Optimization of Regenerator Placement and Wavelength Assignment over DWDM Networks

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Abstract-- The developed work deals with the optimization of the regenerator placement (RP) and wavelength assignment (WA) problem in order to minimize the total cost of optical DWDM networks. The study is performed over translucent backbone optical DWDM networks where regeneration can only occur at specified points of the network. Several algorithms based on optimal and heuristic methods, were implemented in order to minimize the total network cost.

Regarding the RP problem, two heuristic algorithms were developed. Both place the minimum number of 3R regenerators possible in order to keep the connection Optical-Signal-to-Noise-Ratio (OSNR) value above the receiver’s threshold value. A novel RP procedure, which allows for maximization of the number of regenerators on nodes, is introduced.

Regarding the WA problem, two algorithms based on optimal methods (based on integer linear programming, ILP, and on linear programming formulations) and two heuristic algorithms were developed. The heuristic approaches were based, respectively, on the First-Fit (FF) and Most-Used (MU) methods and their results were compared with the optimal ones.

Conclusions were obtained over different scenarios of optimization: a single-transponder RP and WA scenario, a multi-transponder RP and WA problem considering also transponder selection optimization, a multi-transponder RP and WA problem considering multiple paths per traffic demand, and a multi-transponder path-protected RP and WA scenario.

Index Terms-- DWDM Networks Planning, Regenerator Placement, Wavelength Assignment, Transponder Selection optimization, Cost Minimization, Optical Path-Protection

I. INTRODUCTION

Over the years communication has become a more and more relevant issue and efforts were made in order to develop networks and to respond to the rapid growth of society and customer needs. A remarkable development came with the introduction of optical technologies into the telecommunication industry which caused the traditional electrical networks to migrate to a whole new networking dimension.

An optical network is typically composed by several elements. The optical terminal multiplexes (combines) the signals from all of the transponders to be transported through a single network fiber. Each transponder generates a different wavelength so that they do not interfere with each other after being together by the terminal. Optical amplifiers placed in order to compensate the loss in optical power while the signal is travelling along the fiber or by passive components. An Optical Add-drop multiplexer (OADM) is an element capable of adding/extracting wavelengths to/from a fiber without having to electronically terminate all of the wavelengths comprising the WDM signal. The all-optical switch are capable of cross connect optical signals from any input to any output without any O-E or E-O conversion. The input signal is demultiplexed, then each frequency/wavelength is switched by an optical switch and multiplexed back together again before sent through the fiber.

As the signal propagates over the network, there are some unwanted effects that degrade the Quality of Transmission (QoT) degrade and compromise the integrity of the signal before it arrives at the destination point at the optical receiver where it is recovered from corruptive additives. The transmission quality can be measured by two methods: The received Optical- Signal-To-Noise-Ratio (OSNR), which is defined as the ratio between the signal level and the noise level at the receiver side, and the Bit-Error-Rate (BER), which is the probability of receiving an incorrect bit.

To recover from the effect of and optical impairment a keep a satisfactory QoT, a signal must be regenerated. In this study is only considered translucent optical network, this is, signal regeneration is only performed at specific points on a network. Thus, one is able to reduce the number of regenerators which are one of the most influencing factors in the network cost. In order to assure QoT, the connection’s OSNR must be always above the receiver sensitivity (minimum OSNR value allowed by the receiver in order to fully recover the optical signal). The study considers only 3R regenerators which are able to perform re-amplification, re-shaping and re-timing to the optical signal.

Another factor related to the number of regenerators and can be optimized in order to minimize the network cost is the wavelength assignment. An effective WA approach makes use of the propagation characteristics of each wavelength to assign wavelengths to traffic demands. Wavelengths performance can be evaluated in terms of optical reach, this is, the distance the signal can propagate before its quality degrades to a level that needs regeneration. Higher wavelengths have longer optical reach and vice-versa.

Another relevant aspect that must be taken into account when planning and design an optical network is the Quality of
Service (QoS). The only way to assure high quality of service is by protecting networks from fiber cuts, equipment failures, software errors, or even environmental causes. In this study it is considered 1+1 dedicated path protection which consists of having a working and back-up path for each traffic demand. At the transmitter, the signal is replicated and the same signal is transmitted through both working and back-up paths. Besides, the paths must be node-and-link-disjoint paths, that is, they cannot have any link or intermediate node in common. An example of a network design study is presented in [1], where the impact of the optical reach on the network cost is analyzed. Among other results, they were able to conclude that optical reaches between 2500 km and 3000 km minimize the network cost. Article [2] presents ILP formulations to address a routing problem with path-protection and a RP problem which are solved separately. Regarding the routing problem, the article introduces a novel notion of disjoint paths, called shared-risk-link-group disjoint paths, meaning that, the working and restoration paths cannot share any link or any physical conduit which could be cut and affect multiple optical fibers. A different approach for optimizing RP is considered in [3], where impairment-awareness is incorporated into the problem. Two different approaches are considered: distance-based and impairment-aware-based RP. It is demonstrated that, compared with the second approach, the distance-based criterion for the RP can place redundant regenerators, this is, more regenerators than the minimum to fulfill the quality of transmission required. Another relevant problem, which has been reported in the literature, is the WA. Article [4] presents results and arguments which shows the relevance of considering the RP when addressing the routing and wavelength assignment (RWA) problem. According to article [5], authors have studied the impact of impairments on translucent static networks and propose a strategy for the routing, wavelength assignment and regenerator placement problem. Firstly it solves the RWA problem and then, it verifies the QoT requirements by monitoring BER at each intermediate node and by placing a regenerator at the exact previous node before minimum allowed BER is reached (BER estimation is detailed in [6] and [7]). Based on a dynamic traffic scheme, paper [8] presents a novel crosstalk-aware WA approach which selects wavelengths based on a quantitative pre-evaluation of the crosstalk influence.

II. PROBLEM CONSIDERATIONS

A. Network considerations

This study considers translucent backbone optical networks represented by a connected, simple graph \( G = (V, E) \), where \( V \) denotes the set of nodes and \( E \) denotes the set of links. Each fiber link is able to support a common set \( C = \{1, 2, ..., W\} \) of wavelengths, where \( W \) denotes the maximum number of 40 wavelengths ranging in the C-band from 1529.55 nm to 1560.61 nm, or in frequencies, from 192.10 THz to 196.00 THz with 100 GHz spacing.

1) Studied networks

<table>
<thead>
<tr>
<th>Network</th>
<th>Nodes</th>
<th>Links</th>
<th>Nodal Degree</th>
<th>Total km of network fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>COST239</td>
<td>11</td>
<td>26</td>
<td>4.727</td>
<td>24,072</td>
</tr>
<tr>
<td>NSFNET</td>
<td>14</td>
<td>21</td>
<td>3.0</td>
<td>45,432</td>
</tr>
<tr>
<td>EON</td>
<td>19</td>
<td>37</td>
<td>3.895</td>
<td>68,130</td>
</tr>
<tr>
<td>UBN</td>
<td>24</td>
<td>43</td>
<td>3.583</td>
<td>85,800</td>
</tr>
</tbody>
</table>

There were studied four different backbone optical networks with different characteristics as shown in the following table I.

In this paper, results are only presented for COST239 network with the highest average nodal degree among studied networks.

2) Traffic model

The study considers 10 Gbps traffic demands with a static traffic model given in table II.

Table II-Considered configuration of traffic demands

<table>
<thead>
<tr>
<th>( d )</th>
<th>( s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
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<tr>
<td>3</td>
<td>4</td>
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<td>10</td>
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<tr>
<td>10</td>
<td>11</td>
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<tr>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

3) Network elements

Since all network nodes correspond to path terminations, they must support Add/Drop functionalities, that is, all network nodes are composed by OAMD, if nodal degree (number of links connected to the node) is 2, or composed by OAMD-MD, if the degree of the node is higher. For optical amplification Erbium Doped Fiber Amplifiers (EDFA) are used and placed along the fiber-link at each 80 km. For regeneration purposes, OEO transponders are used.

4) Considered transponders

<table>
<thead>
<tr>
<th>Transponders</th>
<th>Output Power [dBm]</th>
<th>OSNR(_{threshold}) [dB]</th>
<th>Normalized Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>XFP 40km</td>
<td>-16.0</td>
<td>20.86</td>
<td>1.0</td>
</tr>
<tr>
<td>Regio</td>
<td>-16.0</td>
<td>20.09</td>
<td>1.52</td>
</tr>
<tr>
<td>XFP C Tunable</td>
<td>-16.0</td>
<td>19.07</td>
<td>1.96</td>
</tr>
<tr>
<td>LH</td>
<td>-16.0</td>
<td>16.8</td>
<td>3.45</td>
</tr>
<tr>
<td>LHD2</td>
<td>-16.0</td>
<td>16.8</td>
<td>5.47</td>
</tr>
</tbody>
</table>
B. Signal propagation considerations

In this study the QoT is estimated based on the OSNR value of each fiber span (each span is 80 km long and separates amplification points) obtained by equation (1).

\[
\text{OSNR} = \frac{\text{Pin}}{\text{NF} \times f \times B}
\]

(1)

where, 
- \( \text{Pin} \) = average amplifier input signal power [W]
- \( \text{NF} \) = optical amplifier noise factor
- \( h \) = Planck’s constant \( 6.626069 \times 10^{-34} \) [Js]
- \( f \) = optical signal center frequency [Hz]
- \( B \) = optical channel bandwidth [Hz]

For links with more than one EDFA, the OSNR of the link is obtained from the OSNR of each span given by (2).

\[
\text{OSNR}_{\text{Total}} = \frac{1}{\text{OSNR}_{\text{Source}}} + \frac{1}{\text{OSNR}_{1}} + \frac{1}{\text{OSNR}_{2}}
\]

(2)

where OSNR\text{Source} is the OSNR measured at the output and OSNR\text{i} is the OSNR value measured at the end of the \text{i}\text{th} span.

From the obtained OSNR values and wavelength performance over the fiber, one can conclude that OSNR values decrease as the number of spans increases due to amplified spontaneous emission noise power increase and, OSNR degrades faster as channel frequency increases because higher frequencies experiences higher attenuation.

The performance of wavelengths over an optical link is shown in Fig. 2 measured at different points of a fiber (1 span mean 80 km).

![Connection’s OSNR over a fiber link](image)

Fig. 2 – Connection’s OSNR over a fiber link for several frequencies

C. Considered routing strategies

Developing new routing strategies was not the main objective of this work. Thus, at the pre-processing routing stage the methods and considerations presented in [9] are used.

1) Single-path with no protection

In section IV.B.1 and A.2. The routing paths (one per traffic demand) are computed using the known Dijkstra algorithm and a load balancing algorithm presented in [9] which is able to balance traffic and reduce the maximum link congestion over the network.

2) Multiple-path with no protection

In section IV.B.3, the analysis is based on a Dijkstra k-shortest path algorithms presented in [9].

3) Single-path with 1+1 dedicated path- protection

In section IV.B.4, the analysis is based on a node-and-link-disjoint path-protected routing strategy. The disjoint pair represents the working and back-up paths which are active at the same time, this is, RP and WA analysis must be done simultaneously for both paths.

III. Developed algorithms

In this section an overview of the RP and WA algorithms is presented. The RP and WA problem is addressed separately and the following explanation is generic and can be adapted for all studied scenarios: single-transponder single-path scenario, a multiple-transponder single-path, a multiple-transponder and multiple-paths, and a multi-transponder path-protected RP and WA scenario.

A. RP algorithms

Two algorithms were developed to address the RP problem: the Minimum Regenerator Placement (MRP) algorithm and the MRP with node-preference (MRP-NP) one. Regenerators can be placed at pre-defined regeneration candidates which correspond to every network node and specific line-amplification sites at the middle of links. The number of regeneration candidates is variable and controlled by the distance between them (which can be any number multiple of 80 km corresponding to the distance between EDFAs).

The MRP procedure is very simple and analyzes each path separately. One candidate at a time, the algorithm verifies if the connection OSNR at the candidate is above the minimum threshold allowed for the used transponder. If it is the case, no regenerator is needed, otherwise, a regenerator is placed at the previous candidate.

The MRP-NP runs MRP on background in order to know the minimum number possible of regenerators for each path. Then, it runs an iterative method in order to shift link-regenerators (the ones placed along links) to network nodes. This procedure is motivated by the lower cost of placing regenerators on network nodes when comparing to the cost of having regenerators along links.

B. WA algorithms

1) Mathematical formulations

It can be resumed by:

- **Parameters:**
  - \( s, d \in V \): source destination network nodes;
  - \( \lambda \): a wavelength;
  - \( e \in E \): a network link;
  - \( p \): Alternative path index;
  - \( t \): a transponder.

- **Constants:**
  - \( d_{sd} \): Number of traffic demands from node \( s \) to \( d \);
  - \( n \): Number of required regenerators for a path, wavelength and transponder;
  - \( c_{e} \): Cost of the used transponder \( t \);
  - \( \gamma \): Indicator constant, equal to 1, if path \( \pi \) uses link \( e \), or equal to 0 otherwise.

- **Decision variables:**
  - \( \pi \): Indicator variable, equal to 1, if demand \( d_{sd} \) uses
alternative path \( p \), wavelength \( \lambda \) and transponder \( t \), or equal to 0, otherwise.

**Optimization problem:**

\[
\min_{\pi_{sd}, \lambda, t, p} \sum_{\pi_{sd}} \sum_{\lambda} \sum_{t} \sum_{p} x_{\pi_{sd}}^{\lambda,t,p} + C_t \cdot (R_{\pi_{sd}}^{\lambda,t} + 1) \tag{3}
\]

subject to

\[
\sum_{\lambda} \sum_{t} \sum_{p} x_{\pi_{sd}}^{\lambda,t,p} = d_{\pi_{sd}}, \text{ for all } (s, d) \text{ pairs} \tag{4}
\]

\[
\sum_{\lambda} \sum_{t} \sum_{p} x_{\pi_{sd}}^{\lambda,t,p} \delta_{\pi_{sd}}^{\lambda,t} \leq 1, \text{ for every link and } \lambda \tag{5}
\]

\( x_{\pi_{sd}}^{\lambda,t,p} \) is binary for all \((s,d)\) pairs, \( t, \lambda \) and \( p \) \tag{6}

The objective function (3) aims to minimize the total cost of the network by adding each demand’s individual cost. The cost of a demand, for the used wavelength, transponder and alternative path, corresponds to the number of transponder pairs (number of regenerators plus the source-destination transmitter-receiver transponder pair) multiplied by the cost of the selected transponder.

The traffic constraints (4) define the number of wavelengths that must be assigned to each routing path. On the other hand, distinct wavelength assignment constraints (5) define which wavelength is assigned to each path regarding the capacity of each link (40 wavelengths). Constraints given by (6) define binary variables for the ILP approach.

2) **Optimal WA algorithms**

Two optimal WA algorithms were developed: one based on Integer Linear Programming (ILP) and other based on Linear Programming with rounding operations (LP+R).

The ILP uses the described mathematical formulation in order to solve the optimization problem.

The LP+R is a little different. It solves the optimization problem as a linear problem changing constraint (6) by:

\[
x_{\pi_{sd}}^{\lambda,t,p} \geq 0, \text{ for all } (s,d) \text{ pairs}, t \text{ and } \lambda \tag{7}
\]

\[
x_{\pi_{sd}}^{\lambda,t,p} \leq 1, \text{ for all } (s,d) \text{ pairs}, t \text{ and } \lambda \tag{8}
\]

Once obtained an optimal solution for the linear problem, it rounds the decision variable which is closer to an integer value (0 or 1) and fixes that variable value. Then, it repeats the same procedure solving the new linear problem until all decision variables are integers. In the end, an optimal solution equal to the one returned by ILP is expected. Although being based on an optimal LP approach, LP+R cannot guarantee an optimal solution due to the rounding procedure.

3) **Heuristic WA algorithms**

Two different heuristic algorithms were developed: Longest Path First (LPF) and Maximum Wavelength Reuse (MWR).

The LPF procedure is based on FF and is described below where a transponder-path pair is a combination of a used transponder on a specific path:

(step 1) Sort every traffic demands according to the distance of the shortest past;

(step 2) Choose the longest non-evaluated demand from the list;

(step 3) Look for all available wavelengths in each alternative path of the chosen demand;

(step 4) Assign the best wavelength (the highest) among the available ones to each alternative path;

(step 5) For each wavelength-path pair, choose the transponder which minimizes the network cost and guarantees QoT;

(step 6) Among all transponder-wavelength-path combination, select the one leading to the lowest network cost.

(step 7) Verify if all demands of the initial list were already analyzed:

Yes: terminate LPF;

No: Go back to (step 2) with the next longest demand from the list.

On the other hand, MWR is based on MU procedure. The motivation behind this scheme is that a wavelength that has already been assigned a lot will be more difficult to use again and, if a scenario arises where a heavily used wavelength can be used, it should be assigned. Its procedure is described below:

(step 1) Sort every traffic demands according to the distance of the shortest path;

(step 2) Choose the longest non-evaluated demand from the list;

(step 3) For each alternative path, look for an available wavelength and a transponders in order to create combinations of wavelength-transponder-path;

(step 4) Among all combinations group the ones leading to the lowest network cost;

(step 5) Among all combinations inside the group, choose the one which contains the most used wavelength until the moment;

(step 6) The solution for the demand is the wavelength, transponder and alternative path of the chosen combination;

(step 7) Verify if all demands of the initial list were already analyzed:

Yes: terminate MWR;

No: Go back to (step 2) with the next longest demand from the list.

IV. Results

A. Analysis of algorithm’s performance

1) Time efficiency of developed algorithms

There were developed and studied six different algorithms: two RP and four WA algorithms. Fig. 13 shows the evolution of the execution time of each algorithm with the number of traffic demands over EON network. Traffic demands are represented in percentage where 100% means that all network nodes are communicating with each other and the other percentages a fraction of this value (corresponds to the traffic matrix presented in Table II).

In Fig.3a, one can see that both ILP and LP+R algorithms show an exponential increase rate with an interesting fact. For fewer traffic demands (less than 80%) ILP goes straight to the solution and is faster than LP+R (which looses too much time rounding variables) and, as the traffic demands increases, the ILP procedure complexity grows much faster than LP+R.

Fig. 3b shows the same results without LP+R and ILP.
algorithms. Now, considering a smaller vertical scale one can see that MRP and MRP-NP experience a well defined linear increase rate with MRP being faster than MRP-NP. On the hand, execution time of LFP and MWR algorithms is almost instantaneous and cannot be perceptible on the graph.

From Fig. 4, one can conclude that, as the distance between candidates gets higher, the number of regenerators increases because the RP algorithms become less able to place regenerators near the optical reach and, the results of both RP algorithms become similar. Besides, Fig.4 shows that MRP-NP is able to minimize the total number of regenerators while maximizing the regenerators on nodes.

2) Performance of the non-optimal algorithms

One of the objectives of this thesis consists in studying heuristic approaches for the problem and evaluating their performance comparing the obtained heuristic results with the optimal ones.

Regarding the RP algorithms, it is not difficult to understand that MRP and MRP-NP are able to place the minimum number possible of regenerators over each path. This is assured by the fact that the distance between regenerators along each path is the optical reach of the signal. In order to guarantee QoT, the distance between regenerators cannot, in any circumstance, be longer than the optical reach of the signal.

Regarding the WA algorithms, the performance of each non-optimal algorithm can be compared with the results obtained by ILP. Surprisingly, the results obtained by LP+R were always equal to the ones obtained by ILP, this is, LP+R is able to yield optimal results for the studied cases.

On the other hand, LPF and MWR were shown to yield results not far from the optimal ones. In the studied cases, LPF obtained results with errors (comparing with optimal results) never higher than 4% and MWR error equal or lower than 3%. This is, the MU approach considered in MWR was able to overcome LPF in all studied networks and scenarios.

B. Analysis of optimization scenarios

The results presented in this section were obtained using solely the optimal algorithms ILP and LP+R.

1) Optimization of the RP and WA problem

At this stage, the optimization scenario corresponding to a single-transponder single-path RP and WA problem is studied. In the next simulations, the XFP C Tunable transponder is used in order to analyze both RP algorithms.

Fig. 5 shows, for 400 or less km between candidates, XFP40Km transponder must always be chosen in order to minimize the total cost of COST239. This result is interesting because, although requiring a larger number of regenerators, the XFP40Km selection originates a lower network cost.
Another relevant result from Fig. 6 comes from the difference in optical reaches which, depending on the distance between candidates, may originate a significant impact in the total network cost.

2) **Optimization of multi-transponder RP and WA problem**

At this stage, the five transponders’ characteristics are considered and algorithms are able to choose different transponders for different traffic demands in order to minimize the total network cost.

Fig. 7 – RP results using (a) MRP-NP and (b) MRP algorithms

As one can see in Fig. 7, the difference between RP algorithms is solely in the number of regenerators on nodes, which is less evident when comparing with the single-transponder scenario (Fig. 4). Another relevant result is the significant drop of the number of regenerators after 480 km between candidates which is motivated by the transponder choice optimization.

Fig. 8 – Transponder selection percentage for COST239 network

As can be seen in Fig. 8, XFP 40km can no longer guarantee QoT for the majority of traffic demands and its selection percentage decreases drastically. Since this sudden drop forces the selection of more expensive transponders with longer optical reach, such as Regio and LH, the number of required regenerators decreases.

Fig. 9 shows the network cost for different distances between candidates comparing the multi-transponder scenario with the single one studied in section IV.A.1. As one can see, the multi-transponder scenario is able to bring significant cost savings, especially for longer distances between candidates.

3) **Optimization of multi-transponder multi-path RP and WA problem**

The multi-path scenario means that each traffic demand has more than one available path to flow and it is chosen the best path (the one that minimizes the demand cost) among a set of k-shortest paths. However, the traffic flow from a demand cannot be separated and is entirely routed through one of the alternative k-paths. In the following simulations, three alternative paths (k=3) are considered.

Fig. 10 – Number of required regenerators over COST239 for both multi-path and single-path scenarios

Since the RP algorithms analyze is the same as before, in Fig.10 is only shown the total number of required regenerators comparing both multi-path and single-path scenarios where the first one is able to reduce the number of regenerators until 480 km between candidates.

Beyond 480 km, the difference in the number of required regenerators in both scenarios can be explained in Fig. 11. Comparing Fig. 8 and 11 one can see that, for a distance between regeneration candidates longer than 480 km, the multi-path scenario is able to select the XFP 40km more often than the single-path one (50% against 38%) which increases the number of regenerators.

However, the higher number of regenerators for longer distances between candidates does not affect negatively the network cost. On the opposite way, Fig. 12 shows that the multi-path scenario is able to reduce the total network cost
comparing with the previous studied scenarios (presented in section IV.B.1 and B.2).

Fig. 12 – Total network cost comparing both multi-path and single-path scenarios

Until this moment, the number of alternative paths per traffic demand was fixed and equal to 3. Fig. 13 shows the total network cost obtained when varying the number of alternative paths, \( k \), comparing with the network cost obtained for the previous studied scenario (single-path multi-transponder RP and WA problem). As one can see, the cost savings yielded by the multi-path one are obvious. For only one path per demands \( (k = 1) \) the single-path scenario is able to yield lower network cost (remember that in the single-path scenario is considered a load-balancing routing strategy) and, as the number of alternative paths increases, the network cost reduces and stabilizes at a certain level. This means that the multi-path scenario is able to yield significant cost savings but only until a certain number of \( k \).

Fig. 13 – Total network cost per number of alternative paths, \( k \).

4) Optimization of the path-protected multi-transponder single-path RP and WA problem

At this stage the impact of considering path protection in optical networks design and planning is studied and compared to the scenario presented in section IV.B.2. As stated in section II.C.3, the working and back-up paths are node-and-link-disjoint and both must be prepared and designed in order to guarantee the required QoT.

As expected, Fig. 14 shows a great increase in the number of required regenerators when considering path protection (the number increases more than twice) because, typically, back-up paths are longer than the working path making the number of required regenerators, due to path protection, to increase for more than the double.

Fig. 14 – Number of required regenerators over COST239 for both single-path unprotected and protected scenarios.

Another consequence of considering node-and-link-disjoint protection paths (this is, longer back-up paths) is the need for selecting expensive transponders. As one can see in Fig. 15, the selecting percentage of LH transponder is much higher in this scenario than in any other one.

The impact of path protection is obviously visible in the total network cost represented in Fig. 16 where the cost increases more than 100% when comparing with the unprotected single-path multi-transponder scenario (studied in section IV.A.2).

V. CONCLUSION

The developed work dealt, fundamentally, with optimization of regenerators’ placement and the assignment of wavelengths in order to minimize the total network cost. Many relevant parameters were evaluated and conclusions are stated and grouped by areas and parameters of optimizations which are: Regenerator placement conclusions, wavelength assignment conclusions, transponder selection optimization and path-protection impact in the total network cost.

Regarding the regenerator placement problem, the algorithms were able to minimize simultaneously the total number of regenerators and reduce the number of regenerators along links. Besides, decreasing the number of regeneration candidates along links (by increasing the distance between candidates) showed to increase significantly the number of required regenerators and total network cost.

Regarding the wavelength assignment problem, the four studied WA algorithms shown different performances in terms of execution time and results. The optimal algorithms (ILP
and LP+R) yielded the same results and completely different execution times, with ILP being faster for fewer traffic demands and much slower otherwise. Thus, it was possible to conclude that an LP+R approach is able to reduce significantly the problem complexity without compromising the results optimality. On the other hand, the results obtained by heuristic algorithms were pretty satisfactory since they yielded results with a relative error never higher than 4%. Also, MWR was able to outperform LPF given its ability to explore wavelengths reuse and maximize the assignment of better wavelengths.

Regarding the transponder selection optimization, the ability to select expensive transponders with longer optical reach to longer lightpaths, and vice-versa, was able to save until 60% (in studied cases) of the total network cost.

Regarding the introduction of dedicated path-protection, one can conclude from the obtained results that it may increase the network cost in 2 or 3 times.

ACKNOWLEDGMENT

Firstly, I would like to thank for all the support and advisory offered by my supervisor J. Pires from Instituto Superior Técnico, and by R. Morais, J. Pedro and J. Santos from Nokia Siemens Networks. This research work would not be finished without their help and support.

Also, to all my friends and family, I would like send the best regards for never stopping to support me and for giving me strength to overcome difficult moments along these last months.

To all of them, thank you.

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