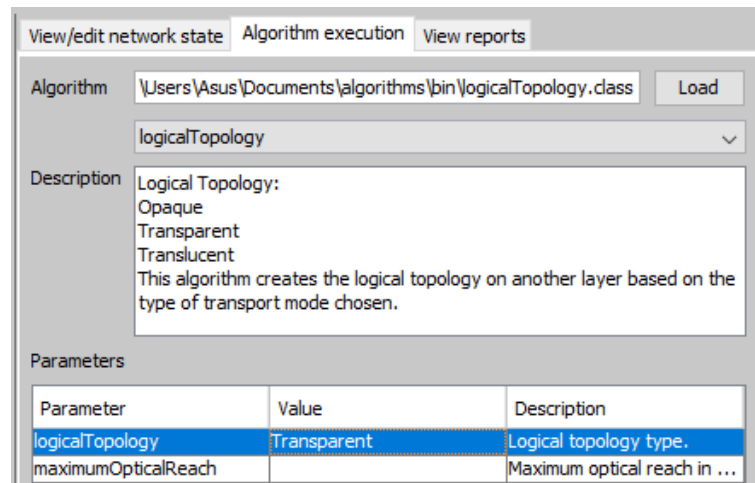


Figura 1.81: Load of the logical topology algorithm for the transparent transport mode.

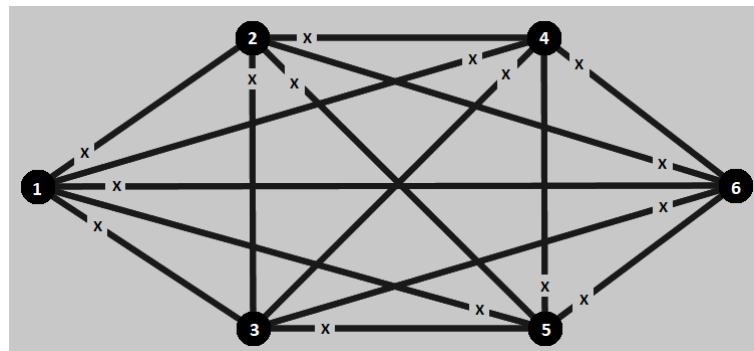


Figura 1.82: Allowed optical topology. It is assumed that each connections between demands supports up to 100 lightpaths.

Creation of routes and aggregation of traffic

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

```
case "Logical Topology Transparent":

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

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

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

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

Figura 1.83: Creation of routes and aggregation of traffic for the transparent without survivability transport mode. The candidate routes are searched by the shortest path type method and the offered traffic demands are set into these routes.

```

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

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

        if(tNodeId==tNodeId1)continue;

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

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

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

```

Figura 1.84: Creation of routes and aggregation of traffic for the transparent without survivability transport mode. The traffic demands are set into the candidate primary path routes found earlier.

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

Tabela 1.28: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

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

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

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

Figura 1.85: Calculation of the number of wavelengths per link for the transparent transport mode. The link capacity is reserved based on the previous traffic aggregation.

View/edit network state Algorithm execution View reports

Algorithm

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

Parameters

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

Figura 1.86: Load of the grooming algorithm for the transparent without survivability transport mode. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 1.1.3 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details.



Figura 1.87: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

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

Low Traffic Scenario:

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

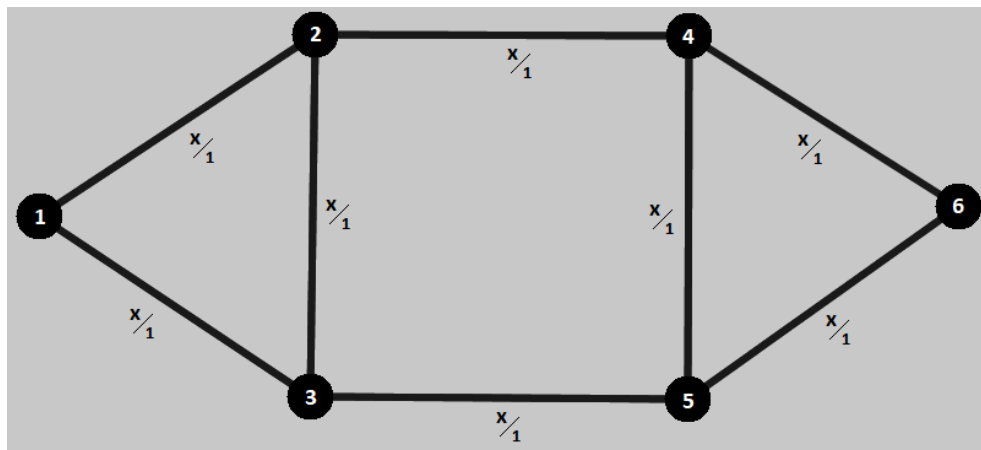


Figura 1.88: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 1.89: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.

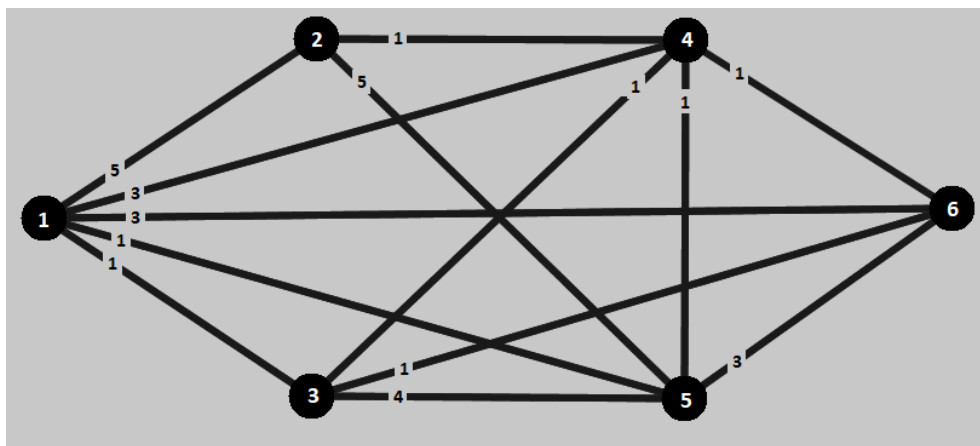


Figura 1.90: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.91: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.92: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 1.93: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.94: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.95: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.29.

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

Tabela 1.29: Table with detailed description of CAPEX of Vasco's 2016 results.

All the values calculated in the previous table were obtained through the equations 1.2 and 1.3 referred to in section 1.1, but for a more detailed analysis we created table 1.30 where we can see how all the parameters are calculated individually.

Medium Traffic Scenario:

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

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

Tabela 1.30: Table with description of calculation

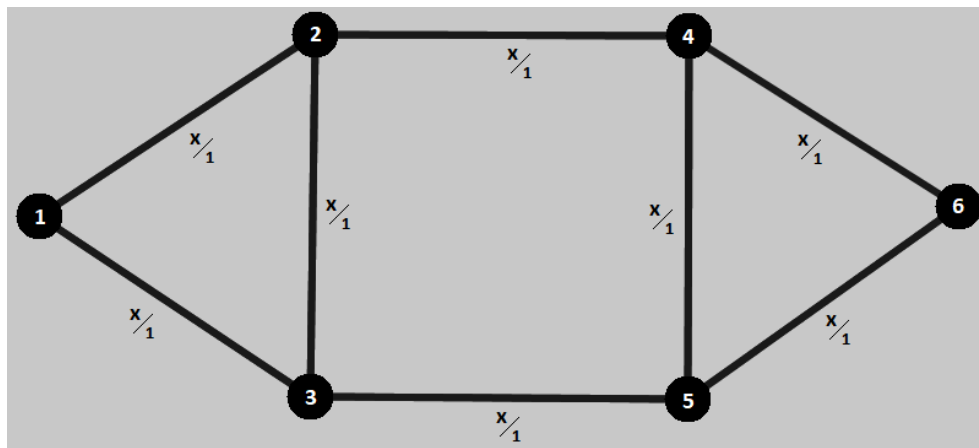


Figura 1.96: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional



Figura 1.97: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 1.98: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.99: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.100: ODU2 logical topology defined by the ODU2 traffic matrix.

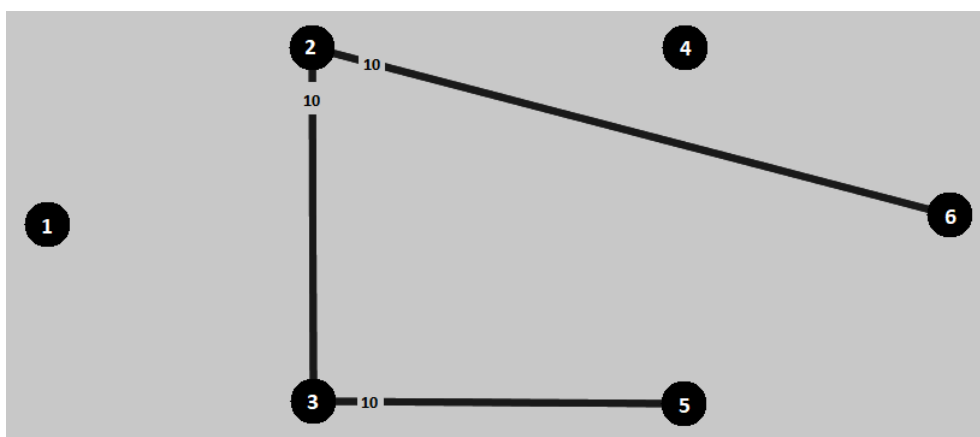


Figura 1.101: ODU3 logical topology defined by the ODU3 traffic matrix.

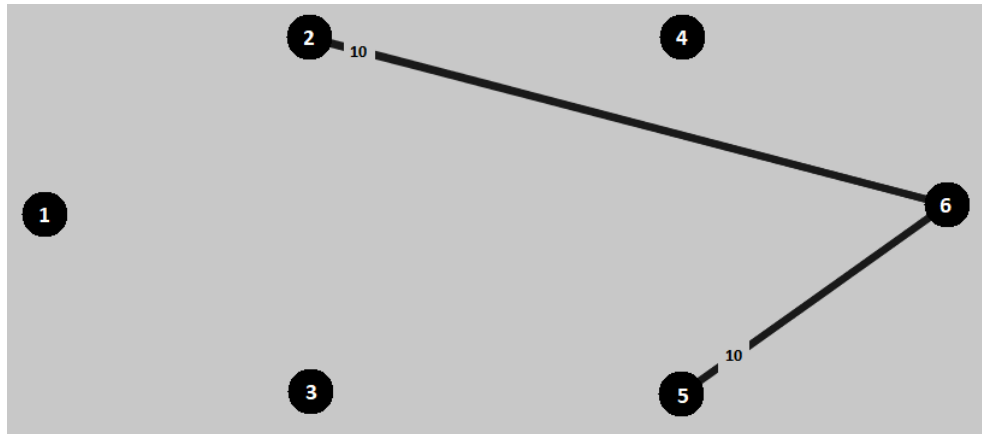


Figura 1.102: ODU4 logical topology defined by the ODU4 traffic matrix.

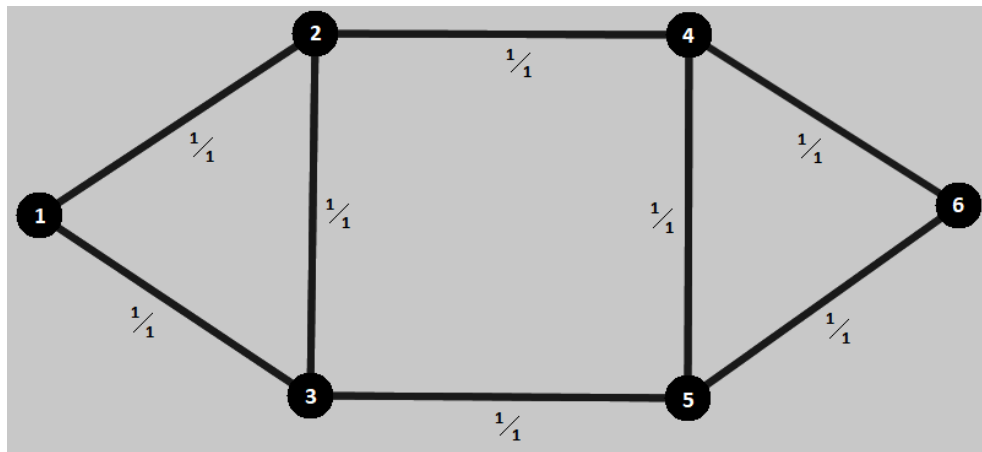


Figura 1.103: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.31. In table 1.30 mentioned in previous scenario we can see how all the values were calculated.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|--------------|----------|----------------|--------------|--------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 84 520 000 € |
| | 100 Gbits/s Transceivers | | 168 | 5 000 €/Gbit/s | 84 000 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 15 180 900 € |
| | | ODU0 Ports | 600 | 10 €/port | 6 000 € | |
| | | ODU1 Ports | 500 | 15 €/port | 7 500 € | |
| | | ODU2 Ports | 160 | 30 €/port | 4 800 € | |
| | | ODU3 Ports | 60 | 60 €/port | 3 600 € | |
| | | ODU4 Ports | 40 | 100 €/port | 4 000 € | |
| | | Transponders | 142 | 100 000 €/port | 14 200 000 € | |
| | Optical | OXCs | 6 | 20 000 € | 120 000 € | |
| | | Line Ports | 168 | 2 500 €/port | 420 000 € | |
| | | Add Ports | 142 | 2 500 €/port | 355 000 € | |
| Total Network Cost | | | | | | 99 700 900 € |

Tabela 1.31: Table with detailed description of CAPEX of Vasco's 2016 results.

High Traffic Scenario:

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



Figura 1.104: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 1.105: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 1.106: ODU0 logical topology defined by the ODU0 traffic matrix.

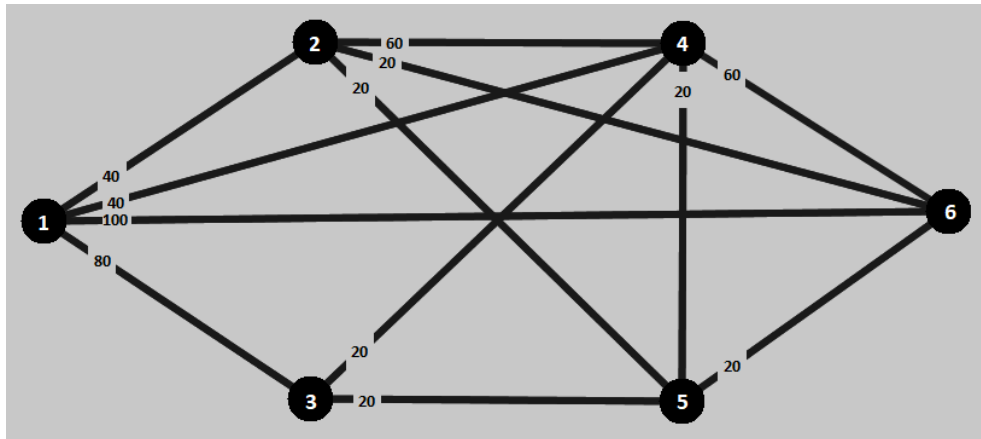


Figura 1.107: ODU1 logical topology defined by the ODU1 traffic matrix.

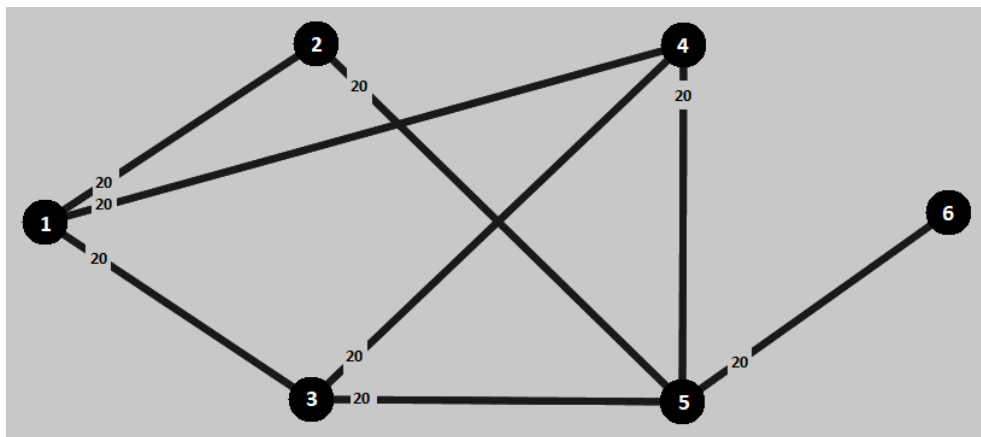


Figura 1.108: ODU2 logical topology defined by the ODU2 traffic matrix.

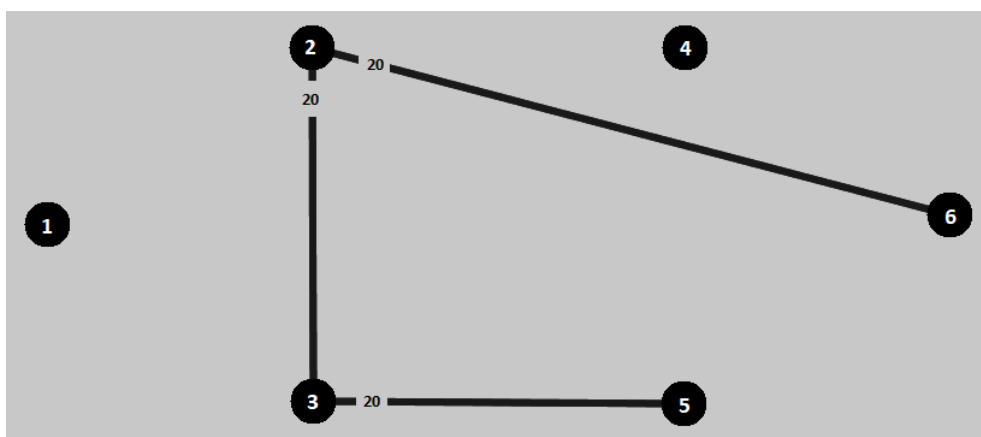


Figura 1.109: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.110: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.111: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.32. In table 1.30 mentioned in previous scenario we can see how all the values were calculated.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|--------------|----------|----------------|---------------|---------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 157 520 000 € |
| | 100 Gbits/s Transceivers | | 314 | 5 000 €/Gbit/s | 157 000 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 28 486 800 € |
| | | ODU0 Ports | 1 200 | 10 €/port | 12 000 € | |
| | | ODU1 Ports | 1 000 | 15 €/port | 15 000 € | |
| | | ODU2 Ports | 320 | 30 €/port | 9 600 € | |
| | | ODU3 Ports | 120 | 60 €/port | 7 200 € | |
| | | ODU4 Ports | 80 | 100 €/port | 8 000 € | |
| | | Transponders | 268 | 100 000 €/port | 26 800 000 € | |
| | Optical | OXCs | 6 | 20 000 € | 120 000 € | |
| | | Line Ports | 314 | 2 500 €/port | 785 000 € | |
| | | Add Ports | 268 | 2 500 €/port | 670 000 € | |
| Total Network Cost | | | | | | 186 006 800 € |

Tabela 1.32: Table with detailed description of CAPEX of Vasco's 2016 results.

Conclusions

Once we have obtained the results for all the scenarios we will now draw some conclusions about these results. For a better analysis of the results will be created the table 1.33 with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

| | Low Traffic | Medium Traffic | High Traffic |
|---------------------------|------------------------|------------------------|------------------------|
| Traffic (Gbit/s) | 500 | 5 000 | 10 000 |
| Bidirectional Links used | 8 | 8 | 8 |
| Number of Add ports | 34 | 142 | 268 |
| Number of Line ports | 52 | 168 | 314 |
| Number of Tributary ports | 136 | 1 360 | 2 720 |
| Number of Transceivers | 52 | 168 | 314 |
| Link Cost | 26 520 000 € | 84 520 000 € | 157 520 000 € |
| Node Cost | 3 797 590 € | 15 180 900 € | 28 486 800 € |
| CAPEX | 30 317 590 € | 99 700 900 € | 186 006 800 € |
| CAPEX/Gbit/s | 60 635 €/Gbit/s | 19 940 €/Gbit/s | 18 600 €/Gbit/s |

Tabela 1.33: Table with different value of CAPEX for this case.

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

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

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

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

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

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

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

Opens Issues

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

- Allow blocking.

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

- Allow multiple transmission system.

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

Allow Blocking

Student Name : Eduardo Fernandes (09/11/2018 -)

Goal : Allows blocking, i.e., creation of a model that supports a partial solution where some demands are not routed (are blocked).

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

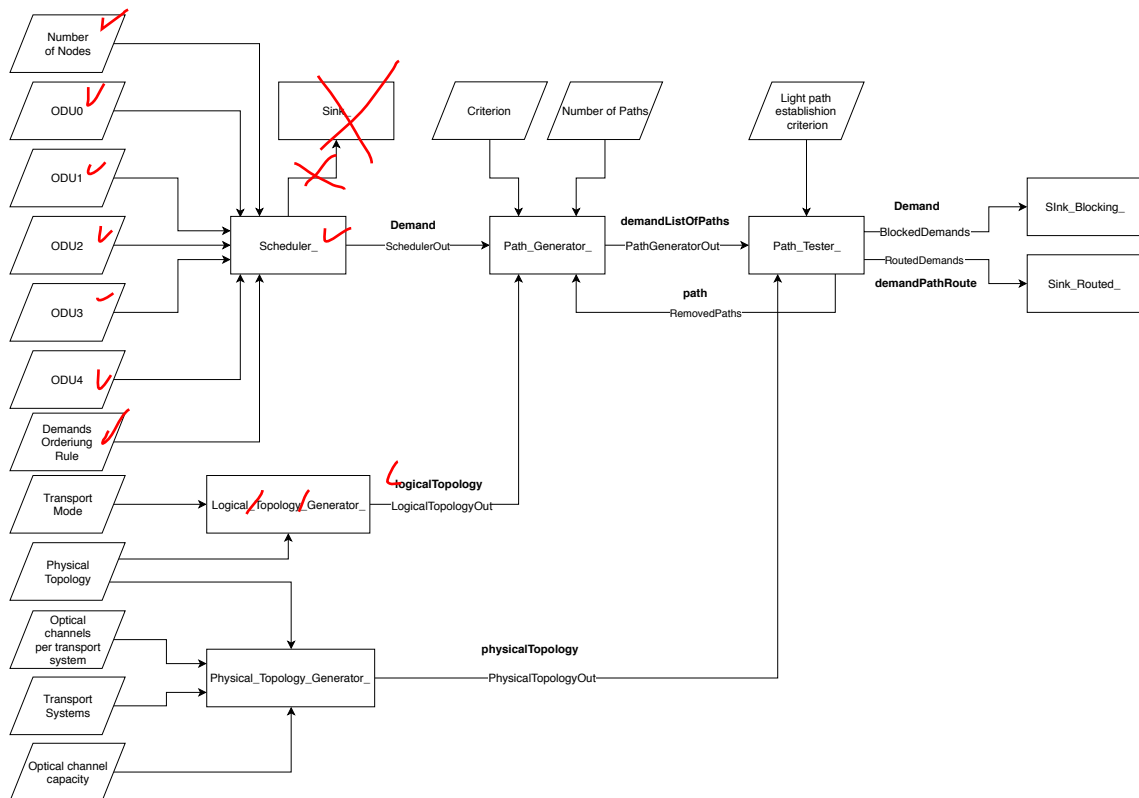


Figura 1.112: High level diagram of the heuristic algorithm performed.

As it is shown in figure 1.112, it is needed a Scheduler block which will be responsible for the creation of an ordered queue containing all the demands entering this network, in an order previously defined (based on the demands ODU type), and ready to be routed. In order to route those demands there will also be the necessity of a Path Generator block which as its own name implies will create a list of logical paths for each demand between its source and destination nodes, through information received by the Logical Topology Generator block. Next in the Path Tester block where the list of paths previously associated to a demand are tested in order to check their availability in terms of physical capacity in each of the necessary links that comprise the light path used. A Logical and Physical

Topology Generators are also needed, the first in order to create the matrix of possible logical connections between nodes and the other to inform us about this network links capacity which will after be continuously updated in the Path Tester block. Finally there are two remaining Sink blocks one to store demands that were routed and their correspondent information and the other to register blocked demands. Both are very usefull to store the information that will later on be present in the final cost report.

| Signal name | Signal type |
|------------------|-------------------|
| SchedulerOut | demand |
| LogicalTopology | logicalTopology |
| PhysicalTopology | physicalTopology |
| PathGeneratorOut | demandListOfPaths |
| RemovedPaths | path |
| BlockedDemands | demand |
| RoutedDemands | demandPathRoute |

Tabela 1.34: System Signals.

Table 1.20 presents the system signals as well as their type.

Signal Types

demand

| Demand Index | Source Node | Destination Node | ODU Type | Restoration Method |
|---------------|-------------|------------------|----------|---|
| 1... ∞ | 1...N | 1...N | 0...4 | 0 - None 1 - Protection 1+1 2 - Restoration |

Tabela 1.35: Constitution of a demand.

N represents the number of nodes present in the network.

logicalTopology

This is the output signal of the Logical topology generator block, it has a matrix NxN where every logical connection existent between nodes in the network is displayed. In this particular case we are studying the transparent trasnport node so our logical topology will be the one presented in table 1.23. In addition here will occur the creation structures corresponding to our network logical links and light paths.

| Nodes | 1 | 2 | 3 | 4 | 5 | 6 |
|-------|----------|----------|----------|----------|----------|----------|
| 1 | 0 | 0/1 | 0/1 | 0/1 | 0/1 | 0/1 |
| 2 | 0/1 | 0 | 0/1 | 0/1 | 0/1 | 0/1 |
| 3 | 0/1 | 0/1 | 0 | 0/1 | 0/1 | 0/1 |
| 4 | 0/1 | 0/1 | 0/1 | 0 | 0/1 | 0/1 |
| 5 | 0/1 | 0/1 | 0/1 | 0/1 | 0 | 0/1 |
| 6 | 0/1 | 0/1 | 0/1 | 0/1 | 0/1 | 0 |

Tabela 1.36: Logical Topology Matrix.

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

Tabela 1.37: Transparent Topology Matrix.

| Index | Link Source Node | Link Destination Node | Number of Light Paths |
|-------|------------------|-----------------------|-----------------------|
| 1 | 1...N | 1...N | -1 |
| ... | ... | ... | ... |
| LO | 1...N | 1...N | -1 |

Tabela 1.38: Logical link variable.

LO represents the number of logical links present in the network.

| Link Index | Light Path Number | Physical Links | Wavelength | Capacity (ODU0s) |
|------------|-------------------|----------------|------------|------------------|
| 1 | 1 | [0/1...0/1] | 1...OC | |
| ... | ... | ... | ... | |
| LO | LP | [0/1...0/1] | 1...OC | |

Tabela 1.39: Light path variable.

LP represents the number of light paths established in the network.

OC represents the number optical channels existent in each physical link.

The Physical Links variable inside of the light paths represents the links existent in our network, in this case they can assume two different values, 0 or 1, depending on whether

they are used or not to route a demand through a certain light path.

physicalTopology

Here the information about every physical connection existent between nodes and their capacity initially existent is sent to the Path tester block where later on will be updated.

| Index | Link Source Node | Link Destination Node | Number of Optical Channels |
|-------|------------------|-----------------------|----------------------------|
| 1 | 1...N | 1...N | OC |
| ... | ... | ... | ... |
| L | 1...N | 1...N | OC |

Tabela 1.40: Link variable.

| Link Index | Optical Channel Number | Capacity (ODU0s) | Wavelength | Source Node | Destination Node |
|------------|------------------------|------------------|------------|-------------|------------------|
| 1...L | 1...OC | | 1...OC | 1...N | 1...N |

Tabela 1.41: Optical channel variable.

path

| Path Index | Source Node | Destination Node | Logical links | Hops |
|------------|-------------|------------------|---------------|------|
| | 1...N | 1...N | [0/1...0/1] | |

Tabela 1.42: Path type signal.

The Logical links variable represents the logical links existent in our network, in this case they can assume two different values, 0 or 1, depending on whether they are used or not to route a demand through a certain path.

demandListOfPaths

Inside of the Path Generator block a list of logical paths associated to a pair of source and destination nodes will be created. This paths will depend directly on the logical topology of the network and on the availability of the links.

| Demand index | Path index |
|--------------|------------|
| 1...∞ | x |
| | x+1 |
| | x+2 |

Tabela 1.43: demandListOfPaths signal.

demandPathRoute

| Demand Index | Path Index | Physical Link Index | 1...L |
|--------------|------------|---------------------|--------|
| 1...N | 1...N | Optical Channel | 1...OC |

Tabela 1.44: demandPathRoute signal.

Knowing the list of possible shortest logical paths associated to a demand (Dijkstra algorithm), the capacity of the physical links that constitute those logical connections have to be tested. That will occur in the next block of the diagram, the Path Tester block.

If there is already an entry in the light path table and if the remaining capacity of that light path, already established, is sufficient to route the demand then our demand is added to that same light path and a demandPathRoute signal is created with information regarding to the demand/path index, route and wavelength used by that same demand. If on the other side the logical path being tested has not enough capacity to process a certain demand or if there is no light path established between that pair of source and destination nodes than an attempt to create another light path entry will be made. If it occurs successfully than a new light path is established in our network and the demand is routed through that same but if there is no possibility of creating a new light path between those nodes than our logical path will have to be ignored and cutted of, and so a next shortest logical path must be tested in the same manner. In order to in further iterations that full path not be considered a path type signal (RemovedPaths) should be created to inform the Path Generator block that those paths must not be considered, this will make the algorithm more efficient. If finally we can not route our demand though none of the logical paths selected then a blocking state occurs, the demand is not routed and a demandsBlocked signal is created. Then finally a cost report is created to obtain a detailed estimation of the network Capex based on user defined equipment costs present on table 1.28.

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

Tabela 1.45: Equipment costs.

| Parameter | Default value | Description |
|------------------------------------|---------------|--|
| Number of Paths | 3 | Number of paths created between a pair of nodes. |
| Number of Nodes | 0 | Number of nodes present in this network. |
| Routing Ordering Rule | 0 | 0 - Descending order 1 - Ascending order |
| ODU0 | Null | ODU0 demands. |
| ODU1 | Null | ODU1 demands. |
| ODU2 | Null | ODU2 demands. |
| ODU3 | Null | ODU3 demands. |
| ODU4 | Null | ODU4 demands. |
| Criterion | Hops | Shortest path type. |
| Transport Mode | Null | Opaque, transparent or translucent modes. |
| Physical Topology | Null | Physical connections of the network. |
| Transport Systems | 1 | Number of transport systems connecting each pair of nodes. |
| Optical Channels | 100 | Optical channels per transport system. |
| Optical Channel Capacity | 100 Gbps | Physical capacity of each channel. |
| Light Path Establishment Criterion | to define | to define |

Tabela 1.46: System input parameters.

| Block | Input Parameters | Input Signals |
|-----------------------------|---|---------------------------------------|
| Scheduler | ODU0, ODU1, ODU2, ODU3, ODU4, Routing Ordering Rule, Number of Nodes | None |
| Logical Topology Generator | Transport Mode, Physical Topology | None |
| Physical Topology Generator | Physical Topology, Optical Channels, Transport Systems, Optical Channel Capacity | None |
| Path Generator | Number of Paths, Criterion | LogicalTopology, RemovedPaths |
| Path Tester | Light Path Establishment Criterion | PathGeneratorOut, PhysicalTopology |
| Sink (Blocking) | None | BlockedDemands |
| Sink (Routed) | None | RoutedDemands |

Tabela 1.47: Blocks input parameters and signals.

| Block | State Variables | Output Signals |
|-----------------------------|---|----------------------------------|
| Scheduler | ODU0, ODU1, ODU2, ODU3, ODU4, Demand Index, Number of Demands | SchedulerOut |
| Logical Topology Generator | Logical Topology Matrix | LogicalTopology |
| Physical Topology Generator | Physical Topology Matrix | PhysicalTopology |
| Path Generator | Logical Topology Matrix, Logical Link, Light Path | PathGeneratorOut |
| Path Tester | Physical Topology Matrix, Link, Optical Channel | RoutedDemands, BlockedDemands |
| Sink (Blocking) | None | None |
| Sink (Routed) | None | None |

Tabela 1.48: Blocks state variables and output signals.

Example:

Having just 4 optical channels per transmission system, each with a capacity of 100 Gbps, and the following traffic model.

These traffic matrices are represented by ODU0, ODU1, ODU2, ODU3 and ODU4 where each one has a certain bit rate. The ODU0 corresponds to 1.25 Gbits/s, the ODU1 corresponds to 2.5 Gbits/s, the ODU2 corresponds to 10 Gbits/s, the ODU3 corresponds to 40 Gbits/s and finally the ODU4 corresponds to 100 Gbits/s. As we can see below, these arrays are bi-directional because they are symmetric arrays and as such, the traffic sent in a certain direction must be the same traffic sent in that opposite direction.

$$\begin{aligned}
 ODU0 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} & ODU1 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \\
 ODU2 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} & ODU3 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \\
 ODU4 &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 9 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 9 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}
 \end{aligned}$$

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

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

$$T_1^3 = 0 \times 40 = 0 \text{ Gbits/s} \quad T_1^4 = 18 \times 100 = 1800 \text{ Gbits/s}$$

$$T_1 = 0 + 0 + 0 + 0 + 1800 = 1800 \text{ Gbits/s} \quad T = 1800/2 = \mathbf{900 \text{ Gbits/s}}$$

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

the network and finally the variable T represents the total of bidirectional traffic.

The demands are first ordered in the Scheduler block considering the entry variable, Routing ordering rule (type of ODU), in a single queue. These demands will constitute the SchedulerOut signal.

| Demand Index | Source Node | Destination Node | ODU Type | Restoration Method |
|--------------|-------------|------------------|----------|--------------------|
| 1 | 2 | 4 | 4 | 0 |
| 2 | 2 | 4 | 4 | 0 |
| 3 | 2 | 4 | 4 | 0 |
| 4 | 2 | 4 | 4 | 0 |
| 5 | 2 | 4 | 4 | 0 |
| 6 | 2 | 4 | 4 | 0 |
| 7 | 2 | 4 | 4 | 0 |
| 8 | 2 | 4 | 4 | 0 |
| 9 | 2 | 4 | 4 | 0 |

Tabela 1.49: Demands queue generated in the Scheduler block.

The demands presented in the previous table will be processed from the lowest to highest index.

Demand 1

First of all a set of shortest logical paths will be selected based on the logical topology of our network. The paths selected and how many will depend on entry variables, Criterion and Number of Paths, respectively. Once our shortest logical path is chosen, we must test the same starting by analysing if there is already an entry on our list of light paths established in the network for that logical link or set of links. If there is none or if the existents do not have enough capacity left to transport our demand an effort must be made to create a new entry, that is, create a new lightpath in that logical link or set of links.

In this particular case as the list of lightpaths is initially void we must create a new lightpath using the direct logical link between nodes 2 and 4, if possible.

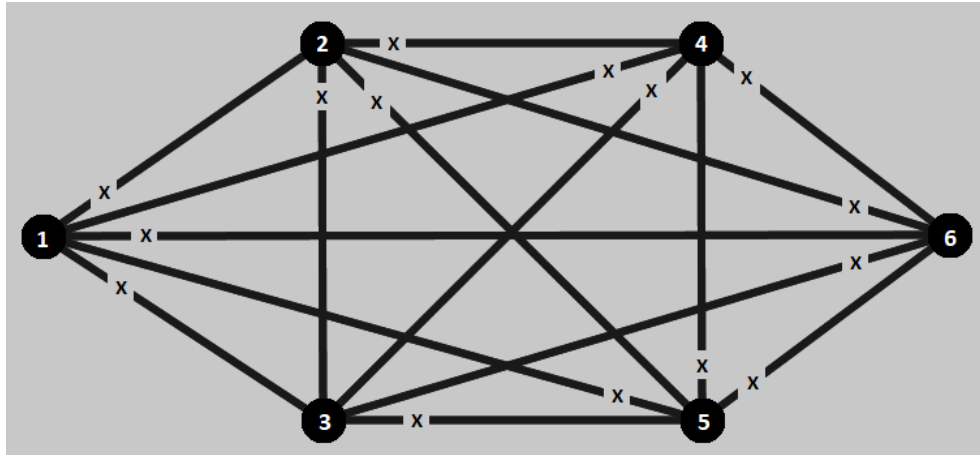


Figura 1.113: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 4 lightpaths (100 Gbps each).

| Demand index | Path index |
|--------------|------------|
| 1 | 1 |
| | 2 |
| | 3 |

Tabela 1.50: demandListOfPaths signal.

Lets now analyze path number 1, supposedly the shortest one.

| Path Index | Source Node | Destination Node | Logical links | Hops |
|------------|-------------|------------------|---------------|------|
| 1 | 2 | 4 | [010000...] | 1 |

Tabela 1.51: Path type signal.

Since it's constituted only by logical link 2 we must test its capacity in order to analyse the possibility of constituting a new lighth path in logical link number 2.

Initial values

| Index | Link Source Node | Link Destination Node | Number of Light Paths |
|-------|------------------|-----------------------|-----------------------|
| 2 | 2 | 4 | 0 |

Tabela 1.52: Logical link 2.

Since its the first light path to be established in this network the index will be equal to 1. In order to see if there is enough capacity to create this light path we will need to test the

physical links that constitutes the very same, in this particular example link number 2.

| Link Index | Light Path Number | Physical Links | Wavelength | Capacity (ODU0s) |
|------------|-------------------|----------------|------------|------------------|
| 2 | 1 | [01000000] | 1 | 80 |

Tabela 1.53: Light path 1.

| Index | Link Source Node | Link Destination Node | Number of Optical Channels |
|-------|------------------|-----------------------|----------------------------|
| 2 | 2 | 4 | 4 |

Tabela 1.54: Physical link 2.

| Link Index | Optical Channel Number | Capacity (ODU0s) | Wavelength | Source Node | Destination Node |
|------------|------------------------|------------------|------------|-------------|------------------|
| 2 | 1 | 80 | 1 | 2 | 4 |

Tabela 1.55: Optical channel 1 of physical link 2.

Final values

So the final values of these variables after processing demand 1 will be.

| Index | Link Source Node | Link Destination Node | Number of Light Paths |
|-------|------------------|-----------------------|-----------------------|
| 2 | 2 | 4 | 1 |

Tabela 1.56: Logical link 2.

| Link Index | Light Path Number | Physical Links | Wavelength | Capacity (ODU0s) |
|------------|-------------------|----------------|------------|------------------|
| 2 | 1 | [01000000] | 1 | 0 |

Tabela 1.57: Light path 1.

All the available capacity of light path 1 was used so it can not be used to route other demands. Other light paths will have to be created to route demands through this link.

| Index | Link Source Node | Link Destination Node | Number of Optical Channels |
|-------|------------------|-----------------------|----------------------------|
| 2 | 2 | 4 | 3 |

Tabela 1.58: Physical link 2.

| Link Index | Optical Channel Number | Capacity (ODU0s) | Wavelength | Source Node | Destination Node |
|------------|------------------------|------------------|------------|-------------|------------------|
| 2 | 1 | 0 | 1 | 2 | 4 |

Tabela 1.59: Optical channel 1 of physical link 2.

1.1.4 Transparent with 1+1 Protection

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

Contrary to the transparent without survivability transport mode, the transparent with 1+1 protection technique has a backup path, so if there is a network failure it is more likely to not suffer large data losses. The backup paths are always different from the primary ones and they prevent that the information going through optical channels could be lost in these occasions. However, the CAPEX will be significantly higher (more than the double), because that includes a secondary path that will increase several network elements.

After the creation of the matrices and the network topology, it is necessary to apply the routing and grooming algorithms created. In the end, a report algorithm will be applied to obtain the best CAPEX result for the network in question.

We also must take into account the following particularity of this mode of transport:

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

The minimization of the network CAPEX is made through the equation 1.1 where in this case for the cost of nodes we have in consideration the electric cost 1.4 and the optical cost 1.5.

In this case the value of $P_{exc,c,n}$ is obtained by equation 1.13 for short-reach and by the equation 1.14 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 1.15.

The equation 1.13 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

$$P_{exc,c,n} = \sum_{d=1}^N D_{nd,c} \quad (1.13)$$

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

$$P_{exc,-1,n} = \sum_{j=1}^N f_{nj}^{od} \quad (1.14)$$

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

The equation 1.15 refers to the number of line ports and the number of adding ports of node n which can be calculated as

$$P_{oxc,n} = \sum_{j=1}^N 2f_{nj}^{od} + \sum_{j=1}^N \lambda_{nj} \quad (1.15)$$

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.

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

In the next pages it will be described all the steps performed to obtain the final results in the transparent transport mode with 1+1 protection. In the figure below 1.114 it is shown a fluxogram with the description of this transport mode approach.

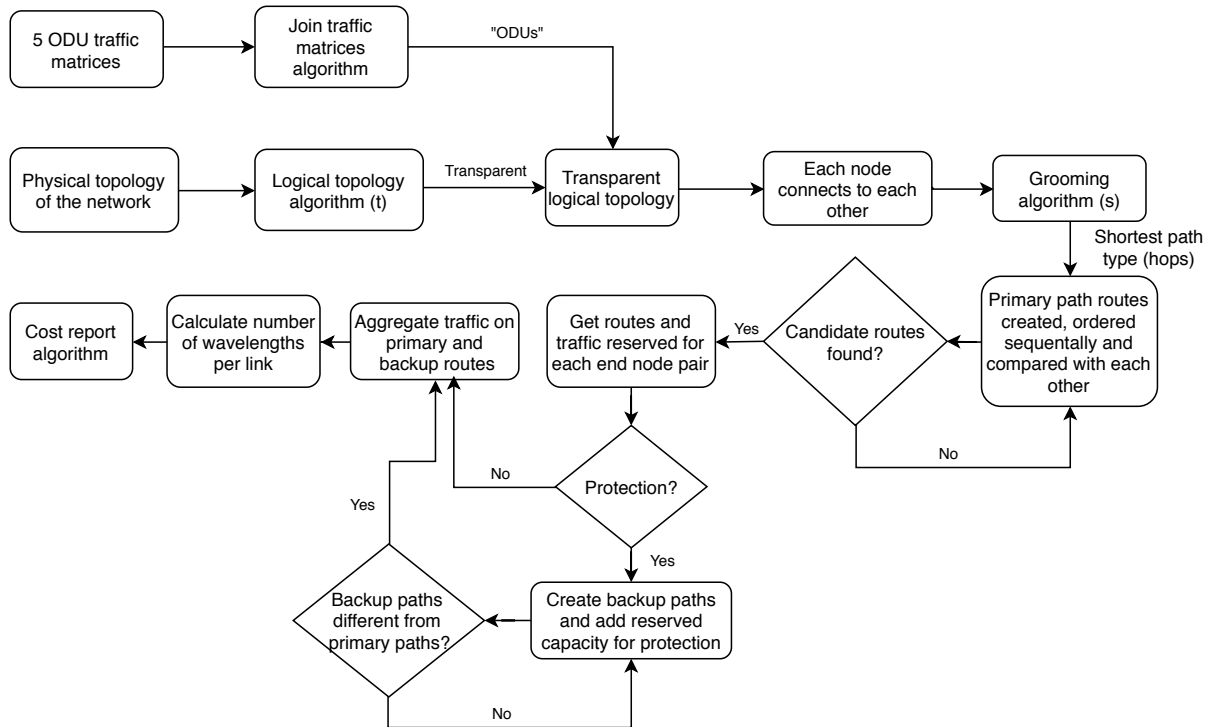


Figura 1.114: Fluxogram with the steps performed in the transparent with 1+1 protection transport mode approach.

Creation and join the traffic matrices

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

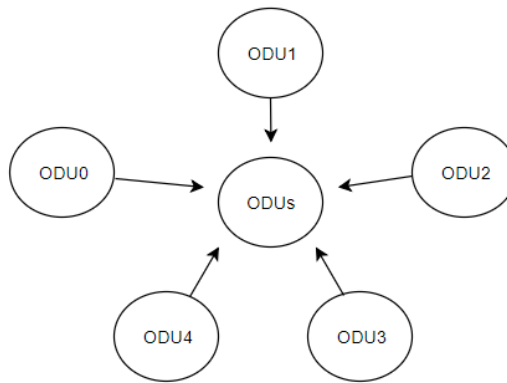


Figura 1.115: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.

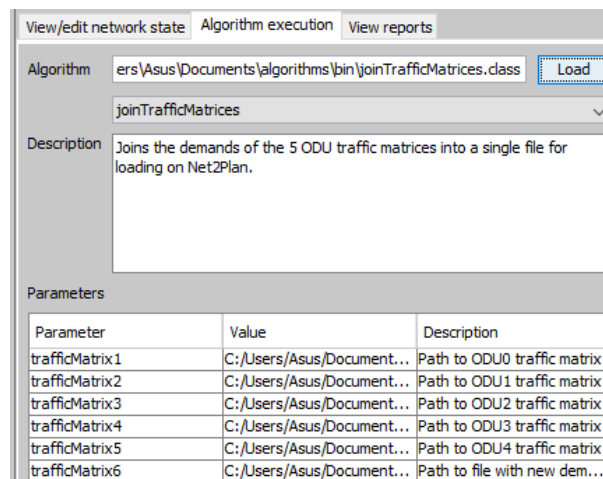


Figura 1.116: Load of the join traffic matrices algorithm for the transparent transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

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



Figura 1.117: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. In the transparent transport mode each node connects to each other creating direct links between all nodes in the network. Going through all nodes, if a node has a different index from other one, then creates a shortest and direct link between them. These additions of links between end nodes are made in the new upper layer of the network. The respective demands are saved in the new upper layer and those demands from the lower layer are then removed. The lower layer is the physical layer of the network and it is now created a new upper layer which is the logical layer of the network and represents the logical topology of the transparent transport mode. The allowed physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 1.1.4 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the transparent transport mode with 1+1 protection.

```

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

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

```

Figura 1.118: Java code of the logical topology approach for the transparent transport mode. The logical layer is created by adding direct links between all end nodes. The new layer is now the transparent logical topology of the network.

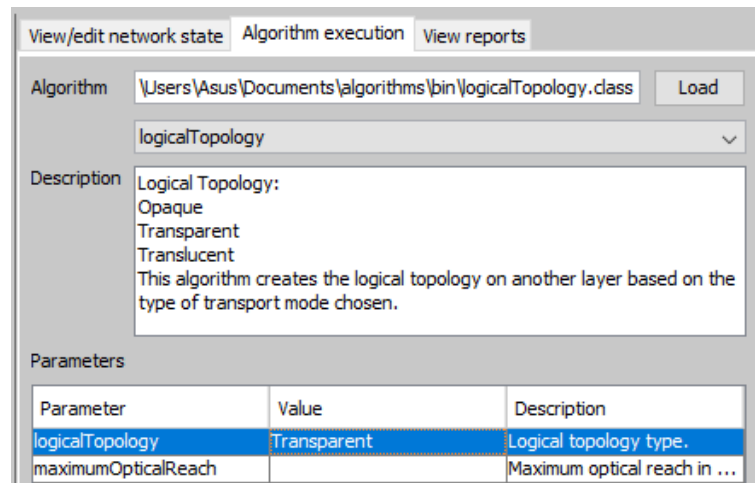


Figura 1.119: Load of the logical topology algorithm for the transparent transport mode.

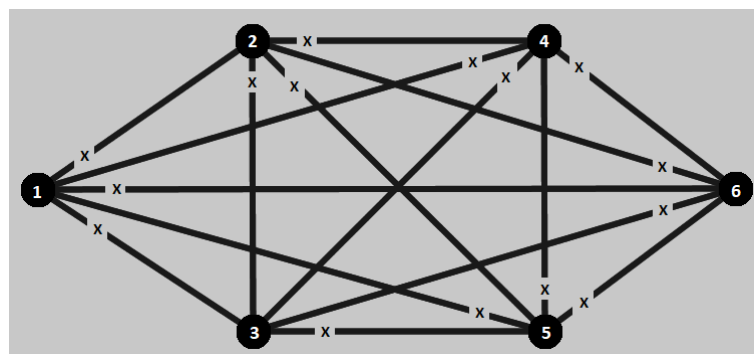


Figura 1.120: Allowed optical topology. It is assumed that each connections between demands supports up to 100 lightpaths.

Creation of routes and aggregation of traffic

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

```
case "Logical Topology Transparent":

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

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

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

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

Figura 1.121: Creation of routes and aggregation of traffic for the transparent with 1+1 protection transport mode. The candidate routes are searched by the shortest path type and the offered traffic demands are set into these routes.

```

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

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

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

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

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

```

Figura 1.122: Creation of routes and aggregation of traffic for the transparent with 1+1 protection transport mode. The protection segments are added to all the primary paths that were chosen by the shortest path type method.

```

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

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

        if(tNodeId==tNodeId1)continue;

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

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

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

        path=compare.getSeqLinksRealPath();
    }
}

```

Figura 1.123: Creation of routes and aggregation of traffic for the transparent with 1+1 protection transport mode. The traffic demands are set in the candidate primary path routes found earlier and also compared with the backup path routes. The traffic demands are also set into these protection path routes.

```

//Protection Segments
totaltraffic=0;

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

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

```

Figura 1.124: Creation of routes and aggregation of traffic for the transparent with 1+1 protection transport mode. The traffic demands are set in the candidate primary path routes found earlier and also compared with the backup path routes. The traffic demands are also set in these protection path routes.

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

Tabela 1.60: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

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

```

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

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

```

Figura 1.125: Calculation of the number of wavelengths per link for the transparent transport mode. The link capacity is reserved based on the previous traffic aggregation.

View/edit network state Algorithm execution View reports

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

grooming

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

Parameters

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

Figura 1.126: Load of the grooming algorithm for the transparent with 1+1 protection transport mode. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 1.1.4 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details.



Figura 1.127: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

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

Low Traffic Scenario:

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



Figura 1.128: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 1.129: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 1.130: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.131: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.132: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 1.133: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.134: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.135: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.61. In table 1.30 mentioned in previous model we can see how all the values were calculated.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|--------------|----------|----------------|--------------|--------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 68 520 000 € |
| | 100 Gbits/s Transceivers | | 136 | 5 000 €/Gbit/s | 68 000 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 4 007 590 € |
| | | ODU0 Ports | 60 | 10 €/port | 600 € | |
| | | ODU1 Ports | 50 | 15 €/port | 750 € | |
| | | ODU2 Ports | 16 | 30 €/port | 480 € | |
| | | ODU3 Ports | 6 | 60 €/port | 360 € | |
| | | ODU4 Ports | 4 | 100 €/port | 400 € | |
| | | Transponders | 34 | 100 000 €/port | 3 400 000 € | |
| | Optical | OXCs | 6 | 20 000 € | 120 000 € | |
| | | Line Ports | 136 | 2 500 €/port | 340 000 € | |
| | | Add Ports | 34 | 2 500 €/port | 85 000 € | |
| Total Network Cost | | | | | | 72 527 590 € |

Tabela 1.61: Table with detailed description of CAPEX of Vasco's 2016 results.

Medium Traffic Scenario:

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



Figura 1.136: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 1.137: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 1.138: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.139: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.140: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 1.141: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.142: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.143: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.62. In table 1.30 mentioned in previous model we can see how all the values were calculated.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|--------------|----------|----------------|---------------|---------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 226 520 000 € |
| | 100 Gbits/s Transceivers | | 452 | 5 000 €/Gbit/s | 226 000 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 15 890 900 € |
| | | ODU0 Ports | 600 | 10 €/port | 6 000 € | |
| | | ODU1 Ports | 500 | 15 €/port | 7 500 € | |
| | | ODU2 Ports | 160 | 30 €/port | 4 800 € | |
| | | ODU3 Ports | 60 | 60 €/port | 3 600 € | |
| | | ODU4 Ports | 40 | 100 €/port | 4 000 € | |
| | | Transponders | 142 | 100 000 €/port | 14 200 000 € | |
| | Optical | OXCs | 6 | 20 000 € | 120 000 € | |
| | | Line Ports | 452 | 2 500 €/port | 1 130 000 € | |
| | | Add Ports | 142 | 2 500 €/port | 355 000 € | |
| Total Network Cost | | | | | | 242 410 900 € |

Tabela 1.62: Table with detailed description of CAPEX of Vasco's 2016 results.

High Traffic Scenario:

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

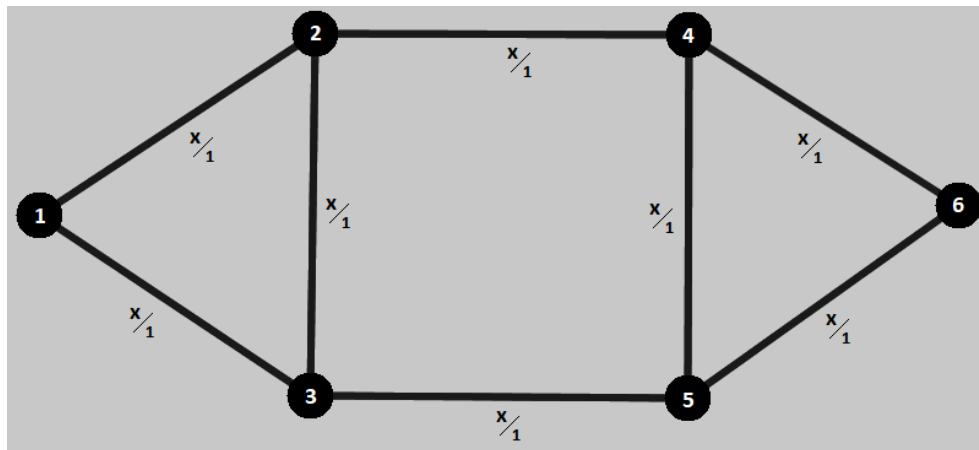


Figura 1.144: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 1.145: Allowed optical topology. The allowed optical topology is defined by the transport mode (transparent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 1.146: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.147: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.148: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 1.149: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.150: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.151: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Vasco's heuristics can be consulted in the following table 1.63. In table 1.30 mentioned in previous model we can see how all the values were calculated.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|--------------|----------|----------------|---------------|---------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 424 520 000 € |
| | 100 Gbits/s Transceivers | | 848 | 5 000 €/Gbit/s | 424 000 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 29 821 800 € |
| | | ODU0 Ports | 1 200 | 10 €/port | 12 000 € | |
| | | ODU1 Ports | 1 000 | 15 €/port | 15 000 € | |
| | | ODU2 Ports | 320 | 30 €/port | 9 600 € | |
| | | ODU3 Ports | 120 | 60 €/port | 7 200 € | |
| | | ODU4 Ports | 80 | 100 €/port | 8 000 € | |
| | | Transponders | 268 | 100 000 €/port | 26 800 000 € | |
| | Optical | OXCs | 6 | 20 000 € | 120 000 € | |
| | | Line Ports | 848 | 2 500 €/port | 2 120 000 € | |
| | | Add Ports | 268 | 2 500 €/port | 670 000 € | |
| Total Network Cost | | | | | | 454 341 800 € |

Tabela 1.63: Table with detailed description of CAPEX of Vasco's 2016 results.

Conclusions

Once we have obtained the results for all scenarios for the transparent without survivability and transparent with 1+1 protection we will now draw some conclusions about these results. For a better analysis of the results will be created the table ?? with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

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

Tabela 1.64: Table with different value of CAPEX for this case.

Looking at the previous table we can make some comparisons between the transparent with 1+1 protection scenario:

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

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

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

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

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

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

We can also make some comparisons between the transparent without survivability and transparent with 1+1 protection scenarios:

- We can see that in the transparent with 1+1 protection transport mode the CAPEX cost for all the three traffic is more than the double;

This happens because in the transparent with 1+1 protection transport mode there is a need of having a primary and a backup path, in case of a network failure, and the backup path is typically longer;

- Comparing the CAPEX cost per bit we can see that has a similar case in both of the two scenarios. In the low traffic the cost is higher than the medium and high traffic, which in these two cases the value is similar;

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

Opens Issues

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

- Allow blocking.

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

- Allow multiple transmission system.

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

1.1.5 Translucent without Survivability

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

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

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

We also must take into account the following particularity of this mode of transport:

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

The minimization of the network CAPEX is made through the equation 1.1 where in this case for the cost of nodes we have in consideration the electric cost 1.4 and the optical cost 1.5.

In this case the value of $P_{exc,c,n}$ is obtained by equation 1.16 for short-reach and by the equation 1.17 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 1.18.

The equation 1.16 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

$$P_{exc,c,n} = \sum_{d=1}^N D_{nd,c} \quad (1.16)$$

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 1.17 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

$$P_{exc,-1,n} = \sum_{j=1}^N \lambda_{nj} \quad (1.17)$$

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

The equation 1.18 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

$$P_{oxc,n} = \sum_{j=1}^N f_{nj}^{od} + \sum_{j=1}^N \lambda_{nj} \quad (1.18)$$

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

To implement this heuristic approach there are used algorithms made in Java in a programming software called Eclipse and they are tested in an open-source network program called Net2Plan. In the next pages it will be described all the steps performed to obtain the final results in the translucent transport mode without survivability. In the figure below 1.152 it is shown a fluxogram with the description of this transport mode approach.

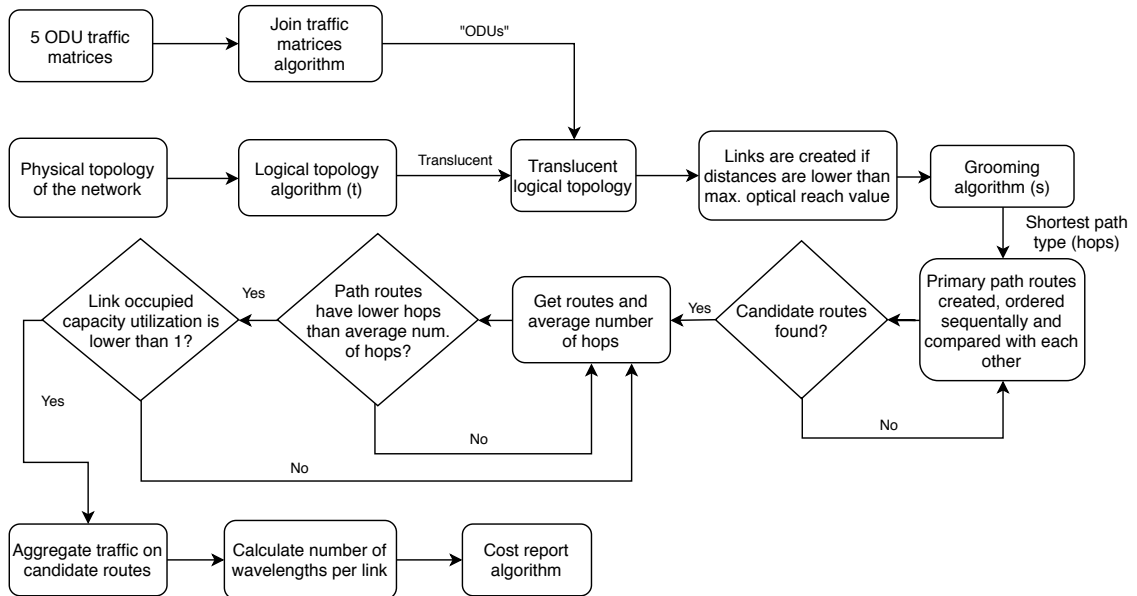


Figura 1.152: Fluxogram with the steps performed in the translucent without survivability transport mode approach.

Creation and join the traffic matrices

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

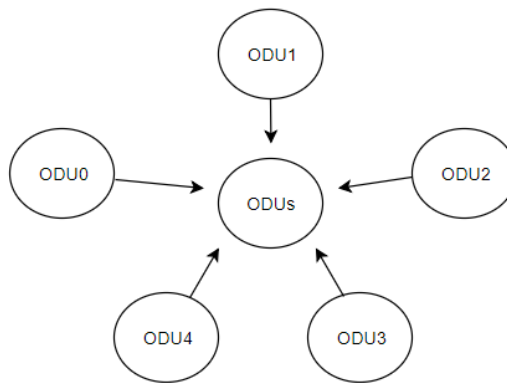


Figura 1.153: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.

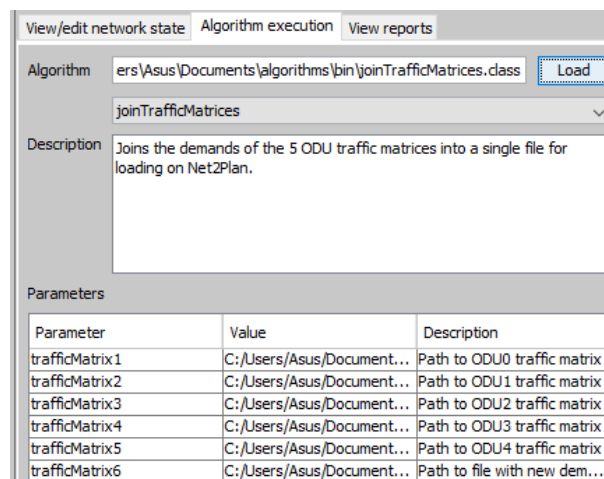


Figura 1.154: Load of the join traffic matrices algorithm for the translucent transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

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



Figura 1.155: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. In the translucent transport mode each node connects to other node if the shortest path distance between them is lower than the maximum optical reach value (in km) that an optical signal can traverse in an optical channel. If the maximum optical reach is higher than the shortest path of a link, then it is not created a logical link of that specific physical link. On the contrary, there are created direct links between all node pairs in the network that follow this rule. These additions of links between end nodes are made in the new upper layer of the network. The respective demands are saved in the new upper layer and those demands from the lower layer are then removed. The lower layer is the physical layer of the network and it is now created a new upper layer which is the logical layer of the network and represents the logical topology of the translucent transport mode. The allowed physical and optical topologies, the logical topologies for all ODUs and the resulting physical topology is shown in the next section below 1.1.5 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the translucent transport mode without survivability.

```

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

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

    sendToFile("opticalReach.txt");

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

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

```

Figura 1.156: Java code of the logical topology approach for the translucent transport mode. The logical layer is created by adding direct links between all end nodes if their shortest path between them is lower than the maximum optical reach value. The new layer is now the translucent logical topology of the network.

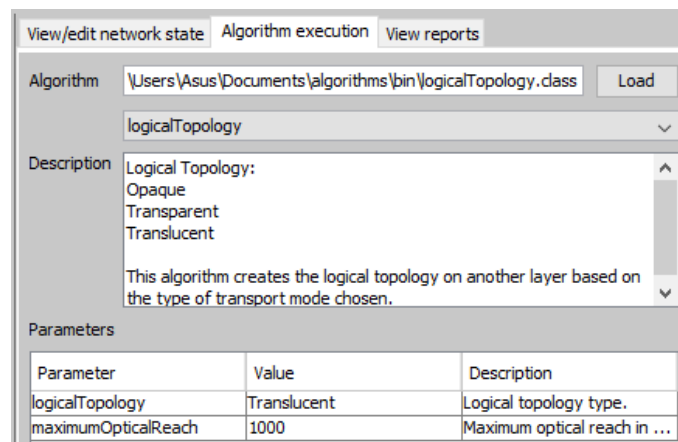


Figura 1.157: Load of the logical topology algorithm for the translucent transport mode on Net2Plan. It is assumed that the maximum optical reach value is 1000 km, so all direct links between node pairs with different index are created in all optical channels.

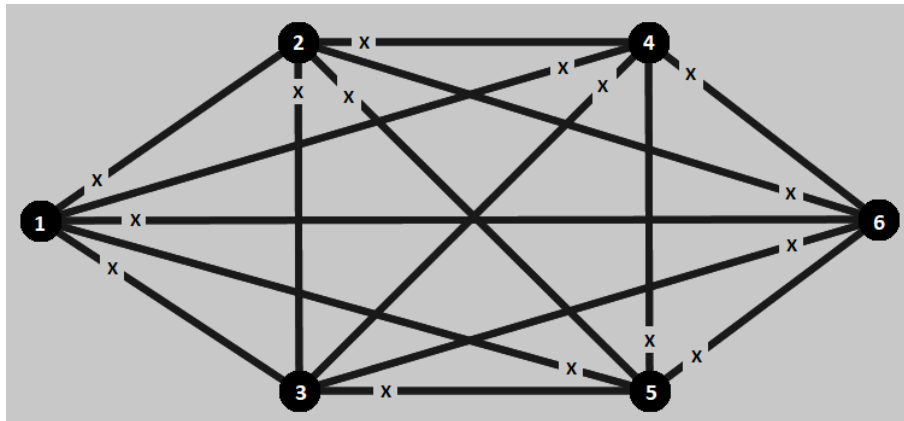


Figura 1.158: Allowed optical topology. It is assumed that each connections between demands supports up to 100 lightpaths. In the translucent transport mode there are several possible logical topologies for a specific network. It depends, for example, on the maximum optical reach value that represents the maximum distance that an optical signal can traverse a link without the need of regenerate.

Creation of routes and aggregation of traffic

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

```

case "Logical Topology Translucent":

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

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

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

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

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

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

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

```

Figura 1.159: Creation of routes and aggregation of traffic for the translucent without survivability transport mode. The candidate routes are searched by the shortest path type method and the average minimum number of physical hops of the routes. The offered traffic demands are set into these routes.

```

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

        if (tNodeId == tNodeId1)
            continue;

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

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

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

        pathTransl = compareTransl.getSeqLinksRealPath();

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

        pathTransl2 = compareTransl2.getSeqLinksRealPath();
    }
}

```

Figura 1.160: Creation of routes and aggregation of traffic for the translucent without survivability transport mode. Minimizing the blocked traffic, the traffic demands are set into the candidate primary path routes found earlier.

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

Tabela 1.65: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

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

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

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

Figura 1.161: Calculation of the number of wavelengths per link for the translucent transport mode. The link capacity is reserved based on the previous traffic aggregation.

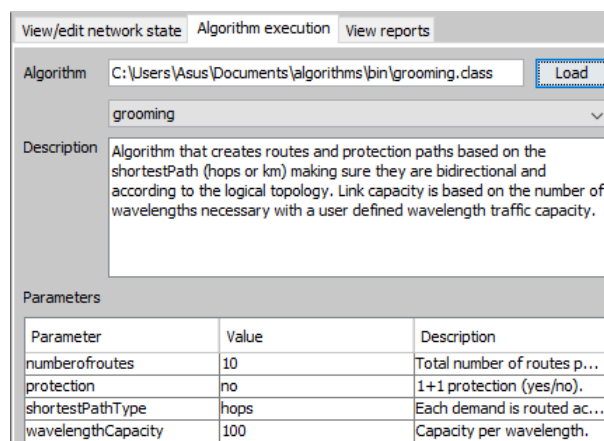


Figura 1.162: Load of the grooming algorithm. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 1.1.5 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details.



Figura 1.163: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

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

Low Traffic Scenario:

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



Figura 1.164: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 1.165: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 1.166: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.167: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.168: ODU2 logical topology defined by the ODU2 traffic matrix.

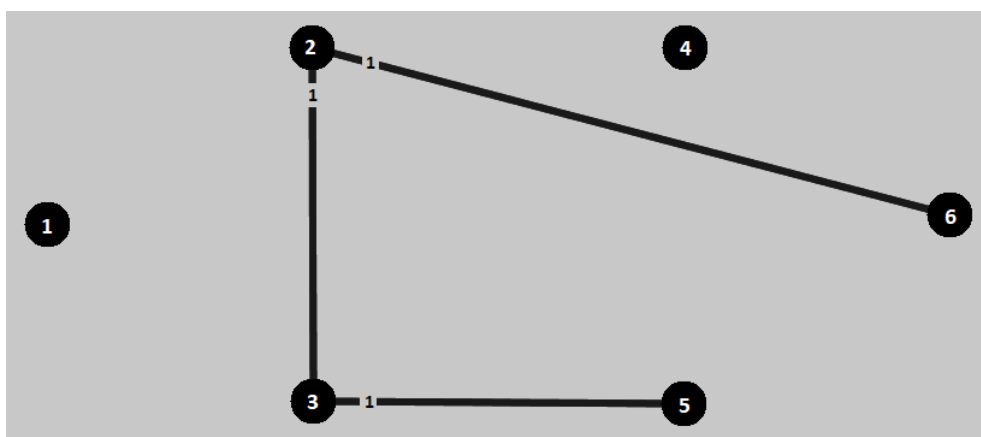


Figura 1.169: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.170: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.171: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Pedro's heuristics can be consulted in the following table 1.66.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|--------------|----------|----------------|-------------|--------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 9 520 000 € |
| | 100 Gbits/s Transceivers | | 18 | 5 000 €/Gbit/s | 9 000 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 2 072 590 € |
| | | ODU0 Ports | 60 | 10 €/port | 600 € | |
| | | ODU1 Ports | 50 | 15 €/port | 750 € | |
| | | ODU2 Ports | 16 | 30 €/port | 480 € | |
| | | ODU3 Ports | 6 | 60 €/port | 360 € | |
| | | ODU4 Ports | 4 | 100 €/port | 400 € | |
| | | Transponders | 18 | 100 000 €/port | 1 800 000 € | |
| | Optical | OXCs | 6 | 20 000 € | 120 000 € | |
| | | Line Ports | 18 | 2 500 €/port | 45 000 € | |
| | | Add Ports | 18 | 2 500 €/port | 45 000 € | |
| Total Network Cost | | | | | | 11 592 590 € |

Tabela 1.66: Table with detailed description of CAPEX.

All the values calculated in the previous table were obtained through the equations 1.2 and 1.3 referred to in section 1.1, but for a more detailed analysis we created table 1.67 where we can see how all the parameters are calculated individually.

Medium Traffic Scenario:

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

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

Tabela 1.67: Table with description of calculation

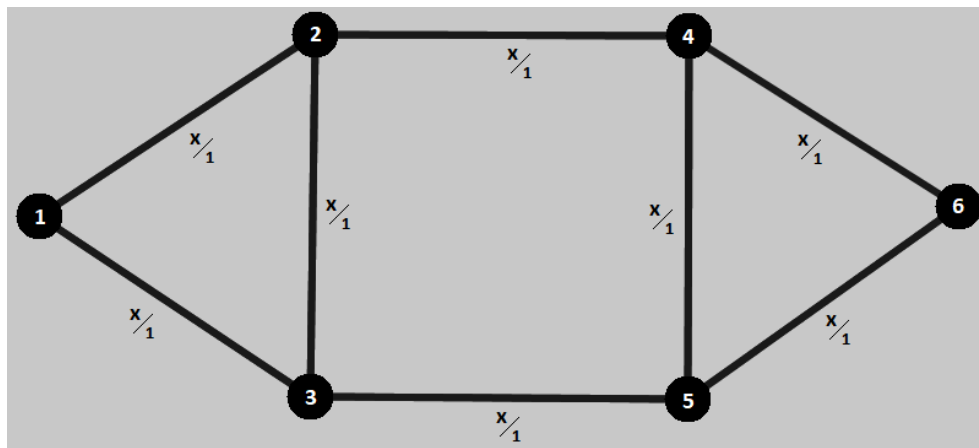


Figura 1.172: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional



Figura 1.173: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 1.174: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.175: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.176: ODU2 logical topology defined by the ODU2 traffic matrix.

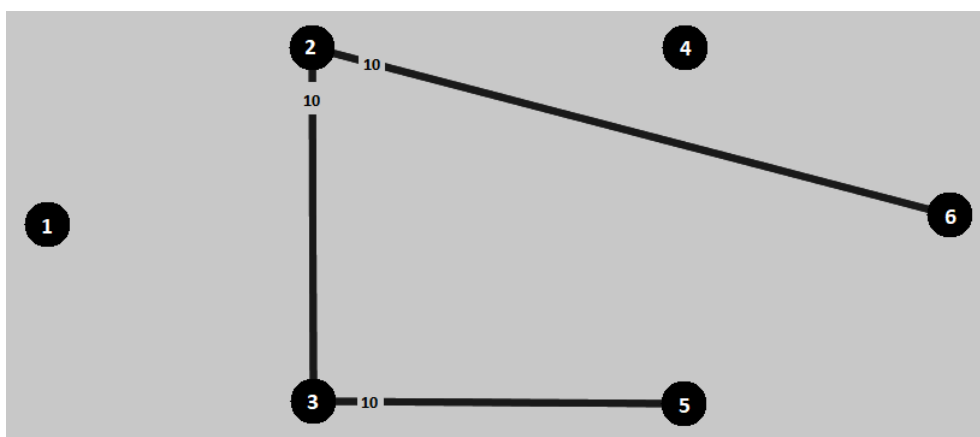


Figura 1.177: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.178: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.179: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Pedro's heuristics can be consulted in the following table 1.68. In table 1.67 mentioned in previous scenario we can see how all the values were calculated.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|--------------|----------|----------------|--------------|--------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 40 520 000 € |
| | 100 Gbits/s Transceivers | | 80 | 5 000 €/Gbit/s | 40 000 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 8 605 900 € |
| | | ODU0 Ports | 600 | 10 €/port | 6 000 € | |
| | | ODU1 Ports | 500 | 15 €/port | 7 500 € | |
| | | ODU2 Ports | 160 | 30 €/port | 4 800 € | |
| | | ODU3 Ports | 60 | 60 €/port | 3 600 € | |
| | | ODU4 Ports | 40 | 100 €/port | 4 000 € | |
| | | Transponders | 80 | 100 000 €/port | 8 000 000 € | |
| | Optical | OXCs | 6 | 20 000 € | 120 000 € | |
| | | Line Ports | 80 | 2 500 €/port | 200 000 € | |
| | | Add Ports | 80 | 2 500 €/port | 200 000 € | |
| Total Network Cost | | | | | | 49 125 900 € |

Tabela 1.68: Table with detailed description of CAPEX.

High Traffic Scenario:

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

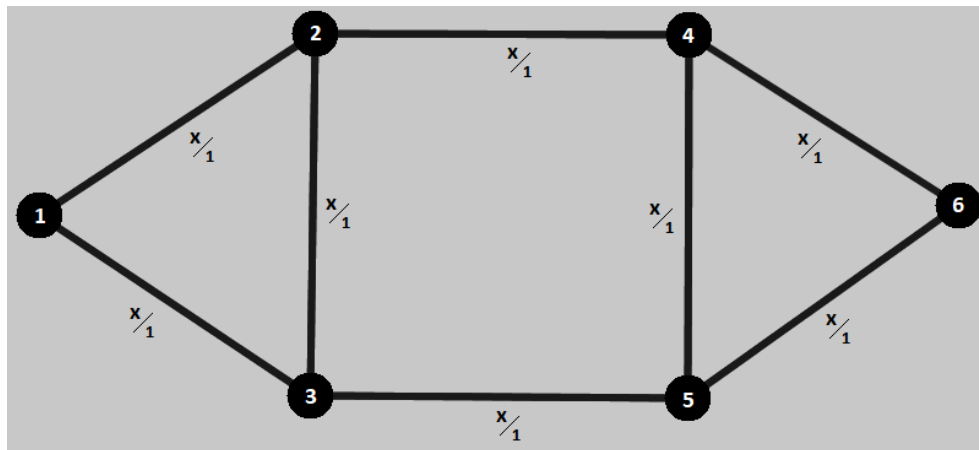


Figura 1.180: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 1.181: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 1.182: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.183: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.184: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 1.185: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.186: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.187: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Pedro's heuristics can be consulted in the following table 1.69. In table 1.67 mentioned in previous scenario we can see how all the values were calculated.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|--------------|----------|----------------|--------------|--------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 77 520 000 € |
| | 100 Gbits/s Transceivers | | 154 | 5 000 €/Gbit/s | 61 000 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 16 401 800 € |
| | | ODU0 Ports | 1 200 | 10 €/port | 12 000 € | |
| | | ODU1 Ports | 1 000 | 15 €/port | 15 000 € | |
| | | ODU2 Ports | 320 | 30 €/port | 9 600 € | |
| | | ODU3 Ports | 120 | 60 €/port | 7 200 € | |
| | | ODU4 Ports | 80 | 100 €/port | 8 000 € | |
| | | Transponders | 154 | 100 000 €/port | 15 400 000 € | |
| | Optical | OXCs | 6 | 20 000 € | 120 000 € | |
| | | Line Ports | 154 | 2 500 €/port | 385 000 € | |
| | | Add Ports | 154 | 2 500 €/port | 385 000 € | |
| Total Network Cost | | | | | | 93 921 800 € |

Tabela 1.69: Table with detailed description of CAPEX.

Conclusions

Once we have obtained the results for all the scenarios we will now draw some conclusions about these results. For a better analysis of the results will be created the table 1.70 with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

| | Low Traffic | Medium Traffic | High Traffic |
|---------------------------|------------------------|-----------------------|-----------------------|
| Traffic (Gbit/s) | 500 | 5 000 | 10 000 |
| Bidirectional Links used | 8 | 8 | 8 |
| Number of Add ports | 18 | 80 | 154 |
| Number of Line ports | 18 | 80 | 154 |
| Number of Tributary ports | 136 | 1 360 | 2 720 |
| Number of Transceivers | 18 | 80 | 154 |
| Link Cost | 9 520 000 € | 40 520 000 € | 77 520 000 € |
| Node Cost | 2 072 590 € | 8 605 900 € | 16 401 800 € |
| CAPEX | 11 592 590 € | 49 125 900 € | 93 921 800 € |
| CAPEX/Gbit/s | 23 185 €/Gbit/s | 9 825 €/Gbit/s | 9 392 €/Gbit/s |

Tabela 1.70: Table with different value of CAPEX for this case.

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

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

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

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

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

- Comparing the CAPEX cost per bit we can see that in the low traffic the cost is higher than the medium and high traffic, which in these two cases the value is similar, but still inferior in the higher traffic. The difference between the low traffic and medium/high traffics is significantly high;

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

Opens Issues

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

- Allow maximum optical reach value in optical channels.

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

- Allow multiple transmission system.

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

1.1.6 Translucent with 1+1 Protection

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

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

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

We also must take into account the following particularity of this mode of transport:

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

The minimization of the network CAPEX is made through the equation 1.1 where in this case for the cost of nodes we have in consideration the electric cost 1.4 and the optical cost 1.5.

In this case the value of $P_{exc,c,n}$ is obtained by equation 1.19 for short-reach and by the equation 1.20 for long-reach and the value of $P_{oxc,n}$ is obtained by equation 1.21.

The equation 1.19 refers to the number of short-reach ports of the electrical switch with bit-rate c in node n , $P_{exc,c,n}$, i.e. the number of tributary ports with bit-rate c in node n which can be calculated as

$$P_{exc,c,n} = \sum_{d=1}^N D_{nd,c} \quad (1.19)$$

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

$$P_{exc,-1,n} = \sum_{j=1}^N \lambda_{nj} \quad (1.20)$$

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

The equation 1.21 refers to the number of ports in optical switch in node n , $P_{oxc,n}$, i.e. the number of line ports and the number of adding ports of node n which can be calculated as

$$P_{oxc,n} = \sum_{j=1}^N f_{nj}^{od} + \sum_{j=1}^N \lambda_{nj} \quad (1.21)$$

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

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

In the next pages it will be described all the steps performed to obtain the final results in the translucent transport mode with 1+1 protection. In the figure below 1.188 it is shown a fluxogram with the description of this transport mode approach.

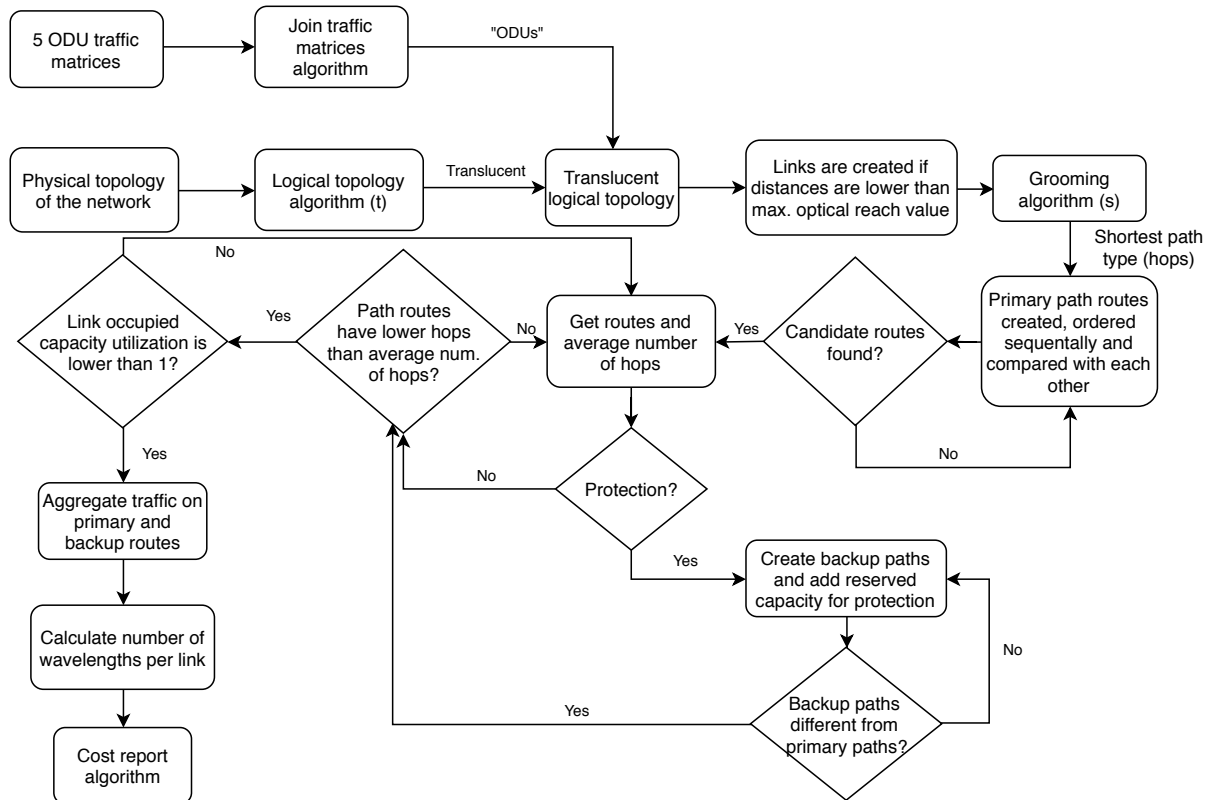


Figura 1.188: Fluxogram with the steps performed in the translucent with 1+1 protection transport mode approach.

Creation and join the traffic matrices

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

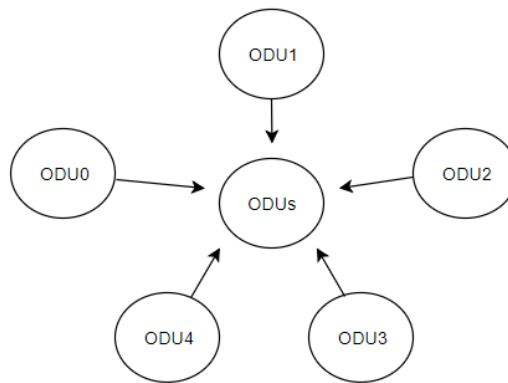


Figura 1.189: Join the 5 ODU traffic matrices into 1 single file "ODUs". The 5 traffic demands from the traffic matrices previously created are joined into 1 file to load it later on Net2Plan.

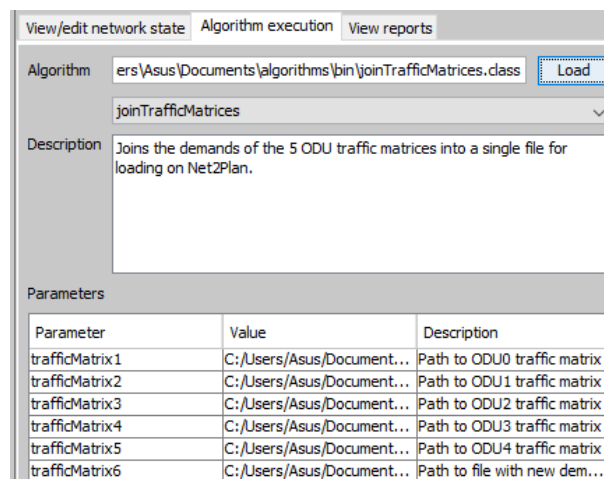


Figura 1.190: Load of the join traffic matrices algorithm for the translucent transport mode on Net2Plan. It is defined the 5 paths to load the 5 ODU traffic matrices and the last path is the one where will be saved the file that joins all 5 the traffic demands.

Creation of the physical topology

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



Figura 1.191: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.

Creation of the logical topology

It is now time to create the allowed logical topology. A network topology represents how the links and the nodes of the network interconnect with each other and the logical topology algorithm creates the logical topology on another layer. In the translucent transport mode each node connects to other node if the shortest path distance between them is lower than the maximum optical reach value (in km) that an optical signal can traverse in an optical channel. If the maximum optical reach is higher than the shortest path of a link, then it is not created a logical link of that specific physical link. On the contrary, there are created direct links between all node pairs in the network that follow this rule. These additions of links between end nodes are made in the new upper layer of the network. The respective demands are saved in the new upper layer and those demands from the lower layer are then removed. The lower layer is the physical layer of the network and it is now created a new upper layer which is the logical layer of the network and represents the logical topology of the translucent transport mode. The allowed physical and optical topologies, the logical topologies for all ODU's and the resulting physical topology is shown in the next section below 1.1.6 for the three traffic scenarios. It is shown below three figures with the code in Java of the creation of the network logical topology, the load of the logical topology algorithm in Net2Plan and the resulting allowed optical topology for the translucent transport mode with 1+1 protection.

```

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

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

    sendToFile("opticalReach.txt");

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

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

```

Figura 1.192: Java code of the logical topology approach for the translucent transport mode. The logical layer is created by adding direct links between all end nodes if their shortest path between them is lower than the maximum optical reach value. The new layer is now the translucent logical topology of the network.

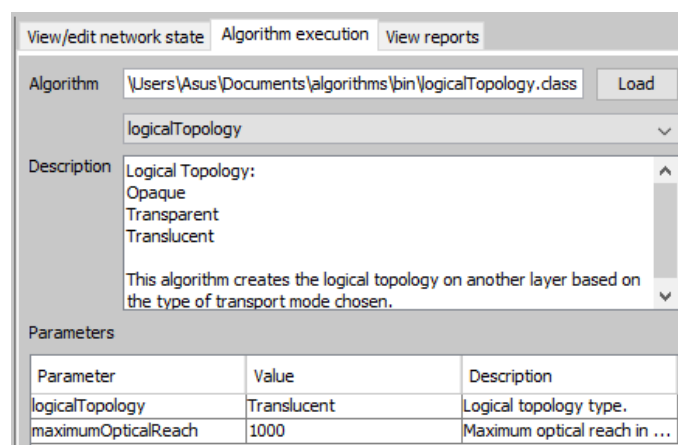


Figura 1.193: Load of the logical topology algorithm for the translucent transport mode on Net2Plan. It is assumed that the maximum optical reach value is 1000 km, so all direct links between node pairs with different index are created in all optical channels.

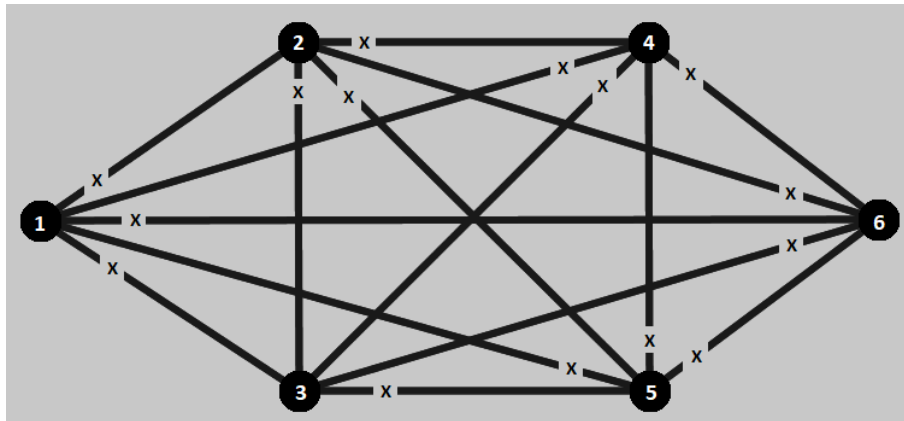


Figura 1.194: Allowed optical topology. It is assumed that each connections between demands supports up to 100 lightpaths. In the translucent transport mode there are several possible logical topologies for a specific network. It depends, for example, on the maximum optical reach value that represents the maximum distance that an optical signal can traverse a link without the need of regenerate.

Creation of routes and aggregation of traffic

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

backup path routes are used to prevent network failures. Despite of the fact the network will be much more secure, the network CAPEX will increase more than the double, due to the creation of primary and backup paths.

```

case "Logical Topology Translucent":

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

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

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

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

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

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

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

```

Figura 1.195: Creation of routes and aggregation of traffic for the translucent with 1+1 protection transport mode. The candidate routes are searched by the shortest path type method and the average minimum number of physical hops of the routes.

```

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

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

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

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

```

Figura 1.196: Creation of routes and aggregation of traffic for the translucent with 1+1 protection transport mode. The protection segments are added to all the primary paths that were chosen by the shortest path type method.

```

netPlan.removeAllRoutesUnused(1);

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

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

        if (tNodeId == tNodeId1)
            continue;

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

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

```

Figura 1.197: Creation of routes and aggregation of traffic for the translucent with 1+1 protection transport mode. The traffic demands are set into the candidate primary path routes found earlier and also compared with the backup path routes.

```

// Protection Segments
totaltraffic = 0;

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

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

```

Figura 1.198: Creation of routes and aggregation of traffic for the translucent with 1+1 protection transport mode. Minimizing the blocked traffic, the traffic demands are also set into the protection path routes and the wavelength assignment is carried out.

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

Tabela 1.71: Table with the description of the main functions in the creation of routes and aggregation of traffic in the grooming algorithm.

Calculation of the number of wavelengths per link

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

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

Figura 1.199: Calculation of the number of wavelengths per link for the translucent transport mode. The link capacity is reserved based on the previous traffic aggregation.

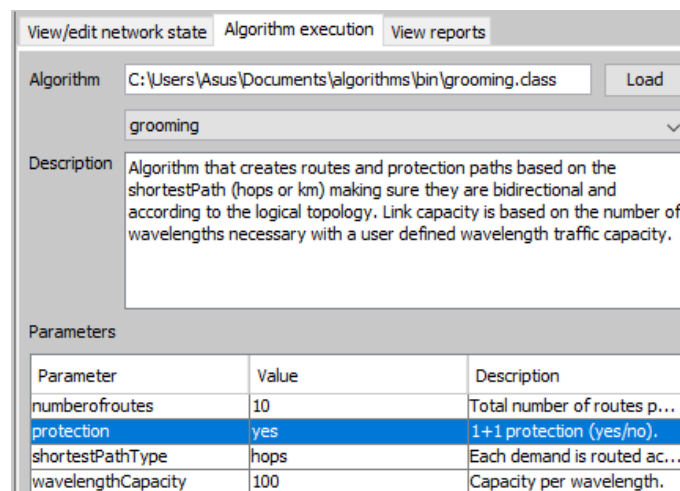


Figura 1.200: Load of the grooming algorithm for the translucent with 1+1 protection transport mode. The total number of routes per demand is set to 10, the user can define if the model is with or without protection, the shortest path type is set to "hops" and the capacity per wavelength is used 100 optical channels.

Network cost report

In order to obtain the network CAPEX results, the formulas needed to calculate the network elements and that are demonstrated previously in the beginning of this section 1.1.6 were "translated" into Java code in a cost report algorithm. This algorithm can be loaded in Net2Plan and calculates and shows in tables the network CAPEX and also the per-link and per-node information with more details.



Figura 1.201: Load of the cost report algorithm on Net2Plan. The result view is an HTML page with the network optical and electrical components and their costs.

Result description

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

Low Traffic Scenario:

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



Figura 1.202: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 1.203: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 1.204: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.205: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.206: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 1.207: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.208: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.209: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Pedro's heuristics can be consulted in the following table 1.72. In table 1.67 mentioned in previous model we can see how all the values were calculated.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|--------------|----------|----------------|--------------|--------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 23 520 000 € |
| | 100 Gbits/s Transceivers | | 46 | 5 000 €/Gbit/s | 23 000 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 2 142 590 € |
| | | ODU0 Ports | 60 | 10 €/port | 600 € | |
| | | ODU1 Ports | 50 | 15 €/port | 750 € | |
| | | ODU2 Ports | 16 | 30 €/port | 480 € | |
| | | ODU3 Ports | 6 | 60 €/port | 360 € | |
| | | ODU4 Ports | 4 | 100 €/port | 400 € | |
| | | Transponders | 18 | 100 000 €/port | 1 800 000 € | |
| | Optical | OXCs | 6 | 20 000 € | 120 000 € | |
| | | Line Ports | 46 | 2 500 €/port | 115 000 € | |
| | | Add Ports | 18 | 2 500 €/port | 45 000 € | |
| Total Network Cost | | | | | | 25 662 590 € |

Tabela 1.72: Table with detailed description of CAPEX.

Medium Traffic Scenario:

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



Figura 1.210: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 1.211: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 1.212: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.213: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.214: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 1.215: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.216: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.217: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Pedro's heuristics can be consulted in the following table 1.73. In table 1.67 mentioned in previous model we can see how all the values were calculated.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|--------------|----------|----------------|--------------|--------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 78 520 000 € |
| | 100 Gbits/s Transceivers | | 156 | 5 000 €/Gbit/s | 78 000 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 8 795 900 € |
| | | ODU0 Ports | 600 | 10 €/port | 6 000 € | |
| | | ODU1 Ports | 500 | 15 €/port | 7 500 € | |
| | | ODU2 Ports | 160 | 30 €/port | 4 800 € | |
| | | ODU3 Ports | 60 | 60 €/port | 3 600 € | |
| | | ODU4 Ports | 40 | 100 €/port | 4 000 € | |
| | | Transponders | 80 | 100 000 €/port | 8 000 000 € | |
| | Optical | OXCs | 6 | 20 000 € | 120 000 € | |
| | | Line Ports | 156 | 2 500 €/port | 390 000 € | |
| | | Add Ports | 80 | 2 500 €/port | 200 000 € | |
| Total Network Cost | | | | | | 87 315 900 € |

Tabela 1.73: Table with detailed description of CAPEX.

High Traffic Scenario:

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

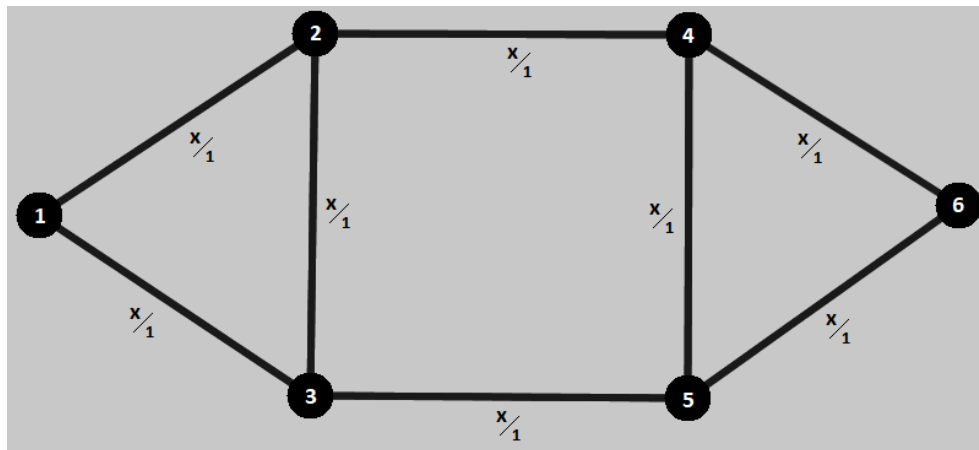


Figura 1.218: Allowed physical topology. The allowed physical topology is defined by the duct and sites in the field. It is assumed that each duct supports up to 1 bidirectional transmission system and each site supports up to 1 node.



Figura 1.219: Allowed optical topology. The allowed optical topology is defined by the transport mode (translucent transport mode in this case). It is assumed that each connections between demands supports up to 100 lightpaths.



Figura 1.220: ODU0 logical topology defined by the ODU0 traffic matrix.



Figura 1.221: ODU1 logical topology defined by the ODU1 traffic matrix.



Figura 1.222: ODU2 logical topology defined by the ODU2 traffic matrix.



Figura 1.223: ODU3 logical topology defined by the ODU3 traffic matrix.



Figura 1.224: ODU4 logical topology defined by the ODU4 traffic matrix.



Figura 1.225: Physical topology after dimensioning.

Following all the steps mentioned in the ??, applying the routing and grooming heuristic algorithms in the Net2Plan software and using all the data referring to this scenario, the obtained result for the Pedro's heuristics can be consulted in the following table 1.69. In table 1.67 mentioned in previous model we can see how all the values were calculated.

| CAPEX of the Network | | | | | | |
|----------------------|--------------------------|--------------|----------|----------------|---------------|---------------|
| | | | Quantity | Unit Price | Cost | Total |
| Link Cost | OLTs | | 16 | 15 000 € | 240 000 € | 147 520 000 € |
| | 100 Gbits/s Transceivers | | 294 | 5 000 €/Gbit/s | 147 000 000 € | |
| | Amplifiers | | 70 | 4 000 € | 280 000 € | |
| Node Cost | Electrical | EXCs | 6 | 10 000 € | 60 000 € | 16 751 800 € |
| | | ODU0 Ports | 1 200 | 10 €/port | 12 000 € | |
| | | ODU1 Ports | 1 000 | 15 €/port | 15 000 € | |
| | | ODU2 Ports | 320 | 30 €/port | 9 600 € | |
| | | ODU3 Ports | 120 | 60 €/port | 7 200 € | |
| | | ODU4 Ports | 80 | 100 €/port | 8 000 € | |
| | | Transponders | 154 | 100 000 €/port | 15 400 000 € | |
| | Optical | OXCs | 6 | 20 000 € | 120 000 € | |
| | | Line Ports | 294 | 2 500 €/port | 735 000 € | |
| | | Add Ports | 154 | 2 500 €/port | 385 000 € | |
| Total Network Cost | | | | | | 164 271 800 € |

Tabela 1.74: Table with detailed description of CAPEX.

Conclusions

Once we have obtained the results for all scenarios for the translucent without survivability and translucent with 1+1 protection we will now draw some conclusions about these results. For a better analysis of the results will be created the table 1.75 with the number of line ports, tributary ports and transceivers because they are important values for the cost of CAPEX, the cost of links, the cost of nodes and finally the cost of CAPEX.

| | Low Traffic | Medium Traffic | High Traffic |
|------------------------------------|------------------------|------------------------|------------------------|
| CAPEX without survivability | 11 592 590 € | 49 125 900 € | 93 921 800 € |
| CAPEX/Gbit/s without survivability | 23 185 €/Gbit/s | 9 825 €/Gbit/s | 9 392 €/Gbit/s |
| Traffic (Gbit/s) | 500 | 5 000 | 10 000 |
| Bidirectional Links used | 8 | 8 | 8 |
| Number of Add ports | 18 | 80 | 154 |
| Number of Line ports | 46 | 156 | 294 |
| Number of Tributary ports | 136 | 1 360 | 2 720 |
| Number of Transceivers | 46 | 156 | 294 |
| Link Cost | 23 520 000 € | 78 520 000 € | 147 520 000 € |
| Node Cost | 2 142 590 € | 8 795 900 € | 16 751 800 € |
| CAPEX | 25 662 590 € | 87 315 900 € | 164 271 800 € |
| CAPEX/Gbit/s | 51 325 €/Gbit/s | 17 463 €/Gbit/s | 16 427 €/Gbit/s |

Tabela 1.75: Table with different value of CAPEX for this case.

Looking at the previous table we can make some comparisons between the translucent with 1+1 protection scenario:

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

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

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

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

- Comparing the CAPEX cost per bit we can see that in the low traffic the cost is higher than the medium and high traffic, which in these two cases the value is similar, but still inferior in the higher traffic. The difference between the low traffic and medium/high traffics is significantly high;

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

We can also make some comparisons between the translucent without survivability and translucent with 1+1 protection scenarios:

- We can see that in the translucent with 1+1 protection transport mode the CAPEX cost for all the three traffic is more than the double;

This happens because in the translucent with 1+1 protection transport mode there is a need of having a primary and a backup path, in case of a network failure, and the backup path is typically longer;

- Comparing the CAPEX cost per bit we can see that has a similar case in both of the two scenarios. In the low traffic the cost is higher than the medium and high traffic, which in these two cases the value is similar;

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

Opens Issues

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

- Allow maximum optical reach value in optical channels.

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

- Allow multiple transmission system.

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

