Dimensioning of an European backbone network in OPNET WDM Guru

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Abstract
Master courses lab sessions at Ghent University use OPNET WDM Guru to evaluate dimensioning of an optical European backbone network. The low connectivity of optical networks increases consequences of single defects. Therefore, an availability analysis was performed, starting from a ring network. Additional links improve reliability and routing cost, but increase installation cost. An evaluation finds the best compromise. A network topology must be designed for a traffic forecast consisting of voice, business IP and residential IP traffic components. Because of high optical equipment prices, different design alternatives concerning grooming and protection/restoration are evaluated to find the most cost-effective solution.

Introduction
The importance of network reliability has increased even more in the last decades, mainly because of the development and acceptance of optical fiber technology in backbone networks. This transmission medium has an almost infinite amount of low-cost, reliable bandwidth. However, this has lead to the fact that optical networks typically operate with a lower connectivity than networks with traditional transmission media, such as copper-based networks, which are usually heavily meshed. The low connectivity seen in optical networks implies that the occurrence of a defect can potentially cause catastrophic consequences for a very large number of users. Providing sufficient backup capacity and equipment is of crucial importance during the design of optical networks.

Obviously, this reliability constraint may clash with cost considerations. One has to evaluate availability against cost, and find the best compromise. Often certain minimal demands are required from the topology (e.g. availability service levels), and against those demands one then tries to achieve minimal costs.

Once an appropriate network topology is found, this network must be designed for a particular traffic pattern. By using the grooming operation, the SDH traffic demands will be mapped into optical wavelength demands. This grooming procedure first designs the logical layer, i.e. the SDH layer. Then, the physical layer, i.e. the optical layer, is designed. Finally, the capacity that is requested by the demand for the physical layer is made available in the network. The grooming procedure will result in a combined SDH-optical channel network design with the lowest possible network cost.

In optical network design, cost is a primary factor. Due to the high prices of optical equipment, a network designer strives for the most cost-effective solution. In addition, the network design is also influenced by the traffic pattern.

This paper gives an overview of two master courses lab sessions at Ghent University that use OPNET WDM Guru 8.5 [1]. The goal of the Availability Analysis lab session is to gain insight into network reliability related problems, using some specific examples. We will use WDM Guru to determine availability results, routing costs and installation costs for certain candidate network topologies. As a starting point, the European backbone ring network is considered. The goal of the Transport Network Design lab session is to design the pan-European backbone network for particular traffic patterns, consisting of voice, business IP and residential IP traffic components. Two grooming alternatives, namely link-by-link and end-to-end grooming are considered and the impact of the traffic demand, cost parameters and recovery strategy on their performance is investigated.

This paper is organized as follows. First the general settings for the lab sessions are discussed. Afterwards, the Availability Analysis lab session and the Transport Network Design lab session are described in detail.

OPNET WDM Guru settings for the lab sessions

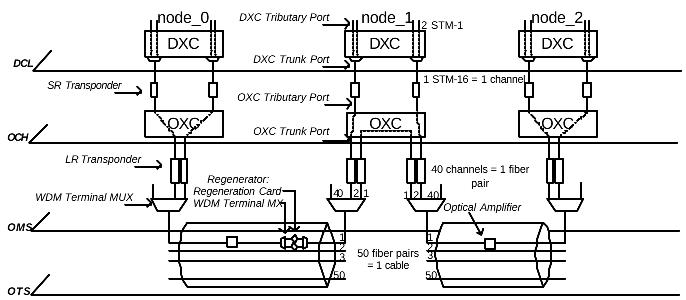

Figure 1: Illustration of the different elements of a transmission network

Layer model
WDM Guru uses four different layers to model a network. Every layer has its own representation. From the lowest layer to the highest layer, one can distinguish the Optical Transmission Section (OTS), the Optical Multiplex Section (OMS), the Optical Channel layer (OCH) and the Digital Client Layer (DCL), see also Figure 1. The physical optical fiber connections represent the topology of the optical channel layer. We call this the physical topology. The optical channels routed through the optical channel layer realize the links in the DCL topology. The OXCs in the optical channel layer can create any imaginable DCL topology, without the need to physically replace the optical

fibers. Therefore, we call the DCL topology the logical topology.

Network properties

During the lab sessions, "opaque" is used as OCH Layer mode. This means that the OXC is surrounded by long-reach transponders at the trunk ports interconnected to the WDM line systems and short reach transponders at its tributary ports. As EOCC Node model, "DXC+OXC" is chosen. Using this, a DXC is used for switching SDH traffic (DCL layer in Figure 1) and a separate OXC is used for switching WDM wavelengths. The DXC trunk ports connect to the OXC tributary ports so nodes can transport SDH traffic over WDM channels. Furthermore, the "continuous mode" is used for the DXC and OXC nodes. For this mode, nodes are assumed to scale continuously. A fixed base cost, independent of the size, and in addition a uniform cost per tributary port and per trunk port is used. For the OCH links, we will use 40-WDM line systems, this means that 1 fiber pair can contain 40 optical channels or wavelengths, see also Figure 1.

Availability Analysis

European backbone ring network and settings

As a starting point for the first lab session, we use an European backbone ring network. This network consists of 10 nodes, interconnected by 10 direct optic fiber cables, as shown in Figure 2.

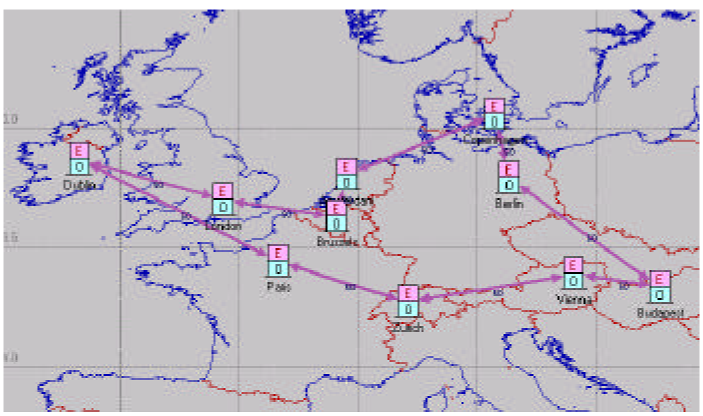

Figure 2: European backbone ring network

The different candidate network topologies in this session are evaluated in terms of installation cost, routing cost and availability. Therefore, the following settings are used:

Traffic matrix: We created a simple OCH traffic matrix that holds the optical connections. A uniform traffic pattern between all nodes is created, adding a single channel with a channel bit rate of STM-16 between every two nodes.

Protection and restoration: By the dimensioning of the network, one can perform a dimensioning with or without reserving spare capacity for recovery in case of failures. During this lab session, two recovery strategies will be used. In the case of "1+1 path protection", the network transmits traffic from the source to the destination, simultaneously using a working path and a protection path. The destination node monitors information on both paths and if the working path gets interrupted, the system switches to the protection path. These paths can be node disjoint (no common nodes except for source and destination, protects against single-node and single-link failures) or link disjoint (no common links, protects against single-link failures). In the case of "path restoration", no pre-established backup path is used. When a node or link fails, the network reroutes each connection individually around the failing entity between the end-points of the connection. The restoration path depends on the failure location and is more flexible with respect to unexpected failures. An important difference between 1+1 protection and restoration, from a network dimensioning perspective, is that in restoration spare capacity can be shared between different connections and/or failure scenarios. In other words, restoration is typically more cost-effective.

Installation cost: In order to compare installation costs, we focus on the link cable cost. The "cable cost per length unit" is set to 100 kEUR per km. Other costs are not taken into account.

Routing cost: When routing an OCH traffic matrix, the "hop + fiber length" cost function is used to calculate the link costs to thereby determine the lowest-cost path. The lowest-cost path is the one with the fewest hops. If multiple paths have the same minimum number of hops, the path with the smallest fiber length is chosen.

Availability settings: In order to specify the link availability properties, the cable length cut model is used. This method uses a "cable length per cut per year" value, i.e. the average estimated cable length in km within which you expect a single cable cut to occur over a year. The "mean time to repair" (MTTR) value is then the average estimated time in hours that is needed to repair each cable cut. Unless otherwise mentioned, the "cable length per cut per year" value is during the whole session set to 300 km and the MTTR is set to 24 hours. The line systems and nodes are assumed to have an availability of 100%.

Analysis

We aim for an average availability above 99.93%. Therefore, an availability analysis is performed on several topologies, starting from the pure ring network and adding additional links as follows:

Ring network: This is the topology as shown in Figure 2.

Meshed base network: The disadvantage of a ring network is that in the case of 1+1 protection or path restoration, every connection with its backup must pass all nodes in the network. This can be avoided by providing a shortcut link in the network. E.g. we can avoid routing of traffic between Brussels and Zurich over the Channel, by adding a single cable to the ring network. Students have to examine which link will be the best to add. Assuming that the same availability parameters are used for the new link, the link Paris-Brussels is preferred as this link results in a minimal additional installation cost, because this is the shortest link and only the cable cost per length unit is taken into account. The ring network with the extra link Paris-Brussels is indicated by the term meshed base network (Figure 3).

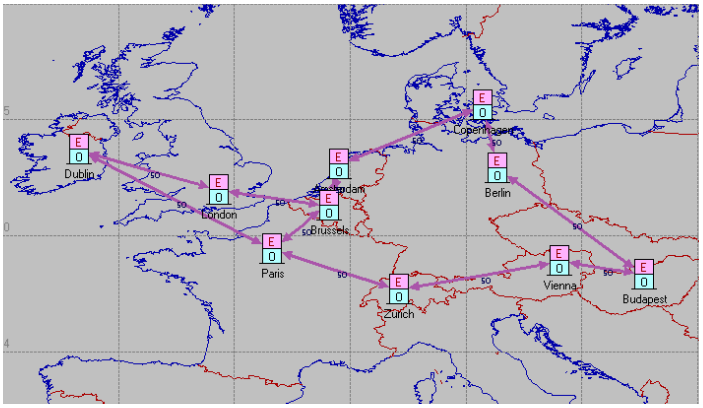

Figure 3 Meshed base network

Additional links: More links can be added to the meshed base network to improve service levels and lower the routing cost. While researching possible extensions to the network, the following links were selected: Amsterdam-Berlin, Paris-Vienna and Berlin-Vienna. Installation of each of these links brings with it an additional installation cost, improved reliability and an improved routing cost. Because of budget constraints, it is impossible to complete all three options. So, simulations make it possible to evaluate all three to compare the marginal gains seen when installing each of the three links. Based on the obtained results of Table 2, students can select the best options.

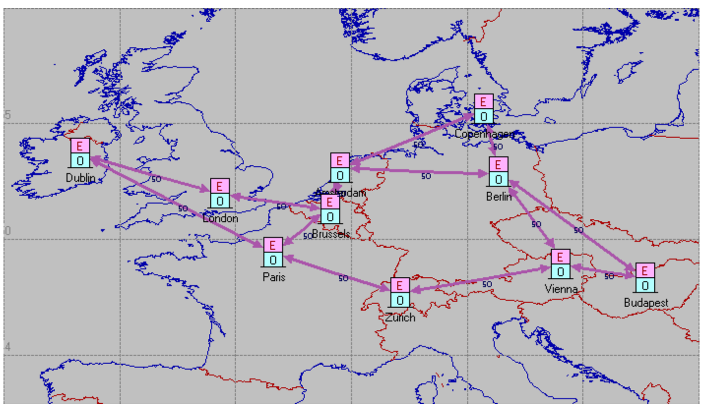

Figure 4 Additional links

Channel problem: The two additional links that are determined to be the best options, are added to the meshed base network in order to form the topology of Figure 4. This topology is considered to investigate the Channel problem. As the North Sea Channel is very shallow and sees very high shipping traffic, cables spanning the Channel are quite vulnerable. Therefore, we need to examine the effects of the higher vulnerability of the channel links Dublin-Paris and London-Brussels (note that Dublin-London is not a Channel cable). These links are assumed to have a MTTR value of 1 week or 168 hours (instead of the 24 hours of the other links).

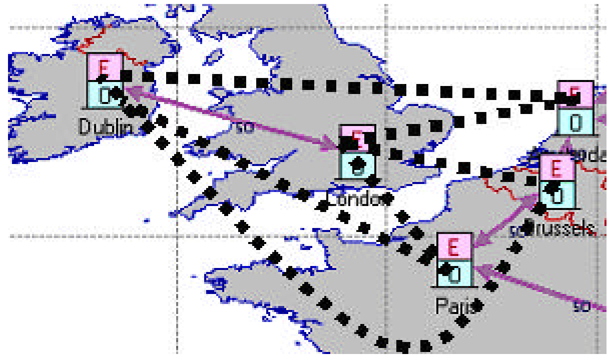

Figure 5 Possible channel links

Channel solution: In order to come up with a solution for the Channel problem, the existing Channel links are removed from the network and all candidate Channel links are considered. As shown in Figure 5, any link between Dublin/London and Amsterdam/Brussels/Paris is a candidate Channel link. The solution will be the cheapest way to interconnect Dublin and London with the mainland, guaranteeing an average availability of 99.93%, using any of the candidate links.

Results: Each of the above introduced network topologies is evaluated by the students in terms of required network investments (total cable cost), routing cost (average hop count) and the offered availability. An overview of the simulation results is given in Table 1. The results show that the ring network can not offer an average availability of 99.93% using unprotected routing. Deployment of 1+1 protection or restoration helps to achieve the aimed availability. The use of an extra link in the meshed base network and adding additional links increases the average availability and decreases the average hop count at the cost of an increasing cable cost. Table 2 shows the gains that are seen when one of the three selected links is installed. The links Amsterdam-Berlin and Berlin-Vienna have the best results in terms of average availability and introduce the smallest additional cable costs, as those are the shortest links. Both links are added to the meshed base network, resulting in

	Ring	**Meshed base**	**Additional links**	**Channel problem**	**Channel solution**
Total link cable cost (kEUR) reflects the installation cost					
	492960	523077	627270	627270	663423
Average hop count reflects the routing cost					
1+1 protection (working/ backup)	2.78/7.22 (sum is 10!)	2.51/5.49	2.20	2.20	2.13
Average availability					
Unprotected	0.98779	0.99009	0.99112	0.98171	0.98194
1+1 protection	0.99964	0.99976	0.99983	0.99915	0.99934
Path restoration	0.99958	0.99961	0.99956	0.99826	0.99781

Table 1: Results for the availability analysis

Additional link	**Average hop count**	**Total cable cost (kEUR)**	**Average availability (1+1 protection)**
Amsterdam-Berlin	2.31	573790	0.99980
Paris-Vienna	2.27	623959	0.99978
Berlin-Vienna	2.36	576558	0.99980

Table 2: Evaluation results when the indicated additional link is added to the meshed base network

the topology of Figure 4. The analysis results of this obtained network are given in Table 1. When we consider the same network, but with a higher vulnerability of the Channel links, this network still turns out to be unable to offer the target 99.93% availability for all connections (the MTTR of the Channel links is now set to 1 week instead of 24 hours). As the already present Channel links are the shortest links, i.e. the most available links, to interconnect Dublin and London to the mainland, more than two links are needed. To find a solution, the shortest links of the candidate Channel links are added one by one until the availability constraint is fulfilled. Adding Paris-London after Brussels-London and Paris-Dublin provides a good solution (Figure 6).

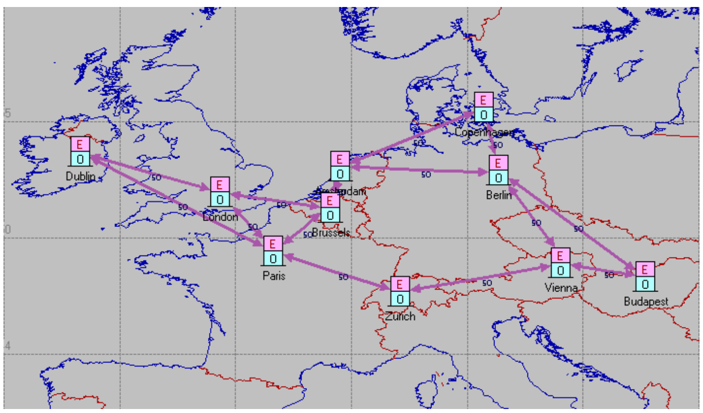

Figure 6 Channel solution

Transport Network Design

Pan-European network

The sample network used in this lab session concerns a pan-European network containing 28 nodes, interconnected by 41 direct optic fiber cables, as shown in Figure 7 [2].

Traffic forecast

In 2002, we made a traffic forecast for this network for the years 2002, 2003 and 2004. The traffic forecast consists of three components: a voice, a business IP and a residential IP traffic component. The total traffic volume for these three components are forecasted based on respectively the population, the number of non-production employees and the number of Internet hosts in each country. The traffic pattern differs for each component: a connection between two network nodes will carry a traffic volume respectively proportional with 1/D, proportional with $1/D^{1/2}$ and independent from D (with D the airline distance between both network nodes) for the three traffic components [2] [3].

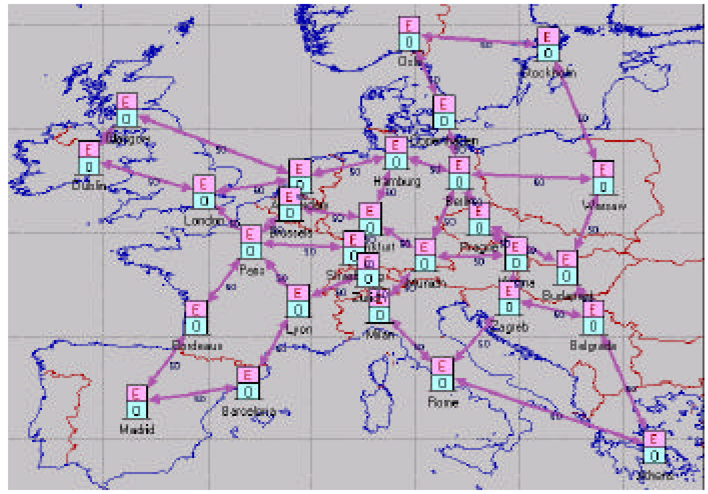

Figure 7: pan-European network

Cost model

Cost is a primary factor in optical network design. Because of the high prices of optical equipment, a network designer strives for the most cost-effective solution. WDM Guru makes use of a lot of cost parameters for the link and node equipment. During this lab session, the different cost parameters will be imported by the students. The "Bill-of-material" in WDM Guru provides the students with an overview of the relevant cost parameters, the amount of node equipment, the amount of line equipment and the total network cost.

Grooming

The aim of the grooming operation is to map a DCL traffic load (i.e. a SDH traffic demand) into an OCH traffic load (i.e. an optical wavelength demand) or in other words onto a logical network topology. Grooming uses a "top-down" approach to design the network, in which DCL traffic demands drive OCH demand [4]. The aim of grooming is to determine a combined DCL-OCH-layer network design that minimizes the total network cost. There are two possible approaches: "end-to-end grooming" and "link-by-link grooming". Which of the two solutions to be preferred, depends on the SDH traffic pattern and the cost parameters. The algorithms "end-to-end grooming with optimization" and "link-by-link grooming with optimization" make combinations of these two approaches in order to find a lower network cost.

Impact of the traffic volume growing in time

To investigate the impact of the growing traffic volume on the network design, the students compare the network design for the total traffic in 2002 with the design for the total traffic in 2004. Link-by-link grooming and end-to-end grooming are evaluated in terms of total network cost and utilization.

Year	Link-by-link grooming		End-to-end grooming	
	Network cost	Utilization	Network cost	Utilization
2002 (STM-16)	392380	99%	393455	67%
2004 (STM-16)	948980	99%	764790	85%
2004 (STM-64)	622975	98%	863575	53%

Table 3: Network design for the total traffic in 2002 and 2004

Traffic pattern	Total traffic volume	Link-by-link grooming		End-to-end grooming	
		Network cost	Mean hop count	Network cost	Average availability
Voice & business IP	7117	409630	2.97	403725	0.9837
Residential IP	7250	453195	3027	431215	0.9825

Table 4: Network design for the voice & business traffic in 2003 and the residential traffic in 2004

The results, given in Table 3, make it possible for the students to make the following conclusions: The total network cost increases from 2002 to 2004, due to the growing traffic volume. In 2002 link-by-link grooming is cheapest, because too much capacity would be wasted in the end-to-end grooming case (filling of 67%). However, due to the increasing traffic volume, the filling in the end-to-end grooming improves (85%) and thus there is no need to invest in breaking up the wavelength channels in intermediate nodes. Thus, in 2004 the end-to-end grooming option is cheapest. When coarser granularities are adopted for the logical lines, link-by-link grooming becomes cheaper again. The coarser granularity again results in an inefficient filling of the capacity (filling 53%) and thus again too much capacity is wasted in the end-to-end grooming, thus making again the link-by-link grooming more attractive. Although the equipment cost for a coarser granularity increases, the total network cost decreases as the coarser granularity also implies a reduced number of wavelength channels to be routed over the optical network. The corresponding reduction in total network cost is thus sufficient to overcompensate the increase in the unit cost.

Impact of the traffic pattern

In order to understand the impact of the traffic pattern on the performance of the different design alternatives, link-by-link grooming and end-to-end grooming were deployed for the voice & business IP traffic demand for 2003 and compared with the design for the traffic pattern consisting of the residential IP component for 2004. This comparison is meaningful as the total traffic volumes are of the same order for both cases. The results can be found in Table 4.

From the mean hop count of the logical connections in the link-by-link grooming case, the students learn that on average, connections carrying residential IP traffic are longer than connections carrying voice & business IP traffic. This confirms the statements made about the D-dependency of the different traffic patterns. This observation is also in accordance with the availability measurements. Since connections carrying residential IP traffic are on average longer, they also perceive a slightly lower average availability than connections carrying voice & business IP traffic.

For both traffic patterns, the link-by-link grooming option is more expensive. Relative to the end-to-end grooming case, the extra cost is 1.46% for the voice & business IP traffic, and 5.10% for the residential IP traffic. The latter value is higher, as on average, residential IP traffic transits more intermediate network nodes than voice & business IP traffic. As a result, for residential IP traffic, one has to invest more intermediate DXC capacity in the link-by-link grooming case.

Impact of cost parameters

In what follows, we investigate how the cost parameters can be modified in order to make the link-by-link and end-to-end grooming case result in exactly the same network cost. The most trivial way would be to reduce the cost to install and connect a DXC to the optical network. However, it is not meaningful to reduce the fixed cost of a DXC, as the same number of DXCs needs to be installed in both the link-by-link and end-to-end grooming case. Reducing the port cost of a DXC is one way to accomplish our goal. If the cost of a DXC tributary port is the same as the cost of a DXC trunk port, the following formula can be used to calculate $CR_{DXC\text{-}port}$, i.e. the cost reduction needed per port to have the same total network cost (NC) for link-by-link (LBL) and end-to-end (E2E) grooming:

$$CR_{DXC-port} = \frac{(NC_{LBL} - NC_{E2E})}{(\#DXCports_{LBL} - \#DXCports_{E2E})}$$

Using this formula, the calculated necessary cost reduction per port is 4.30 for the voice & business IP traffic and 13.29 for the residential IP traffic. However, this cost reduction per DXC port is larger for the residential traffic than the absolute cost per port (i.e. 5). As this is not feasible, another solution is requested. If the same ideas are applied to a short-reach transponder, with the cost of a STM-16 short-reach transponder of 45, the needed cost reduction of a short-reach transponder CR_{sr_transp} is given by:

$$CR_{sr\_transp} = \frac{(NC_{LBL} - NC_{E2E})}{(\#OXCtribports_{LBL} - \#OXCtribports_{E2E})}$$

This results in a cost reduction of a short-reach transponder of 4.30 for the voice & business IP traffic and 13.29 for the residential IP traffic. In both cases, the reduction is the same. The reasons for this are twofold: first of all, the same difference in total network cost must be compensated and secondly, the cost reduction in both cases is the result of the difference in number of OXC tributary ports for which the cost is modified. The main difference between both cases is that in the first case the total network cost decreases more, since in this case also a

Recovery strategy	Availability		
	Minimum	Average	Maximum
Unprotected	95.33%	98.25%	99.79%
1+1 protected	99.72%	99.93%	99.98%
Restoration		99.92% +/- 0.04%	

Table 5: Network availability for the different recovery strategies

Recovery strategy	Total network cost	Contribution in total network cost (%)		
		DXC Fixed + ports	OXC fixed + ports	line
Unprotected	431215	19.32	28.53	52.15
1+1 protected	840935	9.91	21.30	68.8
Restoration	662300	12.58	24.54	62.9

Table 6: Total network cost of the deployment of the different recovery strategies

cost reduction is seen on the DXC tributary ports. Since the number of DXC tributary ports in link-by-link and end-to-end grooming is the same, both grooming strategies will experience the same cost reduction corresponding to the DXC tributary ports.

We have modified the cost parameters to make the link-by-link and end-to-end grooming operations result in equal network costs. However, this does not mean that these grooming strategies are optimal with respect to these cost parameters. By using “link-by-link grooming with optimization” and “end-to-end grooming with optimization”, you may still be able to significantly reduce the total network cost. This is explained by the fact that for the link-by-link grooming case, too much traffic may transit the DXCs unnecessary. Therefore, we may cross-connect these wavelength channels optically, without a too high penalty on the filling of the optical channels and resulting in a reduced total network cost.

Impact of recovery strategy

In this section, the students use as traffic pattern the residential IP traffic forecast for 2004. Different design alternatives for the recovery strategy are performed and evaluated in terms of total network cost, the distribution of the total network cost over the DXC, OXC and line equipment and the availability. The following recovery strategies are investigated: unprotected, 1+1 protection with node-disjoint backup routes, path restoration with the default options. To evaluate the availability in case of path restoration, the most accurate evaluation is chosen (i.e. maximum availability)

The protection and restoration are developed at the optical layer. Therefore, end-to-end grooming is chosen. Only in end-to-end grooming one can avoid traffic passing through intermediate DXCs. Protection or restoration would not be able to recover this traffic when such an intermediate DXC would fail.

Analysis of the network availability results in Table 5 learns that, by deploying protection or restoration, the network availability improves significantly. The average availability increases from less than two nines to more than three nines. However, we are not able to decide which recovery strategy is the best, from an availability perspective. Indeed, in theory the average availability for restoration is situated somewhere between 99.88% and 99.96%, while the average availability for 1+1 protection is situated somewhere in this range.

The impact of the deployment of a recovery strategy on the total network cost is illustrated in Table 6. Both the 1+1 protection and restoration strategy result in a tremendous network cost increase. This is of course the result of the fact that network recovery is only meaningful when spare capacity or equipment is installed in advance and an operator has to pay for all equipment. From a total network cost perspective, restoration is significantly cheaper than 1+1 protection and can be identified as the best recovery strategy.

The importance of the DXC equipment in the total network cost will decrease if a recovery strategy is deployed. This is explained by the fact that the protection and restoration only take place at the optical network level. This means that only at the optical network level, the operator has to invest in spare equipment.

Conclusion

In this paper, we presented two master courses lab sessions at Ghent University that use OPNET WDM Guru 8.5. During the Availability Analysis lab session, the students investigated how adding links to the European backbone ring network improves reliability and routing cost, at the expense of an increasing installation cost. The students evaluated installation cost against reliability to find the best compromise that meets with an average availability above 99.93%. The Transport Network Design lab session learned the students to design the pan-European backbone network, comparing link-by-link grooming and end-to-end grooming against each other. Which of the two grooming alternatives is preferred, is influenced by the traffic volume, the traffic pattern and the cost parameters. By making a combination of link-by-link grooming and end-to-end grooming, the students could lower the network cost even further. Finally, the lab session illustrated that 1+1 protection and restoration both improve the network availability, but that restoration performs better in terms of total network installation cost.

Acknowledgments

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