Planning Strategies for Static and Dynamic Traffic in Optical Transport Networks

Andre Fernandes, Joao Pires
Department of Electrical and Computer Engineering
Instituto Superior Tecnico
Av. Rovisco Pais,1049-001 Lisboa
Email: andre.mira@tecnico.ulisboa.pt

***Abstract*—Today we are witnessing an unprecedented growth in telecommunications traffic. However, this growth becomes uncertain due to the unpredictability both from the technology and the client service development. Therefore, these aspects lead to an urge from the operators not only to provide network resources, which can give response to these high streams of data while maintaining the quality of service, but also to plan the network resources carefully to reduce CAPEX (Capital Expenditure). It is consequently essential and necessary for operators to have good planning tools. This thesis aims to describe a planning tool which handles traffic demands from client services and attempts to plan WDM (Wavelength Division Multiplexing) networks using OTN (Optical Transport Networks) technology for incoming static or dynamic traffic. This tool was also extended to support three multiperiod planning approaches. Using the planning tool, a study was conducted to analyze three routing strategies and four lighpath selection approaches in the traffic grooming process to understand the context in which each of them is more cost-efficient in a dynamic traffic scenery, followed by another study in which were considered three multiperiod planning approaches for incoming static traffic. These were analyzed for three different scenarios, and the impact of the traffic prediction for each planning strategy was put to the test.**

I. Introduction

This thesis aims to compare multiple planning strategies regarding OTN networks using a software adapted to support both incoming static and dynamic traffic. For this purpose, several heuristics were developed in order to route the incoming traffic demands in the network, so that one can achieve an efficient utilization of the available resources. This efficiency can be achieved through the grooming of low order traffic demands. This means that although the capacity of an optical fiber nowadays can reach 100 Gbit/s (OTU-4 line cards) or even 400 Gbit/s (OTU-5 line cards), the traffic demands can be piled in each fiber such that all this capacity is not wasted by the transport of a single lower order demand.

Although the grooming process is in itself key to achieve higher efficiency and lower CAPEX, one should make a set of decisions which can drastically impact the performance of the traffic grooming. For example, it is important to know what strategy to adopt for routing the demands in the network in order to find cheaper paths in terms of 3R regeneration. It is also important to know whether one should enable the use of all the available lighpaths in the network, or if there must be some criterion for this choice. There are other factors that could influence the grooming process, like the grooming policies [1] or the way the 3R regenerators are allocated in the network in order to guarantee the feasibility of the routing process, but these two aren't subject to study in this thesis. The analysis of the routing criteria and the lightpath selection strategies are studied using incoming dynamic traffic, which means that each demand has a characteristic arrival time and duration. When some demand's duration is reached, it may be freed from the network, and the resources it was using are made available for other incoming future traffic demands.

Yet another study was conducted regarding multiperiod planning. In this approach one must plan the network taking in consideration multiple periods of time and also a time horizon. In this thesis three multiperiod planning strategies were taken in consideration: All Periods Planning (AL), Incremental Planning (Inc) and End of Life Planning (EOL). The studies aim to understand which of the strategies are more suitable for planning the network resources in scenarios where the foretasted traffic is different from the real incoming traffic.

II. Aspects of OTN Technology

In this chapter the reader is presented with a summarized description of the state of art OTN technology. The following subsections will present an overview of the OTN layers, the process of header addition in electrical and optical domains, as well as a description of the WDM network constituents through which OTN networks operate. Finally, a brief description of the node architecture considered in the studies conducted in this thesis is presented.

A. OTN layer model

The OTN technology consists on the use of a client-server model between sub layers. Each of these sub layers offers a set of well defined services to their "client layers" [2]. This hierarchy, is formed under two physical domains: the electrical and the optical. Figure 1 shows summarily the formation of the OTN frame in both domains.

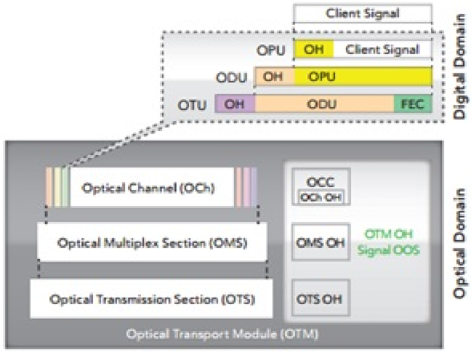

Fig. 1. Addition of headers in electrical and optical domains (extracted from [4])

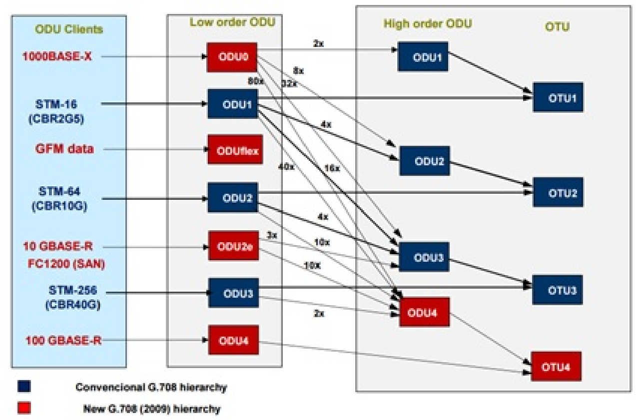

Fig. 2. Multiplexing options in OTN networks (extracted from [5])

In the electrical domain, the OTN frame begins its formation through the insertion of the client signal in the payload area of the OPU (Optical channel Payload Unit). The OPU is responsible for the of the mapping process of the client signal as well as the addition of the header to the first sub layer of the electrical domain. The addition of the next header to this frame forms the ODU (Optical channel Data Unit) which includes OAM (Operations, Administration and Maintenance) for the adequate support of optical signals. The ODU frame also has the particularity of providing various mapping strategies for the support of a range of client signals such as AMP (Asynchronous Mapping Procedure), BMP (Bit-synchronous Mapping Procedure) and GFP (Generic Framing Procedure). As such, the ODU frames are the basis for flexible mapping and multiplexing of client signals. Therefore, as signals of different types and granularities are converted into ODU frames, they are directed to their destinations, being converted to OTU (Optical Transport Unit) frames for transport in the optical domain. To support the different client signals from client services a variety of OTU frames were made available, as shown in Table I. Furthermore, an important feature of OTN technology is that it allows the encapsulation of lower order ODU frames into higher order OPU frames, making hierarchical grooming/multiplexing of traffic possible. Figure 2 shows the different multiplexing options currently available in OTN technology.

TABLE I
OTU FRAMES AND PROVIDED BIT RATE

Tipo de Trama (OTUk)	Dbito [Gbit/s]
OTU1	2,66
OTU2	10,7
OTU2e	11,09
OTU3	43,01
OTU3e2	44,58
OTU4	112
OTU5	400

In the optical domain, the OTN networks comprise transmission links under WDM technology and a set of network elements. WDM networks offer the possibility of establishing optical circuits through lightpaths. A lightpath bypasses the optical switching elements in the network, and requires a wavelength for each physical link it traverses. The main elements of WDM networks which operate in the optical domain are Optical Amplifiers (OAs), Optical Add and Drop Multiplexers (OAMDs) (or its re-configurable version - ROADM), Optical Line Multiplexers (OLTs) and Optical Cross Connects (OXCs). These network elements interconnect in the network by means of optical fibers according to a certain physical topology.

The network element which performs the routing of each lightpath from the origin to its destination is the ROADM. The OXCs also allow the routing of the wavelengths, and can be implemented to provide mesh logical topologies. However, nowadays the ROADM's technology provides the same functions as the OXC. Nonetheless, the OXCs can still be implemented in low cost applications, where the constant reconfiguration of lighpaths is not imperative. The OLTs are comprised of transponders, WDM multiplexers and OAs and their function is to multiplex different wavelengths into an optical fiber and also to demultiplex DWDM signals into several wavelengths. These are deployd in both ends of each point-to-point optical link. Furthermore, transponders and muxponders used in the OLTs have the role of converting signals which are generally generated in the O band ($\approx$ 1310 nm), like in the case of GbE (Gigabit Ethernet) signals, to the C band ($\approx$ 1550 nm), in which WDM networks operate. Although both transponders and muxponders have the role of receiving/transmitting optical signals, the muxponder has the particularity of allowing the multiplexing of low granularity signals into signals of higher bit rate, providing a combination of encapsulations and grooming options [3]. Finally, the OAs are utilized along the optical links in order to amplify the transmitted optical signals so that they can reach their destination in good conditions for information recovery. As mentioned earlier, in the optical domain, data is transmitted through optical circuits which are commonly called lightpaths. Once a lightpath has an associated wavelength it forms an Optical Channel (OCh), which is a physical implementation of the lightpath. OChs have the role of transmitting the optical signals between 3R regeneration points. These OChs are grouped in OMSs using the DWDM technology. Finally, the most deep layer in the optical domain is the Optical Transmitting Section (OTS), which is responsible for management and monitoring of the OAs. Figure 3 shows a simplified network which represents the OTN layers present in each physical domain, as well as the network elements which operate in each of them.

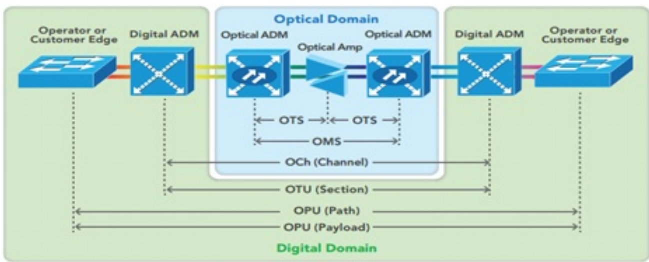

Fig. 3. Simplified Network; OTN layers, network elements and physical domains of operation (extracted from[4])

B. Architecture of the network elements

The architecture of an OTN network element is comprised of an ODU switch and a ROADM. As mentioned earlier, whether the ODU switches operate entirely on the electrical domain, the ROADM operates only on the optical domain. Because the OTN networks operate in the these two physical domains, its architecture is usually called translucid. Figure 4 shows a network element characteristic of OTN networks. ODU switches are compatible with a wide range of different client signals. Once the ODU frames are generated, ODU switches groom and switch them dynamically, optimizing the transport of traffic in the network. This process is called traffic grooming. In the backwards direction, optical signals generated in the DWDM network also go through ODU switches to be delivered to their respective client cards. The line cards include OTN multiplexers/demultiplexers and transceivers, which are uniquely responsible for O/E (Optical to Electrical) and E/O (Electrical to Optical) conversion.

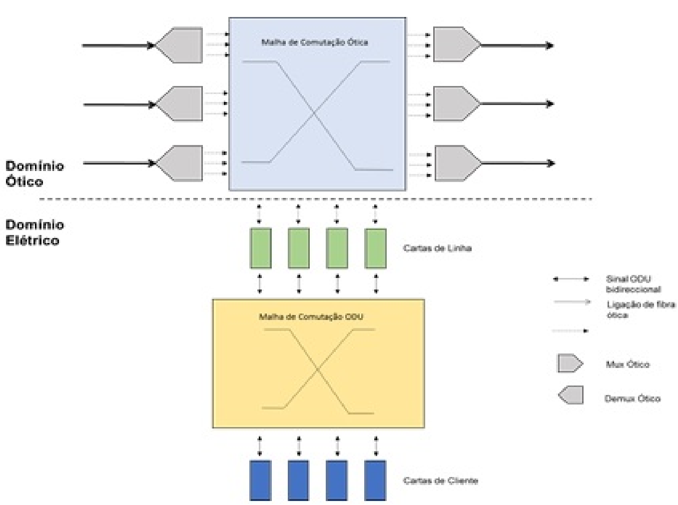

Fig. 4. Translucent network element architecture

Besides translucent architecture, there are also the transparent and opaque architectures. A transparent node architecture performs the switching process only on the optical domain, and makes exclusive use of ROADMs for that matter. As such, wavelengths are directed from origin to destination bypassing all the intermediate nodes in the optical domain, using only one lightpath. In contrast, opaque networks perform the switching only in the electrical domain using ODU switches.

C. ROADMs - Reconfigurable Add and Drop Multiplexers

ROADMs have the role of performing the optical switching of wavelengths in OTN networks or directing the optical signals to the electrical domain for regeneration or grooming of traffic. ROADMs make use of an device called WSSs (Wavelength Selective Switches) which allow the interchange of wavelengths in their input and output ports and well as multiplexing and optical switching functionality. Recent technology are made the ROADM a key piece of equipment in optical transport networks because of its high degree of flexibility and versatility as they be implemented in many different ways. In fact, ROADMs can be classified in one or more than one of the following three categories:

- Contentionless - Avoids blocking of wavelengths when they converge to the same input port of the WSS device;
- Colorless - Allows the remote configuration of wavelength grouping to any add/drop port;
- Directionless - Allows the routing of wavelengths to all possible directions of the switching node.

III. RWA, TRAFFIC GROOMING AND MULTIPERIOD PLANNING

The planning of optical transport networks depends strongly in three key processes: routing, wavelength assignment and traffic grooming. In OTN networks, routing consists in defining a set of links for each lightpath to traverse. Furthermore, the wavelength assignment consists on the assignment of a wavelength to each lightpath in the network. This problem as a whole is called RWA (Routing and Wavelength Assignment). Finally, the traffic grooming allows the grouping of lower granularity client signals in an unique lightpath providing higher bandwidth efficiency. The planning process also depends on the type of incoming traffic, in particular if it is static or dynamic traffic. Static traffic is known *a priori* and can be viewed as a static traffic matrix whereas dynamic traffic is uncertain and has to be routed incrementally, as link requests arrive to the network. Also, contrarily to the static traffic scenery, dynamic traffic demands have a specific duration, and lightpaths established to serve them can be freed once these duration is satisfied. In this work, both traffic approaches, static and dynamic, have been used for the comparison of different grooming strategies.

The planning process also depends on the time horizon and the amount of resources one should allocate in each time period along the network lifespan. In this work, a study was conducted in order to compare three multiperiod strategies. These are explained in the last subsection of this chapter.

A. Routing and Wavelength Assignment

Three routing strategies which have been receiving particular attention are the following:

- Fixed Routing;
- Fixed-Alternate Routing;
- Adaptive Routing.

In fixed routing, the connections are always routed through fixed and predefined routes for each pair of network nodes. In Fixed-Alternate Routing, for each traffic demand, several fixed paths are taken into consideration. This approach has the advantage of providing some flexibility regarding the choice of the routing path. For example, the k-shortest paths algorithm, which is encompassed in this set of routing strategies, allows for the establishment of routing paths with less regeneration requirements. Finally, the Adapting Routing approach allows for the dynamic establishment of routing paths, i.e., the path is chosen depending on the current network state [6].

The wavelength assignment is performed before, or in parallel with the routing process. However, before proceeding with the assignment of wavelengths, one can take into account the length of each lightpath subject to selection. For example, the Shortest Path First strategy prioritizes the shortest lightpaths so that these are the first subjected to the wavelength assignment. Other approach is the Longest First, which prioritizes the longest lightpaths. Once the lightpath selection order is defined, the wavelength assignment is performed.

The developed planning tool used in this work encompasses three wavelength strategies:

- First-Fit;
- Random;
- Most Used/Least Used.

In First-Fit strategy wavelengths are ordered and each lightpath attempts to select the lowest order wavelength. If the lowest order wavelength is already being used in some lightpath, the algorithm will attempt to select the next wavelength, and so forth. The Random approach, like the name implies, assigns the wavelength to each lightpath in a random way, with no specific criterion, after searching for the available wavelengths in each lightpath. Finally, the Most-Used algorithm selects the most used wavelength in all the network. Although the developed planning tool supports these three approaches, all the results presented in this work are obtained by using the First-Fit algorithm.

B. Traffic grooming

As the WDM technology is evolving, the gap between the channel capacity and the bandwidth of a typical traffic demand is increasing. If all the bandwidth associated to a certain wavelength is totally dedicated to a single traffic request, a huge capacity can be wasted, which is highly inefficient. One can solve this problem by grooming (or multiplexing) the traffic demands efficiently.

Given a set of network parameters, the grooming of traffic consists on the establishment of lightpaths in order to satisfy the connection requirements. Generally, this mechanism is divided into four steps:

1) Determination of the virtual topology, which is comprised of lightpaths;
2) Route the lightpaths over the physical topology;
3) Wavelength assignment to the lightpaths;
4) Routing the traffic on the virtual topology.

When the traffic is static and there are enough resources in the network to satisfy all the traffic requests, the main goal is to minimize the cost of the network (for instance, minimize the number of used wavelengths). In case the resources are insufficient, the goal is maximize the traffic flow in the network [7].

It is worth mentioning that in the case of static traffic all the input data is known *a priori*. This allows for the use of ILP (Integer Linear Programming) formulations to solve the grooming problem. By using ILP, one can have an optimal overall solution to the grooming process, however, ILP formulations suffer strongly from scalability problems. This downside of ILP makes the heuristic algorithms a good alternative for solving grooming problems in large networks.

C. Multiperid planning strategies

During the lifespan of a network, changes may occur regarding equipment costs, available technology and also the characteristics of the incoming traffic to route in the network. This changes can influence the performance of the architectures initially deployed. Therefore, the development of strategies which allow for the planning of multiple periods of time during the networks lifespan is vital for the efficient use of resources. The three multiperiod strategies studied in this work are the following:

- All Periods Planning;
- End-Of-Life Planning;
- Incremental Planning.

In All-Periods Planning all the time periods are optimized in a single optimization step. This approach requires knowledge about the client traffic in all the time periods. The End-Of-Life approach also requires the knowledge of the client traffic in all the periods, but, it only aims for optimizing the planning process for the end of the last time period. Finally, in Incremental Plannnig, the optimization is achieved for every individual period. Figure 5 shows a scheme of these three multiperiod planning strategies where the red marks indicate when the planning process is performed [3].

IV. Routing Algorithms and Regeneration

Before the grooming process takes place, it is convenient to use routing algorithms to obtain several candidate routes for each node pair. In this work, for the fixed routing scenario, the well known Dijkstra algorithm was implemented. As for the fixed-alternate routing scenario, the chosen algorithm was k-shortest paths [8]. The developed planning tool allows the user to choose three different types of metrics:

1) Minimum Number of Hops;

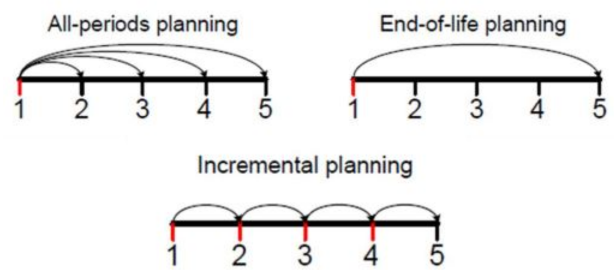

Fig. 5. Multiperiod Planning Aproaches [3]

2) Minimum Distance;
3) Minimum Signal Degradation.

The use of the first metric only takes the number of hops into account. The second metric searches for paths with the minimum distance, independently of the number of hops. The third metric introduces a new parameter which is summed to the total cost for each hop in the path, which is called "per hop reach penalty" (in km). That makes the third strategy a mix between the first two. The developed planning tool gives freedom to the user so that he can choose the "per hop reach penalty" he thinks is most appropriate. The main goal of each metric is to find paths which require less regeneration requirements. This is essential because it is known that the total cost of the network is largely influenced by the amount of electrical terminations (where the regeneration process occurs).

Once the shortest paths are known, it is necessary to determine the regeneration requirements for each node pair and also, to validate each path to be sure that the regeneration point occurs before the signal maximum reach (distance in which the signal needs to be regenerated). In order to perform this task, the algorithm of Figure 6 was implemented.

Definitions and terminology:

- sd — Origin and destination node pair , with $s, d \in V$
- ij — Phisical link $e_{ij} \in E$
- k — k-th shortest path between s e d
- $fiber\_reach$ — Maximum signal transmission reach
- d_{ij} — Length of the physical link e_{ij}
- d_{last_3R} — Path length since last regeneration point
- $minOEO^{sd,k}$ — Minimum number of 3R regenerations required in k-th shortest path between s and d.
- $phrp$ — Per hop reach penalty

Algorithm:

1. $d_{last\_3R} := 0$
2. $minOEO^{sd,k} := 0$
3. Determines k shortest paths between s and d
4. Loop - For each pair sd
   5. Loop - For each path between s e d
      6. Loop - For each physical link e_{ij} in the path
         7. If $d^{ij} + phrp > fiber\_reach$
            8. Path is blocked and returns to step 5
         Else
            9. If $d_{last\_3R} + d^{ij} > fiber\_reach$
               10. $minOEO^{sd,k} = minOEO^{sd,k} + 1$ e $d_{las\_3R} = 0$
            Else
               11. $d_{last\_3R} = d_{last\_3R} + d^{ij} + phrp$

Fig. 6. Calculation of the regeneration requirements per node pair

For each path, the algorithm calculates the minimum number of regenerators based on the distance d^{ij} from origin to destination nodes and the "per hop reach penalty", $phrp$. In the end of the algorithm, the minimum number of regenerators calculated, $minOEO$, is assigned to a field of the data structure which holds the paths calculated by the k shortest paths. The obtained results are further used by the planning tool so that in the grooming process, when traffic demands arrive, they are mapped into the paths with less regeneration requirements.

In order to study the impact of each implemented metric options in regeneration requirements, a study was conducted using networks with varying parameters. The obtained results for network UBN are presented in figures 7 and 8. The network was used with a maximum signal reach of 3000 km and 3500 km. The number of alternate paths between node pairs was chosen to be 10 and the "per hop reach penalty", 80 km.

As expected, the results indicate that for greater maximum signal reaches, less regeneration is required. In regard to the use of the different metrics, we observe that for k<5 the metric which generates more 3R regeneration is "Number of Hops". However, as k is increasing, the algorithm is naturally going to choose paths with less distance. As a consequence, for higher k, the difference in results between the different metrics disappears. In our case, that happens for k>5. As for the the other metrics: "Distance" and "Signal Degradation", there is no difference in terms of regeneration requirements because 80 km of $phrp$ is not enough to make an impact on results. To illustrate the benefits the third strategy would make, the results were also obtained for 120 km of $phrp$ (which is exaggerated and was considered only for comparison purposes). In this last case, we can already observe some differences in results. For example, in Figure 7, for k=2, there is a difference of 7 regenerators.

We conclude that in the context of translucent networks the best solution is the choice of a criterion which takes in consideration the distance between origin and destination. However, the signal degradation can also be taken into account in some cases in order to lower the cost, even if generally it does not make much of an impact in results.

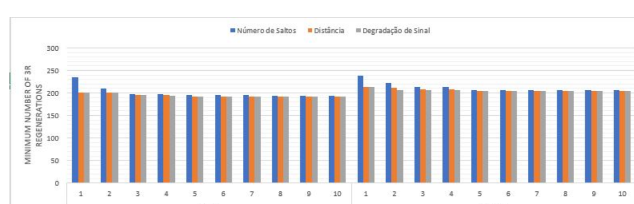

Fig. 7. Minimum number of regenerations for a signal maximum reach of 3000 km - Network UBN

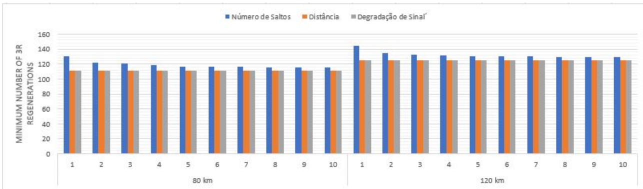

Fig. 8. Minimum number of regenerations for a signal maximum reach of 3500 km - Network UBN

V. Mapping of the client Traffic - Traffic Grooming and Multiperiod Planning

In this chapter the main focus is the analysis of different grooming strategies. Before the presentation of results, there will be a brief description of the implemented grooming process and each strategy, as well as their main goal in the grooming process and their potential impact in the overall end results.

A. Implemented grooming process

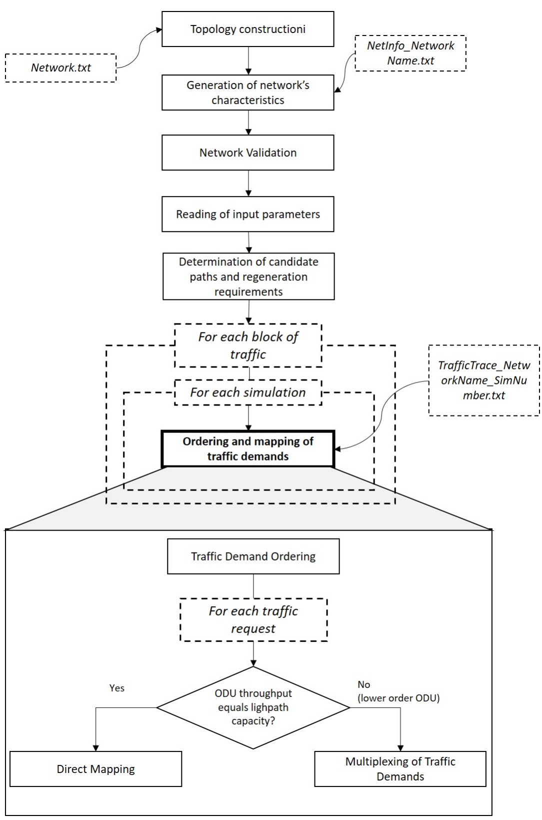

Fig. 9. Block diagram of the implemented planning tool

The implemented planning tool executes the series of blocks presented in Figure 9. In the beginning, two files are read, one for the topology construction of the network, and other for the network characteristics such as the capacity of the installed fibers or type of ROADMs in network nodes. Then, the network is validated i.e. one certifies that any OMS's distance does not exceed maximum signal reach, including the per hop reach penalty (as in Fig.6). If this validation was not performed, there would be blocked demands because some signals could not reach their destination. After this validation, the user should introduce the chosen parameters regarding the routing, regeneration and grooming strategies. The next step consists on the determination of paths which are going to be alternatives for the lightpath establishment in the grooming process. Finally, the traffic demands are ordered and mapped into the network. It is important to note that in some cases the traffic demand throughput can be equivalent to the lightpaths capacity. In this scenario, it is impossible to aggregate several traffic signals into a single lightpath, and therefore, the developed planning tool allows to directly map the signal into a lightpath. Obviously, this lightpath will become unavailable to aggregate more client signals, as its whole capacity is used by a single traffic demand. Other case is when the lightpaths capacity is greater than the traffic demand's throughput, and allows to aggregate more than one client signal. Like mentioned in section III - B, the process which aims to aggregate and organize the traffic demands in an efficient way is called traffic grooming. For this process to be efficient, one must have access to a set of strategies which can generate better results based on different networks and traffic characteristics.

B. Lightpath selection strategy

In the developed planing tool was implemented the possibility of choosing a strategy for the determination of candidate lightpaths for the mapping of client traffic. In particular, the following four strategies were implemented:

1) Lightpaths over static pre-determined end-to-end paths;
2) Any lightpths, without restrictions;
3) Any lightpath with restriction regarding number of regenerations;
4) Any lightpath with restriction regarding the number of regenerations, plus a number of candidate available lightpaths.

The first criterion establishes that the lightpaths should be restrained to the static paths generated offline(paths generated by Dijkstra or k shortest paths algorithm). Figure 10 illustrates the use of this strategy in a sample network. The generated static paths determined by the routing algorithms are represented in bold upon which the establishment of lightpaths (represented in yellow) is allowed. As the Figure shows, this strategy does not allow the establishment of lightpaths where there are no predetermined static paths. Therefore, any other lightpath previously established, even if they have enough capacity to hold the traffic demand, should not be included in the auxiliary graph of lightpaths.

The second strategy allows the use of any lightpaths which have been previously established in the network and have residual capacity to hold the traffic demand. As Figure 11 shows, whether lightpaths have been established in predetermined static paths or not, their usage is allowed. The third and fourth strategies are similar to this last one. The only difference is the existence of a limit of lightpaths that we are allowed to use. That limit as to do with the number of regenerators previously determined for each path in the network, plus two lightpaths of tolerance.

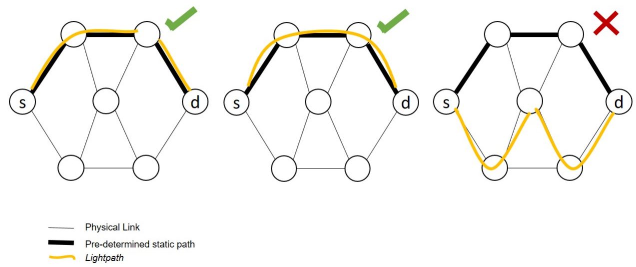

Fig. 10. Use of strategy 1 in a sample network

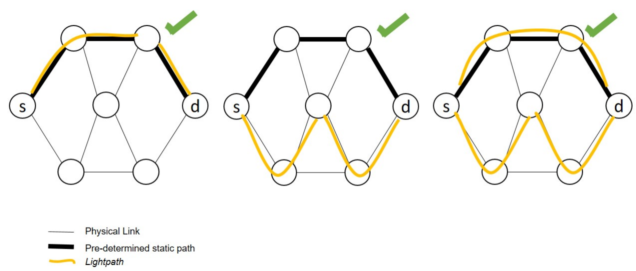

Fig. 11. Use of strategy 2 in a sample network

C. Traffic grooming results for dynamic traffic

In this subsection one presents the results obtained with the developed planning tool using different strategies which can potentially influence the grooming process, given dynamic client traffic as input to be mapped into the network.

1) Impact of routing metrics for in the grooming process: In order to study the impact of the routing metrics for static paths establishment in the grooming process, a simulation was performed using NSFNET network with input traffic signals ODU-0 and ODU-1 and a line capacity equivalent to OTU-4 (100 Gb/s). Traffic demands vary between 1000 and 5000 and the routing algorithm for establishing static paths is Dijkstra (k=1). The results for the number of line interfaces in each case are shown in Figures 12. Each figure shows that, independently of the chosen metrics, there is not a defined pattern which allows to conclude that a certain metric provides better results than other. The number of line interfaces must be directly linked to the number of used regenerators in the network, as well as the choice of different grooming points. The obatined results show that the number of line interfaces is not very affected by the chosen metrics of the routing algorithms for static paths establishment. This happens because there is not much difference in terms of regeneration requirements, independently of the chosen metric.

2) Impact of lightpath selection strategies: To study the impact of the lightpath selection strategies in traffic grooming, NSFNET and UBN networks were used with a line capacity of OUT-5 (400 Gb/s) and as input, the client traffic was ODU-0 (1.25 Gb/s) and ODU-3 (40 Gb/s) signals. The number of

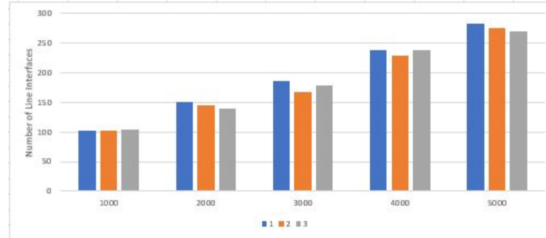

Fig. 12. Number of line interfaces as a function of the number of traffic demands - network COST239

input client demands simulated was 100, 1000 and 10000. The results presented in this subsection are just relative to the use of the first and second lightpath selection strategies because the third and fourth ones are just variations of the second.

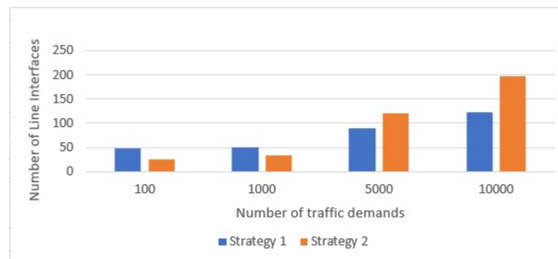

Fig. 13. Number of OTU-5 interfaces for ODU-0 traffic demands - NSFNET

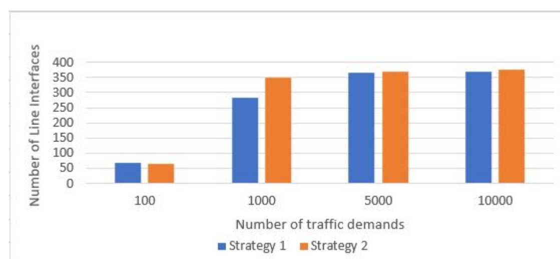

Fig. 14. Number of OTU-5 interfaces for ODU-3 traffic demands - NSFNET

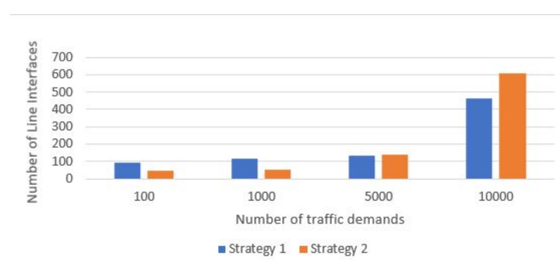

Fig. 15. Number of OTU-5 interfaces for ODU-0 traffic demands - UBN

The results obtained for these two networks, in respect to the used line interfaces, are represented in Figures 13 to 16. We can observe that for ODU-3 traffic the second strategy generates better results for 100 demands in both networks. However, when 5000 demands are considered, the first strategy

Fig. 16. Number of OTU-5 interfaces for ODU-3 traffic demands - UBN

is the one which obtains less line interfaces in both cases. The same stands for 10000 demands. This behavior shows that although the first strategy establishes more lightpaths in an initial stage, it will than fill them progressively, generating less usage of line interfaces in a long term basis. On the other hand, when we consider client signals of lower traffic, in this case ODU-0 signals, the second strategy obtains better results not only for 100 demands but also for 1000, even though the tendency is that the first strategy will generate better results as the number of traffic demands increase. Nonetheless, these results allow us to conclude that the second strategy is only indicated for cases when the line capacity is high and the traffic signals have low throughput. We can also conclude that the first strategy is more indicated for dealing with large amounts of traffic demands.

D. Comparative analisys of multiperiod planning approaches - Static traffic

In this subsection will be presented results relative to be three multiperiod strategies mentioned in section III - C. For each simulation, we considered 4 periods of time and the following traffic forecast: 1000 ODU-2 demands; 200 ODU-3 demands and 40 ODU-4 demands. The real traffic, i.e., the traffic which actually ends up being the input to the grooming process was studied in three different scenarios:

1) Real traffic corresponds to the forecast traffic.
2) Change of the origin and destination nodes of
   - 30% of all demands;
   - 70% of all demands.
3) Change of client signals:
   - Decrease half of ODU-4 signals to ODU-3 (overestimation);
   - Increase half of ODU-3 signals to ODU-4 (underestimation).

The results shown in Figure 17 confirm that AP obtains the best overall results for all considered periods. This happens because the planing process is done in such a way that the final result should be the best possible from period 1 to each of the other periods. Furthermore, as expected, EOL generates the worst results in the first period, but it progressively improves as it reaches the final period. Finally, the "Incremental Planing" approach predictably gets the the best results for the first period (along with AP) as its main goal is the generation of the best results in the short term.

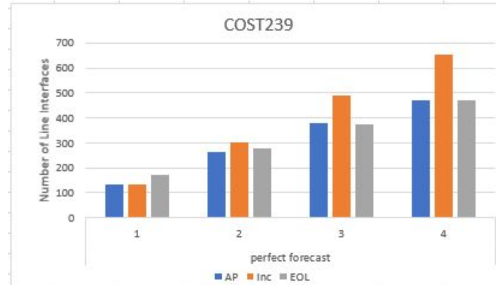

Fig. 17. Number of obtained OTU4 line interfaces for each of the multiperiod strategy - perfect forecast (1st scenario).

Figure 18 shows the impact of the change of origin and destination nodes relatively to the perfect forecast scenario. The results show that the strategy which better handles this changes is "Incremental Planing". One the other hand, EOL is the one which deals worse origin and destination nodes change. Even so, it was verified that on the long term AP and "Incremental" approaches were the ones which generate better results in this scenario.

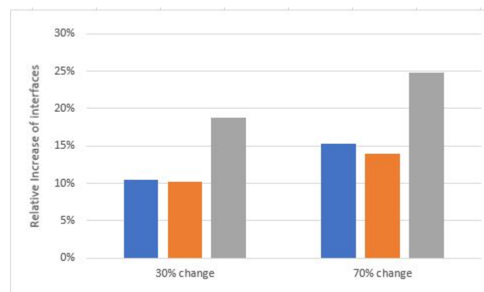

Fig. 18. Relative variation of OTU-4 line interfaces in respect to the perfect forecast scenario for each multiperiod strategy - change of client signals

Concerning the impact of the underestimation and overestimation of client traffic in the planning process, Figure 19 shows the relative variation of the number of line interfaces in respect to the perfect forecast scenario. In this case, the results show that the all considered multiperiod strategies deal badly with throughput unpredictability. In overestimation, the relative increase of line interfaces is about 40%, which is considerably high. One the other hand, in overestimation, although the real traffic is much lower in throughput comparing to the forecast, the number of relative decrease is not high, on the contrary, is about only 5%.

VI. Conclusion

With the rapid increase of client traffic and the evolution of technologies which have been influencing that growth, it is more than ever necessary that the operators proceed to a careful planning of the networks in order to meet the requirements, as well as guaranteeing a good service quality and an efficient use of the available resources. This planning process is usually executed using planning tools in order to virtually generate traffic to be mapped in the networks. In this

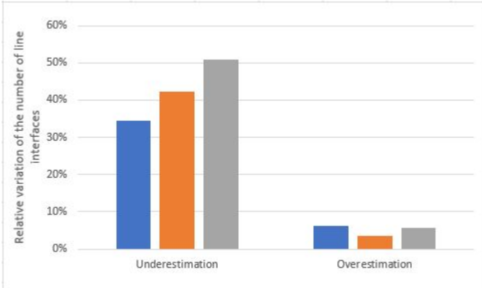

Fig. 19. Relative variation of OTU-4 line interfaces in respect to the perfect forecast scenario for each multiperiod strategy - overestimation and underestimation of traffic

work, a planning tool was implemented and adapted in order to study several strategies and their influence in the overall results of the planning process.

The study of the impact of the three implemented metrics of the routing algorithms for the establishment of static paths showed that for k<5 paths, the metric which generates higher regeneration requirements is ”Minimum Number of Hops”, whereas the other two obtain similar results whatever the case. Concerning the number of line interfaces, the study carried out using dynamic client traffic showed that the ”Minimum Number of Hops” metric obtained slightly worse results, probably due to the higher regeneration requirements.

The study of the lightpath selection strategies allowed us to conclude that the strategy ”Lighpaths over static pre-determined end-to-end paths” is more suitable for grooming higher order ODUs, whereas ”Any lightpaths, without restrictions” is more efficient for the grooming lower order ODUs.

Three multiperiod strategies were also subject to study using different scenarios and we could conclude that AP produces the best possible results for all the considered periods; Incremental Planning obtains better results in earlier periods, however, because it focuses on individual periods, it is not a good solution for long term planning; The EOL approach is not a good solution for earlier periods planning, but it achieves the best possible results in the end of the last period. We could also conclude that Incremental Planning is the strategy which deals better with origin-destination pair change in demands, as well as in underestimation of traffic throughput.

Acknowledgment

I would like to thank Professor Joao Pires for all the given support and direction throughout this work as well as Doutor Joao Pedro and Doutor Rui Morais whose contribution was also essential.

References

[1] H. Zhu, ”A Novel Generic Graph Model for Traffic Grooming in Heterogeneous WDM Mesh Networks,” IEEE/ACM TRANSACTIONS ON NETWORKING,, vol. 11, 2003.
[2] R. Vaez-Ghaemi, ”Next-Generation Optical Transport Networks,” JDSU, 2010.
[3] R. Morais, Planeamento e Dimensionamento de Redes de Multicamada, Tese de Doutoramento, Universidade de Aveiro, 2015.
[4] S. Whitehead, OTN - What is it and how does it work?, Anritsu, 2014.
[5] J. Pires, ”Optical Transport Networks,” em Redes de Telecomunicaes - Apontamentos , Cap. 5, 2015
[6] J. M. Simmons, ”Routing Algorithms,” em Optical Network Design and Planning, Springer, p. 62, 2008.
[7] K. Zhu, Traffic Grooming in an Optical WDM Mesh Network, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, vol. 20, 2002.
[8] E. Martins, ”An Algorithm for Ranking Optimal Paths,” 2000.