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Path Protection in WDM Networks with Quality of Transmission Limitations

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***Abstract*— We consider path protection in the routing and wavelength assignment (RWA) problem for impairment constrained WDM optical networks. The proposed multicost RWA algorithms select the primary and the backup lightpaths by accounting for physical layer impairments. The backup lightpath may either be activated (1+1 protection) or it may be reserved and not activated, with activation taking place when/if needed (1:1 protection). In case of 1:1 protection the period of time where the quality of its transmission (QoT) is valid, despite the possible establishment of future connections, should be preserved, so as to be used in case the primary lightpath fails. We show that, by using the multicost approach for solving the RWA with protection problem, great benefits can be achieved both in terms of the connection blocking rate and in terms of the validity period of the backup lightpath. Moreover the multicost approach, by providing a set of candidate lightpaths for each source destination pair, instead of a single one, offers ease and flexibility in selecting the primary and the backup lightpaths.**

I. Introduction

In WDM optical networks data are transmitted through lightpaths; that is, all-optical channels that may span multiple consecutive fibers. The problem of establishing a lightpath for a connection request, consists of selecting a route (path) and a free wavelength for serving the connection, and is called routing and wavelength assignment (abbreviated RWA) problem. The objective of the RWA operation is to minimize the network resources used or maximize the traffic served with limited network resources. The majority of RWA algorithms proposed in the literature assume an ideal physical layer, where signal transmissions are considered to be error-free. This is the case in opaque networks, where the signal is regenerated at each intermediate node along a lightpath via optical-electrical-optical (OEO) conversion. However, translucent or transparent networks, where regenerators are only employed at some nodes or at no node at all, the quality of transmission (QoT) of the signal degrades due to physical layer impairments. The signal degradation can occur to the extent that the bit-error rate (BER) makes the signal detection infeasible at the receiver. As a result RWA algorithms that consider the QoT of the candidate lightpaths are important; these algorithm are called impairment aware (IA)-RWA algorithms.

Regarding network failures, there are two types of mechanisms for recovering from faults: i) protection [1], where backup lightpaths are pre-computed and reserved in advance, and ii) restoration [2], where in case of a failure a lightpath is dynamically discovered in order to serve the interrupted connection. The tradeoffs between these two approaches are the fast recovery time and guarantee of recovery for the protection schemes against the efficient use of resources and the flexibility for the restoration schemes. In the protection case, the backup path may either be activated (1+1 protection) or it may be reserved and not activated, with activation taking place when/if needed (1:1 protection). When a backup lightpath is activated, it causes interference and QoT degradation to other lightpaths, while this is not the case when it is not activated.

The importance of QoT and fault tolerance is based on the simple fact that under some scenarios the probability of lightpath reaching an unacceptable level of QoT may be higher than the probability of a lightpath failure, due to a broken link. The former can be considered as a "soft failure", while the latter as a "hard failure". However, both failures make the lightpath useless and the establishment of a new lightpath the only solution. Moreover, in case of protection if the backup lightpath does not have acceptable QoT when the primary lightpath fails, then the backup lightpath is useless and a new lightpath needs to be calculated (restoration). In this way several resource are wasted for a long period of time. These two facts highlight an interesting, new field of research, that is proposing and investigating protection mechanisms that are efficient for impairment constrained optical networks. Such an efficient protection mechanism must be able to both serve as many connection requests as possible, but also should be able to ensure the long survivability, in terms of QoT, of both the primary and the backup lightpaths.

Our work is based on an existing multicost IA-RWA algorithm [3] that is extended so as to select both the primary and the backup lightpaths. In the multicost routing approach, a vector of cost parameters is assigned to each link; then, by defining appropriate operations between these cost parameters, we can calculate the cost vector of a path. Some of the parameters of the cost vector record estimates of the effects of the impairments of the path. The focus of this work is to show that the multicost approach can be quite beneficial for the selection of the primary and the backup lightpaths. This is because the multicost approach provides a set of candidate lightpaths (instead of a single one) for each source destination pair, together with their QoT parameters, which makes easier the joint selection of the primary and the backup lightpaths. In this context, we apply and evaluate different optimization functions that correspond to different IA-RWA algorithms. Moreover, in order to increase the duration of the validity, in terms of its QoT, of the backup lightpaths we propose the differentiation of the way the primary and the backup lightpaths are chosen. In particular, for the selection of the primary lightpath we use actual current network utilization, while for the backup lightpath we use worst case interference assumption. Also, when considering establishing a new lightpath, we check whether it is going to affect the already established primary paths, in which case the lightpath is not established.

Our results show that selecting jointly the primary and the backup lightpaths is a better approach than selecting them sequentially, in particularly for large network loads. In addition, we observe that the usage of the worst case interference assumption for the selection of the backup lightpath reduces the blocking probability. We also discuss the tradeoff between the level of protection (1+1, 1:1, no protection) and the blocking probability.

The remainder of the paper is organized as follows. In Section II we report on previous work. In Section III we give a short description of the physical layer impairments. In Section IV we present the proposed mechanisms used for providing protection in impairment constrained optical networks along with increased survivability of the backup lightpath. Simulation results are presented in Section V. Our conclusions are given in Section VI.

II. Previous Work

Previous studies address the Routing and Wavelength Assignment (RWA) algorithms for various protection schemes [1] under ideal physical layer. A number of exact ILP formulations for the design of survivable WDM networks have been proposed [1][4]. Authors in [5] proposed an ILP-based model to jointly compute the shared protected primary-backup path pair for dynamic traffic. The model takes both network resource usage and backup distance into consideration. The problem of computing a pair of link disjoint paths in WDM network with the wavelength continuity constraint is NP-complete [6]. Several heuristics, LP (Linear Programming)-based have been proposed to solve the problem. In [8] authors propose two ILP formulations, with reduced number of integer variables compared to existing ILPs and a simple heuristic for larger networks for which ILP formulations become computationally intractable. Other studies propose several online impairment aware algorithms without protection schemes as seen in the review paper [7]. Our work is based on the IA-RWA algorithm presented in [3].

Very few studies address protection RWA schemes under physical layer impairment constraints. In [9] authors consider path protection in transparent optical network under dynamic traffic load and investigate the performance of their algorithm under two scenarios: keeping the backup path dark and lighting it up. Lighting up the backup path worsens the impairments for other lightpaths due to added crosstalk and thus increases the blocking probability of lightpaths. Keeping the backup path dark can lead to increased traffic restoration times. In [10] authors address the issue of survivability in optical networks considering the optical layer protection and signal quality constraints. They consider two linear constraints on PMD and ASE noise and ignore all the other physical constraints. Three kinds of resource sharing scenarios are investigated in this work, including wavelength-link sharing, regenerator sharing between protection lightpaths and regenerator sharing between working and protection paths. The ILP formulation proposed is very complex and it is not practical for large-sized networks. For the reason, the authors develop a local optimization heuristic and a tabu-search heuristic to solve large scale problems. In [11] backup multiplexing is used, where the backup lightpaths can share wavelength channels under the single failure assumption, that is if their primary lightpath are link-disjoint. In [12], authors present a IA-RWA algorithm for transparent all-optical networks, while considering dedicated path protection for offline demands.

III. Physical Impairments and Quality of Transmission

In transparent WDM networks the signal quality degrades due to the non-ideal physical layer [13] [14]. Linear and non-linear physical layer impairment can be categorized to those that affect the same lightpath that generated them, and to those that affect and are affected by the other lightpaths:

- **Impairments that affect the same lightpath**: Amplified Spontaneous Emission noise (ASE), Polarization Mode Dispersion (PMD), Chromatic Dispersion (CD), Filter concatenation (FC), Self-Phase Modulation (SPM),
- **Impairments that are generated by other lightpaths**: Crosstalk (XT) (intra- and inter-channel crosstalk), Cross-Phase Modulation (XPM), Four Wave Mixing (FWM).

The second class of impairments is more difficult to deal with in RWA algorithms, since, because of these impairments, decisions made for setting up one lightpath affect and are affected by decisions made for other lightpaths.

There are several criteria that could be used to evaluate the signal quality of a lightpath. The Q-factor is the electrical signal-to-noise ratio at the input of the decision circuit at the receiver, and, under the assumption of Gaussian shaped noise, is related to the system's BER through the function:

$$BER(\mathrm{Q}) = \frac{1}{2}\, erfc\left(\frac{Q}{\sqrt{2}}\right)$$

Thus, the higher the Q-factor value the smaller the BER and the better the quality of the signal. Q-factor is not readily available before a lightpath is actually set up. Instead, models of physical-layer impairments can be used to estimate the BER or the Q-factor in advance. Various analytical models for the linear and nonlinear impairments have been proposed in the literature and different methodologies exist for calculating the Q-factor. In our work, we have used a quality of transmission evaluation module (Q-Tool) developed within the DICONET project [14] that uses analytical models to account for the most important physical layer effects.

IV. Multicost Based Protection Mechanisms

In an impairment constrained optical network the primary and the backup lightpaths should be selected so as: i) to have valid QoT, ii) to do not damage the QoT of the established lightpaths, iii) to result in low future connection blocking, iv) to result in increased survivability of the backup lightpath. We define the survivability of a backup lightpath as the probability that it will have valid QoT for the duration of the primary's lightpath lifetime. This of course has only meaning in case of 1:1 protection where the backup lightpath is not activated but only the corresponding resources are reserved. On the other hand in the 1+1 protection scheme the survivability of the backup lightpath (but also of the primary) is preserved by checking whether the QoT of the already established lightpaths (primary and backup) is affected by the establishment of a new primary lightpath and of the corresponding backup.

A. *Multicost IA-RWA Algorithm*

The IA-RWA algorithms [3] that we use in this paper, follow the *multicost* approach, which is significantly more powerful than single-cost routing. In traditional single-cost routing each link is characterized by a scalar cost. On the other hand, in the multicost approach a vector of cost parameters is assigned to each link. The cost vector of a path includes the utilization of wavelengths so as to be able to calculate the available lightpaths over that route. Moreover, it includes impairment related parameters. By defining appropriate operations between these cost parameters, we can calculate the cost vector of a path. In multicost algorithms, operators like minimization and maximization can be used, something that is not possible in the single-cost approach. Moreover, single-cost routing calculates a single path between two nodes that optimizes a single-cost criterion, while in the multicost approach more than one paths between two nodes are calculated, since the optimization parameters are more than one.

Assuming that the network supports m wavelengths, the multicost IA-RWA algorithm presented in [3] uses the utilization state of the network in order to calculate a cost vector per link l that has $1+4\cdot m$ cost parameters,

$$V_l = (d_l, \overline{G_l}, \overline{\sigma^2_{'1',l}}, \overline{\sigma^2_{'0',l}}, \overline{W_l}),$$

where $\overline{G_l}$, $\overline{\sigma^2_{'1',l}}$, $\overline{\sigma^2_{'0',l}}$ and $\overline{W_l}$ are vectors of size m that map the gain, noise variance of bit 1 and bit 0, and the utilization per wavelength. Similarly to a link, a path has a cost vector with $1+4\cdot m$ parameters, in addition to the list of labels of the links that comprise the path. The cost vector of p can be calculated by the cost vectors of the links l=1,2,...,n, that comprise it as follows:

$$V_p = (d_p, \overline{G_p}, \overline{\sigma^2_{1,p}}, \overline{\sigma^2_{0,p}}, \overline{W_p}, *p) = \begin{pmatrix} \sum_{l=1}^{n} d_l, \sum_{l=1}^{n} \overline{G_l}, \sum_{l=1}^{n}\left(\overline{\sigma^2_{1,l}} \cdot \prod_{i=l+1}^{n} 10^{2\cdot\overline{G_i}/10}\right), \\ \sum_{l=1}^{n}\left(\overline{\sigma^2_{0,l}} \cdot \prod_{i=l+1}^{n} 10^{2\cdot\overline{G_i}/10}\right), \&_{l=1}^{n} \overline{W_l}, (1,2,...,n) \end{pmatrix}$$

The multicost approach we use consists of two phases. In the first phase the algorithm computes the set of non-dominated paths from a given source to all network nodes (including the destination); this can be viewed as a generalization of Dijkstra's algorithm that only considers scalar link costs. The basic difference is that instead of a single path, a set of non-dominated paths between the origin and each node is obtained. A path that is dominated by another path, has worse delay (or length), wavelength availability, and QoT than the other path, and there is no reason to consider it or extend it further. During the calculation of the non-dominated paths when we expand a path we check the Q-factor of its wavelengths and we drop the path if it is not further extendable. In this way in the end the non-dominated paths that the algorithm returns have at least one available wavelength. Moreover, the paths and available wavelengths have at least acceptable Q-factor performance, since lightpaths with unacceptable Q-factor were made unavailable in the process of the algorithm. In the second phase of the proposed algorithm we apply an optimization function or policy to the cost vector of each path. The function yields a scalar cost per path and wavelength (per lightpath) in order to select the optimal one. The function can be different for different connections, depending on their Quality of Service (QoS) requirements. Note that the optimization function applied to the cost vector of a path has to be monotonic in each of the cost components. For example, it is natural to assume that it is increasing with respect to delay, increasing with increased noise variance, etc.

B. Fault Tolerance Extensions of the Multicost Algorithms

Our focus is on protection schemes that can be relatively easily implemented by extending our previously proposed multicost algorithm. The fault-tolerance schemes to be discussed are proof of the usefulness and the importance of the multicost approach. In particular, both dedicated and shared *link* protection and *path* protection can be provided. In link protection, a link used by the primary lightpath is protected by a pre-established backup lightpath that reroutes the traffic over an alternative path between the two endpoints of the link. In path protection, for each primary lightpath a completely link-(node-) disjoint backup lightpath is found, which can be used in case of a link (or node) failure in the primary lightpath. Our multicost algorithms can easily be extended to implement both schemes by selecting both the primary and the backup lightpath(s) from the set of candidate lightpaths calculated in the first phase of the multicost algorithmic approach. As presented in the previous sections, in the first phase of the multicost approach a *set* of candidate non-dominated lightpaths is calculated for the given connection request. All the lightpaths in this set have valid QoT, measured through the Q-factor. The proposed fault tolerance mechanisms take advantage of this set of lightpaths, which usually contains a rich set of alternatives.

In the path protection mechanism, from the set of candidate lightpaths a primary lightpath is selected to serve the connection request, while a second link-(or node-) disjoint lightpath, from the same set is selected as backup, so as to serve the connection in case of link or node failures in the primary (Figure 1). As a result, in order to provide dedicated path protection, the multicost schemes must be augmented by two operations. Initially, the set of candidate lightpaths calculated by the first phase of the multicost algorithm must be searched so as to find disjoint *pairs* of lightpaths. One of these pairs is then selected according to some optimization function or policy to form the primary and the backup lightpaths. It is evident, that more than one backup lightpath can also be selected. Shared path protection can be provided in a similar way. In our work we consider the following approaches for the selection of the primary and the backup lightpath(s):

- *bestQ-bestQ:* First, the primary lightpath is selected using the maximum Q-factor value as criterion. Next, the disjoint backup lightpath is selected from the ones available, using again the maximum Q-factor criterion.
- *sumQ:* In contrast to the previous policy, it is possible to select the primary and the backup jointly. One such possible scheme is to select the lightpaths (primary and backup) with the largest sum of Q-factor values.

We are mainly interested in showing that through extensions to the multicost approach, fault tolerance can be easily provided and also examine the effects (e.g., in terms of network blocking) of its application. Moreover, the multicost approach offers inherently quality of service (QoS) differentiation features, since it is possible to apply different optimization functions to select a lightpath from the set of candidate lightpaths, so as to serve differently the connection requests belonging to different users. Similarly, different policies can be used for selecting the primary and the backup lightpath(s) of different connections.

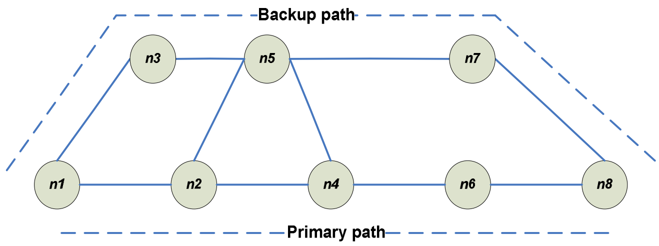

Figure 1: Shared/dedicated path disjoint protection.

Another important point that needs to be discussed is what happens when the selected primary and backup lightpaths affect the QoT of already established lightpaths. One option is to simply drop the selected lightpaths and search for other paths among the set of candidate lightpaths found from the first phase of the multicost approach. This is of course a unique and advantageous characteristic of the multicost approach. In the end, if no primary and backup lightpaths are found then the connection is blocked. Another option would be to reroute the affected lightpaths. However, in our work we do not consider rerouting of established connections. Rerouting is a process that we want to avoid, since it involves tearing down the previous lightpath, re-executing RWA and establishing a new lightpath, which would interrupt the service of the connection.

C. *Worst Case Assumption*

The criteria used for selecting the primary and the backup lightpaths, in the previous approaches, do not directly consider the survivability of the lightpaths. Of course the survivability can be achieved by simply dropping candidate lightpaths affecting the QoT of already established ones (1+1 case). However, this will increase the blocking ratio in favor of the survivability. An approach that we propose and evaluate in this work, in the case of 1:1 protection, is to consider the actual current interference among lightpaths so as to select the primary lightpath (with the best Q-factor), while using the worst case interference assumption for the backup lightpath (selecting the lightpath with the best Q-factor). In the latter assumption the wavelengths on all links are considered as fully utilized and the transmission quality of the candidate lightpaths is calculated under this assumption. A lightpath that is chosen in this way is bound to have acceptable transmission quality during its entire duration, even if future connections that interfere with it are established. However, such an approach reduces the candidate path space, leading to the selection of backup lightpaths that are not the best possible (in terms of hops, QoT etc), considering the actual interference in the network.

V. SIMULATION EXPERIMENTS

We consider an all-optical transparent network, where connections arrive dynamically and have to be served as they come. The experiments were performed assuming the DT network topology (Figure 2), which is a transparent candidate network, as identified by the DICONET project [14]. We assumed 10Gbps transmission rates and channel spacing of 100 GHz. The span length in each link was set to 100 km. Each link was assumed to consist exclusively of SSMF fibers with dispersion parameter D=17 ps/nm/km and attenuation parameter a=0.25 db/km. For the DCF we assumed parameters a=0.5 dB/km and D=-80 ps/nm/km. The launch power was set to 3 dBm/ch for every SMF span and -4 dBm/ch for the DCF modules. The EDFAs' noise figure was set to approximately 6 dB with small variations ($\pm$0.5 dB) and each EDFA exactly compensates for the losses of the preceding fiber span.

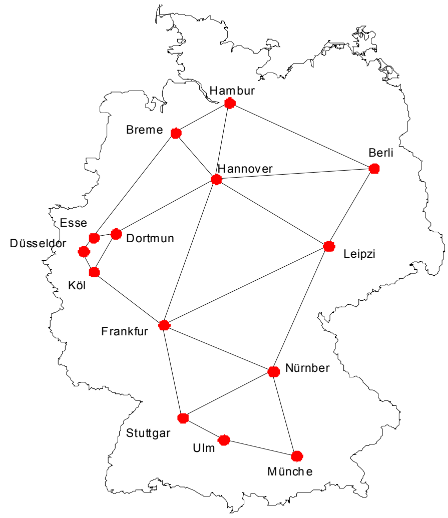

Figure 2: DTnet topology used in the simulation experiments.

Connection requests (each requiring bandwidth equal to 10Gbps) are generated according to a Poisson process with rate λ (requests/time unit). The source and destination of a connection are uniformly chosen among the nodes of the network. The duration of a connection is given by an exponential random variable with average $1/\mu$ (time units). Thus, λ/μ gives the total network load in Erlangs.

Figure 3 shows the blocking probability of several multicost based IA-RWA algorithms as a function of the number of available wavelengths, performing 1+1 and 1:1 protection. We observe that in case of 1+1 protection, the sumQ and bestQ-bestQ policies result in similar blocking probabilities. We also observe that the usage of the worst case interference assumption for the selection of the backup lightpath reduces the blocking probability. The fact that the selected backup lightpath is not the optimal one, leaves room for the selection of valid, in terms of QoT, lightpaths for serving future connection requests. In the case of 1:1 protection the differences between the different protection policies are minimized. It seems that since the backup lightpath is not activated, its QoT related selection has small impact on the network performance. Moreover, as expected, the blocking probability is increased when using 1+1 and 1:1 protection, since more lightpaths are established (case of 1+1) or reserved (case of 1:1) in total, reducing in this way the possibility of future connection requests finding a valid lightpath to use. Moreover, in the 1+1 case the blocking probability is even larger since the backup lightpaths are not only reserved (as in the 1:1 case), but are also activated, increasing in this way the impairments effects in the network and the number of blocked connection requests. In any case there is clearly a tradeoff between the level of protection (1+1, 1:1, no protection) and the blocking probability. Also, we observe that the blocking probability decreases as the number of available wavelengths increases.

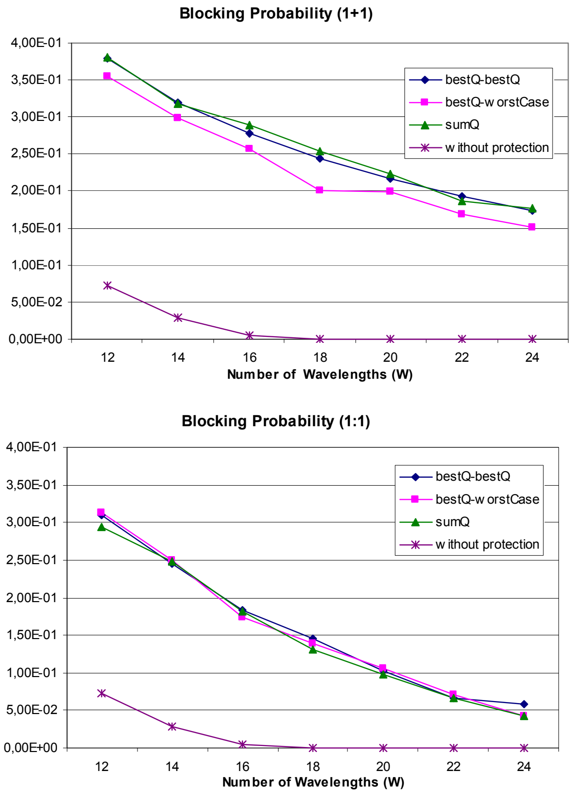

Figure 3: The blocking probability versus the number of available wavelengths, for a) 1+1 and b) 1:1, protection, using the bestQ-bestQ, sumQ, bestQ-worstCase and no protection (bestQ) policies, for fixed network load (equal to 100 Erlangs).

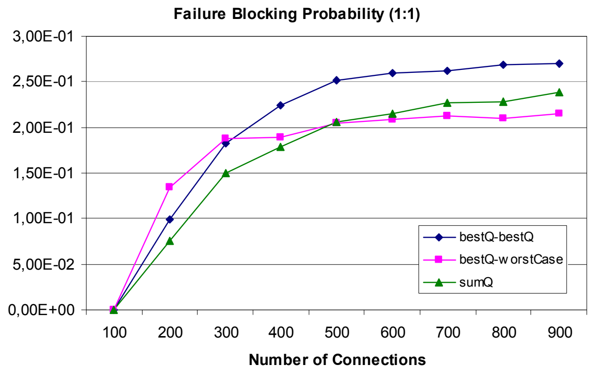

Figure 4: The failure blocking probability as a function of the number of connection requests, for 1:1, protection, using the the bestQ-bestQ, sumQ, bestQ-worstCase policies.

Figure 4 shows the failure blocking probability as a function of the number of connection requests, for 1:1 protection. We use the failure blocking probability as an indicator of the survivability of the backup lightpaths. In our experiments we measure this parameter as follows. We assume that the connections' durations are infinite. After all the connections have been served we assume that a particular link has a failure and measure the number of backup lightpaths used (in the place of affected/failed primary lightpaths) that do not have valid QoT over all the established lightpaths. Next, we re-establish this link and perform the same operation/measurement for all the other links, sequentially. In the end we average the measured values. In our experiments, we observe that when the network is lightly loaded the sumQ metric produces the best results, increasing the survivability of the backup lightpaths (decreasing the failure blocking probability), while the bestQ-worstCase policy the worst. On the other hand as the network load increases the performance of the sumQ deteriorates, while the bestQ-bestQ policy results in a large number of backup lightpaths with invalid QoT. On the other hand the bestQ-worstCase policy seems to behave better under this heavy load scenario. This is due to the fact that the worst case interference assumption leads to the selection of backup lightpaths, which are not affected by future established lightpaths. This characteristic becomes more evident when the number of affected by a failure primary lightpaths is large.

VI. CONCLUSIONS

We used the multicost approach to provide protection in impairment constrained optical networks. Using this approach is possible to apply easily different optimization criteria for the selection of the primary and the backup lightpaths, among a set lightpaths with good quality of transmission (QoT). We also demonstrated the importance of considering the survivability of the backup lightpaths that is the duration for which the backup lightpaths remains valid, in terms of their QoT. We performed several experiments where we observed that the joint selection of the primary and the backup lightpaths is generally more preferable than choosing them separately. Moreover, we proposed the application of the worst case interference assumption for the selection of the backup lightpath. We showed that this can be quite beneficial for the survivability of the backup lightpaths, when the network is heavily loaded.

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