Protection by Diversity in Elastic Optical Networks Subject to Single Link Failure

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Abstract

Among the multipath protection schemes found in the literature, the Partitioning Dedicated Path Protection - PDPP proposes to divide the total transmission rate required by the connection in equal parts, and then proceed the transmission of each part using multiple disjoint paths. Nevertheless, it is also possible to partition the transmission rate unequally among paths, enabling benefits to network performance. This article proposes a mixed-integer linear programming (MILP) formulation to find an optimised unequally partitioning of connections' transmission rate among multiple disjoint paths, in order to provide dedicated protection and reduction in maximum number of slots on network and average bandwidth squeezing. The solution is analysed over a number of realistic networks, showing that the proposed formulation significantly reduces the spectral usage compared to traditional protection mechanisms and reduces the amount of squeezing required compared to the former PDPP approach.

Keywords: Elastic optical network, Protectipn, Routing and spectrum assignment.

1. Introduction

Elastic optical networks (EONs) improve on the limited spectrum usage in existing wavelength-division multiplexing (WDM)-based optical networks by using flexible spectrum allocation to deliver scalable transport of 100 Gbit/s services and beyond, [1, 2, 3]. EONs can aggregate the throughput per fiber link to approximately 10-100 Tb/s. However, adverse events in EON networks, such as optical fiber cuts, can disrupt communications for millions of users, causing a substantial loss of data and leading to loss of revenue; thus, motivating the work of this paper. Although other components can incur even more harmful failures, they are infrequent [4, 5, 6, 7], consequently this paper will concentrate on the failures due to fiber cuts.

Most research has focused on improving the service availability of WDM, EONs or high layers against failures [8, 9, 10]. EONs do not have the fixed wavelength channels that are inherent in traditional WDM networks; instead, EONs, introduce bandwidth-variable wavebands that share the entire spectrum in a fiber. Specifically, EON proposes various grids that are different from the 50 GHz fixed grid of traditional WDM systems. Slot sizes have been defined by the ITU-T G.709, which the most commonly assumed is 12.5 GHz.

The advent of EONs leads naturally to new, improved, mechanisms to protect against failures. For example, dedicated path protection (DPP) has traditionally been the most common survivability option, however it incurs a 100% resource overhead that remains unused most of the time [11]. Thus, DPP tends to result in overprovisioning.

To reduce the overprovisioning inherent in DPP, a technique termed *squeezing protection* was introduced, this allows the network operator to optimize the amount of available bandwidth under failure conditions [2, 8, 12, 13, 14]. The technique *squeezes* the original working lightpath capacity to a reduced capacity during the "best-effort" recovery. As network resources are always limited, the *squeezing* has the desirable feature of ensuring network connectivity and availability by partially recovering the bandwidth of an affected optical channel, while complying with the guarantees agreed in the service level agreement (SLA) [15].

This paper addresses the conflicting needs of the network: to be parsimonious in the assignment of the network spectral resources while still meeting the requirements of users from a multi-tenant environment, which may be heterogeneous. In the case of heterogeneous demands, offering the same bandwidth protection for all pairs will result in overprovisioning for some demands. Consequently, it is important that a protection mechanism for EONs has adaptive protection to suit individual demands while also efficiently using the available capacity. Recentely, [16, 17, 18] provided evidence to support our claim for a detailed study

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in that area.

In the literature, there are several studies for single-link-failure protection mechanisms with DPP [8, 19]. Another efficient approach for DPP is the partitioned dedicated path protection (PDPP). However, little is known about PDPP with squeezing, and it is not clear how much some aspects used on PDPP bring advantages for elastic optical network planning. Some of these aspects are brought for discussed in this paper together with the required optimization MILP formulation, heuristics and a detailed analysis of the important parameters in PDPP.

So far, the effectiveness of PDPP comes from the recognized reduction in network resource usage that traffic partitioning (through multi-path routing) causes when compared to the lack of flexibility on resource duplication in dedicated path protection. However, PDPP has been limited to solutions that evenly distribute the total (i.e. aggregated) required reserved resource among the k chosen link-disjoint routes for protection. And this seems to be the most appropriate decision, but, as shown in the paper, may be not. This occurs because it is true that traffic evenly reserved among the k disjoint routes is the solution with the lowest required reserved excess traffic in the network, but not necessarily with the lowest slot resource usage. In addition, an even traffic distribution among the k link-disjoint routes in PDPP also generates the same (i.e. constant) squeezing factor whatever fiber (among those in the k established routes) is broken, which may seem to be the most adequate solution. However, it is shown in this paper that it is possible to find an appropriate asymmetric solution that, even with superior reserved excess traffic, either keeps the network slot resource usage or even slightly decreases it, and still benefits from a reduction in the traffic squeezing factor. In other words, by properly and carefully adjusting the traffic partitioning among the k used routes, it is possible to benefit, either individually of even collectively, from the two most important aspects of PDPP, which are reduced resource consumption and maximum traffic squeezing during link failures according to guarantees established in the service level agreement.

In the literature, researchers have not treated unequal traffic partitioning in much detail. However, since available routes of some source-destination node pairs may have different physical attributes and operational conditions, which results in greater or lower network link occupation and path interference, an unequal partitioning of traffic (asymmetric) can enable the network control plane for the PDPP strategy use more efficient routing and spectrum allocation (RSA) solutions [1]. For instance, on using asymmetric partitioning, lower bit-rate partitions can be allocated to the most occupied/longest routes, whereas higher bit-rate partition are assigned to least occupied/shortest routes, in order to provide network load balance and reduced spectrum usage.

Therefore, the main motivation of this paper is exactly to show that the somehow counter-intuitive strategy of incurring in higher required reserved excess traffic in the network as well as with unequal squeezing factors conditioned to which of the route is in failure it is possible to reduce the average squeezing factor and increase the excess traffic required in dedicated path protection mechanism, but keeping or even reducing resource usage in the network. This can be achieved under proper traffic splitting choices. This paper proposes a demand distribution between source and destination node pairs with a new *partitioning dedicated path protection* strategy: this proposes to divide the total transmission rate required by the connection in properly designed unequal parts, and then organise the transmission of each part using multiple disjoint paths.

The main aim of this investigation is to show the advantages of this kind of partitioning to protect EONs' traffic against single link failures. Our particular contributions are as follows.

- A mixed integer linear programming (MILP) path-link formulation able to provide different protection levels, or service level agreement (SLA). Therefore, the proposed solution by partitioning the transmission rate unequally between paths as suits the network capacity and heterogeneous demands enabling overall benefits to network performance.

- The formulation optimizes the partitioning of connection transmission rates across multiple disjoint paths while providing dedicated protection and minimising the ratio of rejected requests and average bandwidth squeezing.

- The proposed formulation using path-link formulation is also suitable for large networks. Therefore, it can be applied to a few real networks without need of heuristics.

The remainder of the paper is organized as follows: Section 2 is a brief review of related published works. Section 3 begins by laying out the theoretical dimensions of the research and is concerned with the methodology used for this study. In Section 4 a traditional formulation is explained and in Section 5, the proposed MILP is presented. Section 6 presents the findings of the research, focusing on a small and large networks. Finally, Section 7 gives a brief summary, a critique of the findings and identifies areas for further research.

2. Related Works

Several studies investigating multipath routing in EONs have been carried out on literature in the last years [20, 21, 22, 23, 24, 25, 26, 27, 28, 29]. The partitioning dedicated path protection (PDPP) scheme over EON was first introduced in [12, 30] for single failures. PDPP can be employed either exclusively or encompassed with bandwidth squeezing (PDPPS). The central idea is that the strict differentiation between working and protection paths no longer applies, so that a total bandwidth may be reserved through the use of as many disjoint paths as needed (obviously constrained to the connectivity of the physical topology or other aspect of interest). Therefore, the approach must coordinate the distribution of the traffic and reserved bandwidth among the routes with some optimization aim, for instance spectrum saving. Obviously, in a failure event that affects one of the adopted disjoint paths, the SLA must be guaranteed. In other words, the user must still receive an agreed minimum fraction of the original traffic. In [8], the squeezing strategy has been proposed for a single failure with a different squeezing factor for each source-destination pair and the MILP formulation assumes RSA and the modulation format during the optimization process.

Previous studies have reported on the single path routing protection in EONs. In [31] the author studied the RSA problem in EONs for 1+1 dedicated path protection, which is one of the DPP techniques that tolerate a single failure scenario. Studies of [12] show the importance of architecture and control framework for 1+1 dedicated path protection in EONs. The authors in [19] and [32] draw on optimization models for the shared backup path protection in EONs which consider a single link failure.

In [33] the authors carried out the RSA problem for the shared backup path protection in EONs in a dynamic scenario. Recently, [29] formulates an optimization problem over multiple disjoint paths for data transmission to tolerate network failures, which allows allocating the different number of spectrum slots and different amount of transmission capacity to each path to minimize required spectrum resources in EONs. By drawing on the concepts, [34] provides in-depth analysis of multiple disjoint paths and single path routing techniques for protection in EONs. Surveys such as that conducted by [35] have also shown the advantages of multipath on EONs, and another recent study by [36] proposed a kind of multipath formulation against multiple failures on EONs.

Despite the proven benefits of multipath routing, previous studies have not treated in much detail the combination of routing with different probabilities of failure. Moreover, the previous studies only consider an equal (symetrical) distribution of the transmission rate among the disjoint paths when survivable scenario is investigated. In this study, we show that it is possible to partition the transmission rate unequally between paths, enabling benefits to network performance. Finding an optmized partitioning of connections transmission rate among multiple disjoint paths can be a good approach in order to provide dedicated protection and reduction in maximum number of slots on network and average bandwidth squeezing.

So far, squeezing traffic methods from [35, 36], have only been applied to scenarios have not addressed the problem of providing rate unequally between paths. In particular, in this paper, by applying such assymetrical transmission rate among the disjoint paths, it may be feasible to set up lightpaths with protection between all node pairs with a reduced use of resources. Therefore, there still remain important challenges regarding the partition of the transmission rate in optical networks with protection, mainly with the 6th generation of mobile networking (6G) on our doorstep, and [10, 37] provides evidence to support our claim for the need of a detailed study in this area. The above supports the need to study strategies of protection to design EONs in a scalable and cost-effective manner.

3. Survivability Design in Optical Networks with Multipath Routing

In this section, the principle behind the most commonly used protection schemes is reviewed and discussed, in particular showing how *squeezing* can be applied to them.

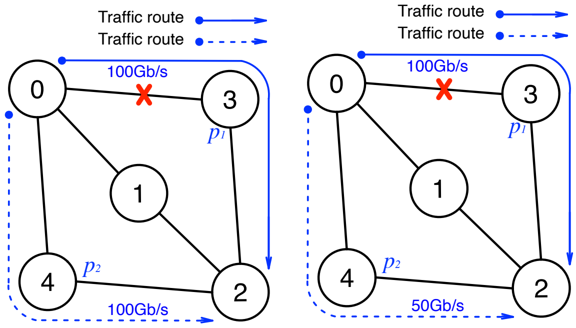
3.1. Dedicated Path Protection

A large and growing body of literature addresses the problem of restoration/protection in EONs [8, 9, 13, 14]. For instance, Fig. 1(a) shows a 5-node network with an active virtual link between nodes 0 and 2 mapped on a set of physical links connecting the same source-destination pair. Let us suppose that the virtual link is transporting 100 Gbit/s of traffic. An alternative to protect this traffic against a failure of its working physical path is by the activation of another physical path with the same 100 Gbit/s of capacity on a disjoint route, as shown in Fig. 1(a).

When a link failure occurs, for example in link 0-3, the disrupted virtual link is obviously restored using the backup path 0-4-2. It also could use the backup path 0-1-2. This approach is known as DPP and is frequently dealt with in the literature on survivability [11].

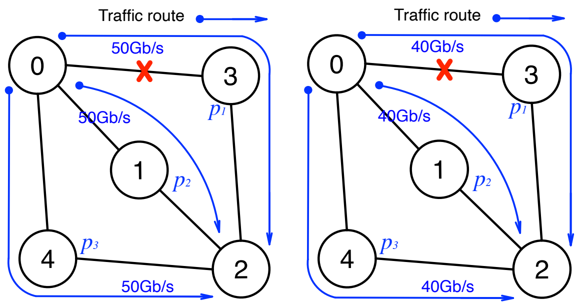
The investigation of spectrum savings is a major concern in the elastic networking field [1]. For WDM networks, an inflexible protection scheme such as DPP was envisaged without major objections due to the old framework of the fixed grid, where the bandwidth of a wavelength is kept constant and therefore DPP was seen as just another, necessary, source of overprovisioning among many others. However, in an EON this kind of protection has become one of the major sources of inefficient spectrum usage. Thus, it is crucial to employ a mechanism to provide effective dedicated protection with spectrum savings compared to schemes such as DPP. What is not yet clear is the impact of the choice of the protection scheme on planning network costs or user satisfaction. Since spectrum is treated as a scarce resource, a spectrally more efficient substitute for DPP is certainly needed.

Therefore, in EONs, *traffic squeezing* can be applied as a new feature during service recovery, in addition to the conventional DPP. By applying traffic squeezing to the protection capability, the traffic of disrupted lightpaths at failure time may be reduced in a manner commensurate to the previously running working traffic. This case is named in this paper as DPP with squeezing capability (DPPS) and is illustrated in Fig. 1(b). Note that if, under a link failure, the original 100 Gbit/s of traffic (route 0-3-2 in Fig. 1(b)) may be squeezed by 50% of its normal operation



(a) (b)

Figure 1: (a)Dedicted Path Protection (DPP); (b)DPP plus squeezing (DPPS)



(a) (b)

Figure 2: (a)Protection by multipath or Partiotined DPP (PDPP); (b) PDPP plus squeezing (PDPPS)

bitrate, just an extra of 50 Gbit/s traffic flow has to be reserved for protection purpose (route 0-4-2 in Fig. 1(b)), requiring from the network a total of 150 Gbit/s, i.e., much less capacity than the 200 Gbit/s with DPP.

3.2. Protection by Multipath

Other studies in the literature discuss the design of a more efficient protection mechanism that allows traffic flow be diverted along multiple paths, which is referred to as partitioning dedicated path protection (PDPP), [30, 38]. This approach reduces the amount of required bandwidth when compared to DPP, as shown in Fig. 2(a). Notice that, under PDPP, the traffic may be diverted along three network routes so that an extra of just 50% in the established traffic is able to preserve the total demanded traffic in case of a single link failure in the network, whilst reducing the load on any single recovery path. If squeezing is combined with multipath routing capability, forming the PDPPS mechanism, further reductions on the total traffic established in the network can be achieved, as shown in Fig. 2(b) for a 20% of squeezing factor. In Fig. 2(b), three disjoint traffic flows of 40 Gbit/s are established. Under the occurrence of a single link failure in either of the three established routes, two traffic flows of 40 Gbits/s remain active, providing a total of 80 Gbit/s, which represents a 20% of transmission bit-rate squeezing compared with the original traffic demand of 100 Gbit/s. It is clear that DPPS and PDPPS can both relieve the stress on network spectral resource usage when compared to DPP and PDPP, respectively. Note that, in multipath routing, differential delay is a problem that must be dealt with for the correct operation of the network.

4. Multipath Routing: Linear Formulation

We start this survivability mechanism section discussing the problem of optical network design related to the simplest multipath protection mechanism that purely diffuses the demanded traffic among two or more of the available routes without requiring any additional traffic provisioning [39].

This kind of path diversity is a common requirement that forces splitting demand volumes into more than one path. Typically, this is considered so that a single link (node) failure cannot affect too much any demand, provided that the paths used for a demand pair are link-disjoint (node-disjoint). Notice that the strategy is similar to PDPP design problem, with multipath routing, but no additional traffic is reserved. The symmetrical partitioning allows a kind of resilience with squeezing when a single link failure, because the other 2 paths guarantee a partial protection. The traffic engineering goal of minimizing the total link capacity (C_T) over all links is now formally stated (using the definitions in Table 1). Please see [39], chapter 4, for details about this traditional formulation:

$$Minimize : C_T \tag{1}$$

– ***subject to:***

$$\sum_{d=1}^{|D|} \sum_{p=1}^{|P_d|} \delta_{e,p}^{d} X_p^d \leq C_e \qquad \forall e \in E \tag{2}$$

$$\sum_{e} C_e = C_T \qquad \forall e \in E \tag{3}$$

$$X_p^d \leq h^d/3 \qquad \forall d \in D, p \in P_d \tag{4}$$

As an example, consider the allocation of the demand d between the nodes 0 and 2 in Fig. 3 with $h^d = 100$ Gb/s and demand partitioned among 3 distinct paths (by constraint 4), where the symmetrical established flow is as shown in Fig. 3. The multipath routing through this technique may have a limited application on contemporary communication networks asking full protection, as it is often not practical to split the demands across different paths and keep the same SLA. Consequently, the following analysis will consider differential split.

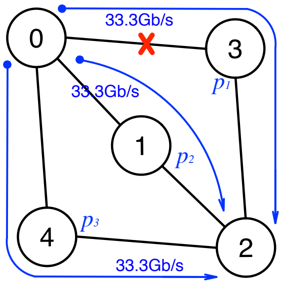


Figure 3: Symmetrical traffic partitioning

5. Optimized PDPP (OPDPP)

The multipath routing formulation in Section 4 applied a symmetrical traffic partitioning between the multiple link-disjoint paths (ex.: three link-disjoint paths or PDPP3). This saves the amount of extra required traffic and provides the same traffic squeezing independently on the broken link-disjoint path. However, there have been no specific studies which compare the difference between symmetrical and asymmetrical partition. Here we propose the OPDPP which allows an asymmetrical partition.

Let $\overline{\beta^d}$ be the expected squeezing factor for a demand d according to the conditional probability $\rho_{d,p}$ of a link failure occurring over link-disjoint path p of d. Therefore, $\rho_{d,p}$ depends on the probability of failure on the links that belong to p and other routes in P_d. If we assume every link has the same probability of failure, then $\rho_{d,p}$ depends on the size (i.e. number of links) of p and the routes in P_d. In this case, we may write:

$$\rho_{d,p} = \frac{\sum_e \delta^d_{e,p}}{|E^d|} \quad \forall d \in D, p \in P_d, \tag{5}$$

in which the sum in the numerator gives the number of links that belong to p in P_d, and $|E^d| = \sum_{p=1}^{P_d} \sum_{e=1}^{|E|} \delta^d_{e,p}$ is the total number of links that belong to any of the link-disjoint routes of d. Therefore, the expected value for demand d squeezing factor is given by:

$$\overline{\beta^d} = \sum_p \rho_{d,p} \beta^d_p, \quad \forall d \in D, \tag{6}$$

In the next Section, the proposed MILP formulation and some analysis are presented, in which β is specified for each demand d according with a given SLA and a protection overhead factor α_d. In this study, the number of slots, modulation format and their spectral efficiency were analysed to explore the features of elastic optical networks. Analysis follows the formulation.

5.1. OPDPP - Proposed MILP Formulation

$$Minimize : \sum_d \overline{\beta^d} + \phi \; C^s_T \tag{7}$$

Table 1: Notations Used Throughout the Paper

	Notation	Description
Input	D	set of demands to be allocated in the network. $d = 1, 2, \ldots, |D|$ is one of the existing demands.
	N_d	number of pairs source-destination of traffic for a demand d.
	P_d	set of link and/or node disjoint candidate paths for demand d. $p \in \{1, 2, \ldots, |P_d|\}$ is one of the candidate paths for demand d.
	E	set of existing links in the network. $e = 1, 2, \ldots, |E|$ are the existing links in the network.
	δ^d_{ep}	equals to 1 if link e belongs to the p-th path of demand d; 0, otherwise.
	h^d	traffic intensity of demand d (Gb/s) .
	$|E^d|$	total number of links of disjoint candidate paths for the demand d.
	β^{max}_d	maximum squeezed bandwidth ratio for demand d.
	η^d_p	spectral efficiency of the modulation format used in path p and demand d (bit/s/Hz).
	W_s	bandwidth occupied by a slot (GHz).
	F	the minimum spectrum width between wavebands (in number of slots).
	ϕ	a small number
Variable	C_e	used capacity of link e (Gb/s).
	C_T	Sum of used capacity of all links in the network (Gb/s).
	C^s_e	used capacity in terms of maximum number of slots used per link e.
	C^s	maximum number of slots used over any link, $C^s = max(C^s_e)$.
	C^s_T	Sum of used capacity (in terms of slots) of all links in the network.
	X^d_p	traffic flow allocated to path p of demand d (Gb/s).
	T^d_p	number of slots allocated on path p of demand d.
	α_d	protection overhead, it is the fractional excess bandwidth reserved for protection of demand d.
	β^d_p	squeezed bandwidth ratio for demand d in path p.
	$\overline{\beta^d}$	average squeezed bandwidth ratio for demand d.
	$\rho_{d,p}$	conditional probability of a link failure on path p given that a failure occurred in one of the paths in P_d.

– ***subject to:***

$$\textstyle\sum_p X^d_p = h^d(\alpha_d + 1) \qquad \forall d \in D \tag{8}$$

$$X^d_p \leq h^d(\beta^{max}_d + \alpha_d) \qquad \forall d \in D, p \in P_d \tag{9}$$

$$\beta^d_p = \frac{h^d - \sum_{p' \neq p} X^d_{p'}}{h^d} \qquad \forall d \in D, p \in P_d \tag{10}$$

$$\beta^d_p \leq \beta^{max}_d \qquad \forall d \in D, p \in P_d \tag{11}$$

$$T^d_p \geq \frac{X^d_p}{W_s \eta^d_p} \qquad \forall d \in D, p \in P_d \tag{12}$$

$$\textstyle\sum_{d,p} \delta^d_{e,p}(T^d_p + F) - F \leq C^s_e \qquad \forall e \in E \tag{13}$$

$$\textstyle\sum_e C^s_e = C^s_T \qquad \forall e \in E \tag{14}$$

In addition, the MILP formulation has includes the Equations (5) and (6).

5.2. Explanation

There are two conventional ways of analyzing the problem for static traffic: 1) consider to insert all traffic in the network and work on minimizing the network resource (in our case, the number of used slots); 2) Limit capacity (resources) and maximize the amount of inserted traffic. In this paper we consider the former one.

Equation (7) is the objective function, which works to minimize the average squeezed bandwidth ratio for all demands. The maximum slot number used by the physical network is also included on the objective function, but with a small weight ϕ, so as not to interfere with the main objective of minimizing the average squeezing factor in the network $\left(\sum_d \overline{\beta^d}\right)$. By this way we can partition the traffic according to path length and also to avoid defragmentation, [40], as we can see on the simulation study section. Equations (8)-(9) can be explained as the following. When path $p = 1$ breaks, the whole of traffic from $p = 2$ and $p = 3$ must satisfy the SLA, i.e.:

$$X_2^d + X_3^d \geq (1 - \beta_d^{max})\, h^d \tag{15}$$

From (8), we have:

$$X_1^d + X_2^d + X_3^d = (1 + \alpha_d)\, h^d \tag{16}$$

Therefore, taking out $X_2^d + X_3^d$ from equation (15) and replacing it in (16), we have:

$$X_1^d \leq (\alpha_d + \beta_d^{max})\, h^d \tag{17}$$

The same explanation can be applied for X_2^d and X_3^d.

Equation (10) gives the squeezed bandwidth ratio for demand d in path p. And (11) gives an upper bound for that rate. (12) gives the number of slots for each demand. Equation (13) denotes that the utilized bandwidth (including Filter Guard Band F) should not exceed the spectrum capacity of the fiber e. Therefore, the sum of used capacity (in terms of maximum number of slots used) of all links in the network is given by (14).

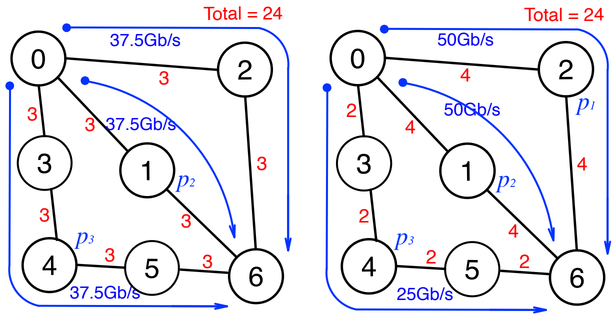
6. Simulation Study

6.1. Example with a Small Network

To give a simple demonstration of the effectiveness of the proposed optimization, the 5-node network topology shown on Fig. 1(a) was employed. IBM ILOG CPLEX v.11.0 [41] was used on an Intel i7 3.6 GHz 32GB machine to solve a small problem with a single demand, d=1 with h^1=100 Gb/s, from node "0" to node "2". Three disjoint paths ($|P_1| = 3$) were used, a $\beta_1^{max} = 0.25$, $\eta_1^1 = \eta_2^1 = \eta_3^1 =$ 1 bit/s/Hz and $W_s = 12.5GHz$

For the symmetrical and asymmetrical cases, we can use the same formulation. In asymmetrical case, $\overline{\beta^d}$ is variable. However, for symmetrical case, we need to fix $\overline{\beta^d} = \beta_d^{max}$.

Fig. 4(a) and Fig. 4(b) show the results for symmetrical and asymmetrical approaches, respectively, in term of slot utilization (red identifier beside the link). In Fig. 4(a), each path uses 37,5 Gb/s ($X_1^1 = 37,5$ Gb/s, $X_2^1 = 37,5$ Gb/s and $X_3^1 = 37,5$ Gb/s), which requires three slots ($T_1^1 = 3\ slots$, $T_2^1 = 3\ slots$ and $T_3^1 = 3\ slots$) per link and results a squeezing factor of $\beta = 0.25$, independently on which link of the three routes failure occurs. The number of links used by the three paths is 8. Therefore, there are 24 slots ($C_T^s = 24$) consumed in total and a protection overhead $\alpha_1 = 0.125$.



(a) Symetrical Case, PDPP3 (b) Asymetrical Case, OPDPP

Figure 4: Simulation results

On the other hand, in Fig. 4(b), $\overline{\beta^1}$ was made as low as 0.125, since paths 1 and 2 have two links each and were assigned with 50 Gb/s (i.e. 4 slots per link), whereas path 3 has four links and was assigned with just 25 Gb/s (i.e. 2 slots). Therefore, the total number of slots consumed is (4x4)+(2x4) = 24, which is the same number as in PDPP3. However, it was found $\alpha_1 = 0.25$, since the total traffic going out from node "0" with the optimization is 125 Gb/s. Notice that this extra traffic can be used for non-prioritized traffic without resulting in slot utilization increase.

In conclusion, the analysis show that, for the same consumption of resources in the network, asymmetrical partitioning may offer less expected traffic squeezing ($\overline{\beta^d}$) under failure than symmetrical partitioning whilst satisfying the agreed β_{max} whatever link is broken in the network, which is a significant advantage for the network operator to its clients without sacrificing network capacity. In addition, asymmetrical partitioning can reduce the number of rejected connections for eventual future traffic demands, since β^d that requires fewer slots can be easily allocated on long paths, because those routes, in general, have less resource availability (free slots) and have commonality with other paths.

6.2. Examples with Large Networks

Here we analyse the performance of the proposal on larger realistic networks.

6.2.1. Pan European Network

The first analysis uses the Pan European network where its physical substrate is presented in Fig. 5 and can be found in [42]. All assumed parameters (slot width, filter guard band, number, spectrum efficiency and maximum reach of modulation formats) are kept identical as before.

Comparisons between the different protection techniques were made using the concepts described before and using the variables defined in Table 1. Table 2 summarizes the approaches used in the simulations. The generated traffic matrices employ $h^d = 100$ Gbit/s for all source-destination node pairs in the network and $|D| = N(N-1)$ where N is the number of the nodes of the network. Results of the approaches in terms of C^s (on the left axis) and C^s_T (on the right axis) for three different maximum squeezing factors β_d^{max} (0.1, 0.2 and 0.3) can be seen in Fig. 6.

Table 2: Summary of kinds of protection schemes. * In this paper, the terms DPP and PDPP2 are used indistinctly to mean dedicated protection with 2 disjoint routes.

Description	Protection scheme
Dedicated Path Protection	DDP
*Partitioning DPP with 2 disjoint paths	PDPP2
*Partitioning DPP with 3 disjoint paths	PDPP3
DPP with Squeezing	DPPS
PDPP2 and squeezing	PDPP2S
PDPP3 and squeezing	PDPP3S
Optimized Partitioning DPP	OPDPP

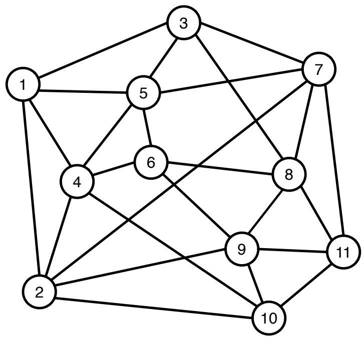


Figure 5: Pan European network topology [42]

Similarly to what is observed in previous sections, traditional DPP requires many more slots from the network than any other analysed approaches. In some cases, the resource utilization is practically double compared to other approaches, for example the PDPP3S and OPDPP cases. Again, this occurs because, under DPP, each traffic demand needs to be assigned with the double of the required traffic when the protection scheme is resilient to one link failure.

When one compares OPDPP with the PDPP3S approach, it is possible to observe that it achieves either less (ex. maximum slot occupancy (C^s) for $\beta_d^{max} = 0.2$ and 0.3) or the same resource usage. When compared to the other heuristics with an inferior number of disjoint paths (PDPP2S or DPPS), significant reductions in spectrum usage are observed. Moreover, notice that the values of C^s and C^s_T achieved by the algorithms DPP, PDPP3 and DPPS remains the same if the β_d^{max} is changed (compare the results of the same algorithm in different graphs), wheras the the values of C^s and C^s_T achieved by the algorithms PDPP2S, PDPP3S and OPDPP decreases as the β_d^{max} value increases. Results show that, with the added flexibility by partitioning with squeezing, we could utilize network resources better when network resources are scarce. For example, we could provision more future connections with the extra capacity by degrading paths. One study by [16] examined a similar aspect.

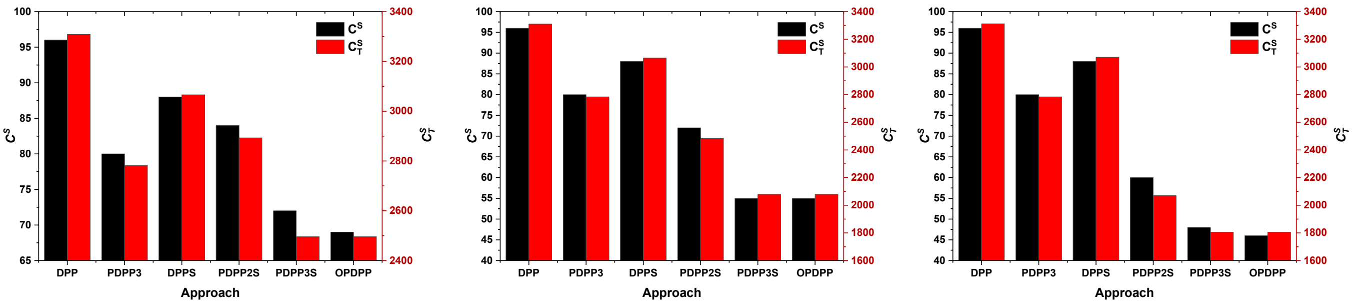
Fig. 7 shows the average squeezing factor ($\overline{\beta^d}$) provided by OPDPP for the different source-destination traffic demands in the network as well as the average excess of traffic ($\overline{\alpha}^d$) in the network. It may be observed that considerably lower squeezing factors can be observed in the network when OPDPP is used instead of the other policies with squeezing. For instance, values as low as 0.08, 0.23 are observed for maximum squeezing factors of 0.2 and 0.3, respectively. This represents reductions of 60% and 23% compared to the symmetrical PDPP3S case. In Fig. 7, we can also observe that there is a slight increase in the excess of traffic established in the network, however, as mentioned before, due to the properly designed traffic partitioning among short and long routes, this does not necessarily reflect in increase of network spectrum occupancy. Actually, it was shown in Fig. 6 that, in some cases, the network spectrum occupancy is even reduced with OPDPP.

The results clearly show that the use of traffic partitioning along with squeezing provides significant resource savings compared to techniques without partitioning and/or squeezing, as also observed for the previously analyzed small network. In addition, it is shown there is a considerable reduction in the expected squeezing factor under the asymmetrical OPDPP without sacrificing spectrum usage, although a small amount of additional extra traffic must be reserved. However, as discussed before, this extra traffic may be used for non-prioritized traffic, which does not require protection.

Regarding the simulation time, even for a network with a large amount of nodes and links, the final solution was found with less than 10 seconds in all scenarios, since the spectrum allocation phase was omitted.

6.2.2. Other physical Topologies

It this section, we extend the analysis performed for the Pan European network and verify the performance of OPDPP in four different topologies: an 8-node network [43], DBN 13-node network [44], a 14-node network [45] and a toroidal network [46], as shown in Fig. 8. The generated traffic matrices employ $h^d = 100$ Gbit/s and maximum squeezing rate $\beta^d_{max} = 0.2$ for all traffic demand (i.e. source-destination node pairs demand) in the network. All other



(a) β_d^{max}=0.1 (b) β_d^{max}=0.2 (c) β_d^{max}=0.3

Figure 6: Simulation results. Maximum slot occupancy (on the left axis) and total number of slots (on the right axis) for the Pan European topology under three possible values of β_d^{max}.

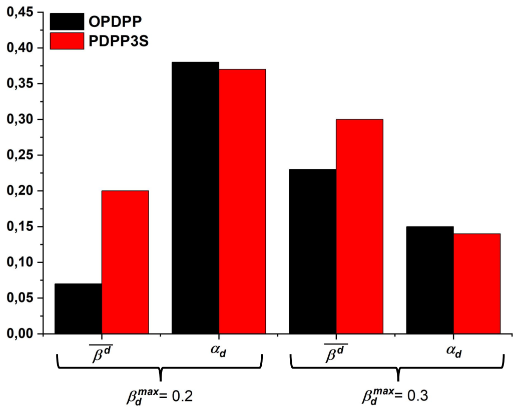


Figure 7: Average squeezing factor ($\overline{\beta^d}$) and average traffic excess ($\overline{\alpha_d}$) in the network for three values of maximum squeezing factor (β_d^{max}).

assumed parameters (slot width, filter guard band, number, spectrum efficiency and maximum reach of modulation formats) are kept identical as before. Table 3 summarizes some important aspects of the four assumed topologies and presents the values for the average squeezing factor ($\overline{\beta^d}$), average network excess traffic ($\overline{\alpha_d}$), maximum slot capacity C^s), number of used slots in the network (C_T^s) and simulation run time t for the OPDPP and PDPP3S techniques.

Similarly to what is observed in Fig. 6 and 7, OPDPP is able to provide a large reduction in the average squeezing ratio when compared to PDPP3S. Reductions of around 65% are observed in the four analysed scenarios. It is important to say that this occurs at the expense of an additional average excess traffic α. However, as discussed before, this excess traffic represents a reserved capacity on the combined lightpaths, which can be used by extra non-protected traffic. Even more importantly, this extra excess traffic does not result in additional spectral usage. Actually, OPDPP was able to achieve reductions in both maximum slot capacity (C^s) and number of used slots in the network (C_T^s) for the four analysed networks, which shows a combined benefit of OPDPP in squeezing ratio and required number of slots from the network compared to the most efficient approach until now (PDPP3S). Such benefits occur because the MILP formulation is able to distribute the traffic in an optimized way among the alternative routes with different lengths (number of hops).

6.2.3. Networks with flexible traffic demands

We simulate OPDPP and PDPP3S cases with traffic demands uniformly distributed among 40, 100 and 400 Gb/s, which means that each node demands 40, 100 or 400 Gb/s to be sent to every other node. In this case, the traffic matrix has been referred to as "rand". OPDPP and PDPP3S performance are shown in Table 4. Again, we observe a clear gain in terms of saved bandwidth for the OPDPP compared to PDPP3S. However, a bit less than the distribution with fixed traffic demands of 100 Gb/s (Table 3).

6.2.4. Varying the Number and Nature of Demands per Source-Destination Node Pairs

In the proposed simulations of the last subsections, the number of traffic demands is simply set as $N(N-1)$, which means that there is only one demand for each source-destination node pair. This setting may be unusual for some kinds of network planning. Therefore, it is worth check the behaviour of the analysed approaches under other possibilities of traffic demands. Notice that the MILP formulation allows the assumption of an arbitrary number of traffic demands per source-destination node pair. It is just necessary to inclue all of them in the input file.

To assess the performance of the analysed approaches with different number of traffic demands (1, 2, 3 and 4) per source-destination node pair, we performed simulation for OPDPP and PDPP3S approaches with traffic randomly chosen between 40, 100 and 400 Gb/s. Also, we set β_d^{max} of each demand to either 0.2 or 0.25, with equal probability. All other parameters are the same as in the last simulations. The results, as shown in Fig. 9, indicate the increase of C_T and C_T^s in function of number of traffic demands per source-destination node pairs. When we compare OPDPP with PDPP3S, we can confirm the advantages of OPDPP strategy to reach less utilized capacity, and therefore save resources to the future. The maximum simulation time was of 8.53s, which can be seen in Table 5 for the four networks over study under the hardest case (i.e., four traffic demands per source-destination node pairs).

6.3. Spectrum Allocation and Heuristic

Actually, the complete problem presented in this paper is a heuristic. This occurs because the strategy presented in the proposed MILP formulation (OPDPP) as well as in the other comparative approaches do not consider the spectrum allocation problem (neither contiguous nor continuous spectrum ranges) together with the routing decision phase, as the joint problem is a complex and time consuming task. However, the spectrum allocation may follow a formulation similar to that presented in [38], but now, the set P of pre-calculated paths, as defined in [38], is fed with the set of disjoint paths calculated in a previous routing phase. Following the methodology proposed in this paper, this task is performed with a new ILP spectrum allocation using an objective function with the target to minimize the total number of allocated slots. Then, the spectrum allocation phase minimizes the maximum slot index, F_{max}, among all links. Therefore $F_{max} \leq C^s$, since C^s is the upper bound on the number of slots as stated before. The proximity between C^s and F_{max} indicates the efficiency of the spectrum allocation phase for the paths found by the MILP. The ILP spectrum formulation is omitted for brevity purposes. The diagram in Fig. 10 shows the steps taken to execute a complete solution of the problem. From Table 3 and 4, it can be seen that the simulation time for the complete problem is less than 1s even for large networks and this is a strong evidence of the efficiency of the strategy in terms of running time.

6.4. Does traffic partitioning require extra number of slots?

The simple case of partitioning a traffic in two parts may not be beneficial in terms of network capacity usage due to the discrete capacity (ex. 12.5 GHz) of each slot. However, in our analysis, traffic splitting may indeed bring benefits.

Let us assume the case of a 56 GHz traffic demand, which, under a spectrum efficiency of $1bps/Hz$, requires five 12.5-GHz slots. This is a peculiar case, since 56GHz requires 5 slots and 56GHz/2=28 GHz requires 3 slots, which is not opportune for traffic splitting. Indeed, if multipath is employed and this traffic is equally split among two routes, it is enforced the use of 3 slots per route, which results in an additional slot in the aggregated traffic.

On the other hand, if the same 56 GHz had to be protected with conventional DPP, this traffic must be sent to both working and backup paths. Therefore, it would be necessary 62.5 GHz in the working path and 62.5 GHz in the backup path (i.e. 5 slots per route, since 4x12.5 GHz $<$ 56 GHz and 5x12.5 GHz $\geq$ 56 GHz). This utilizes an aggregated capacity of 125 GHz, or 10 slots. Since without squeezing DPP and PDPP2 work exactly the same (i.e. are identical), they both would require the same 5 slots per route and 10 slots in total. However, if multi-path is introduced to DPP, forming the PDPP3 strategy, for instance, notice that it would be required 28 GHz per path (or 84 GHz in total), which, due to fixed slot capacity, enforces a total of 37.5 GHz per path. This results in an aggregated traffic in the three paths of 112.5 GHz, and a single failure in either path results in a residual capacity of 75 GHz, which is larger than the required 56 GHz. In this case, just 3 slots per route (9 slots in total) are required. On the other hand, if 130 GHz (the double of 56 GHz) is assumed, notice that the use of a single path requires 9 slots against 10 in multipath routing, i.e., single path continues to be beneficial compared to multipath routing; However, PDPP3 requires just 15 slots against 18 in DPP. Obviously, the total network usage capacity depends on the number of hops in each route, which is one of the issues analysed in this paper.

Therefore, due to the discrete spectrum nature of elastic optical networks, it is true that multi-path routing usually requires more slots than single-path routing. However, when dedicated path protection is required, PDPP3 is usually beneficial when compared to DPP.

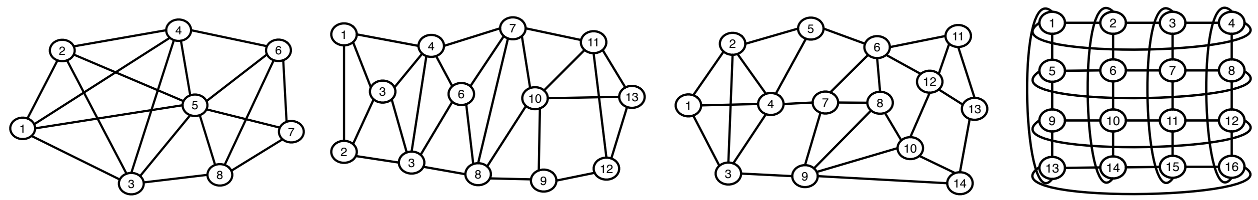
6.5. Traffic Recovery Time

Regarding the traffic recovery time under link failure, protection and restoration mechanisms perform differently from each other, as well as under some of their possible variants. For instance, in 1+1 dedicated path protection (DPP), since the traffic is simultaneously sent in both working and protection paths, traffic interruption is almost promptly recovered. With 1:1 DPP, there already is a delay for releasing the extra traffic in the protection path and swapping the traffic from working to protection path. Notice that all the paths in the investigated PDPP are pre-established and runs diverse traffic. Therefore, PDPP traffic-recovery time is similar to 1:1 DPP, since under fiber break in one of the paths, traffic has to be reorganized among the remaining (i.e. not broken) but already active paths.

Although traffic recovery requires traffic reorganization under PDPP, it is much quicker than under restoration, since in the former all required capacity is pre-established (i.e reserved and available during all traffic transmission period), whereas in the latter this is not the case and a Routing and Spectrum Assignment (RSA) process must be run whenever link failure occurs.

6.6. Node requirements

Multi-path routing is one of the strategies for diminishing fragmentation. This occurs because, when there is no possibility for establishing a single path for a demand (ex. lack of continuity and/or contiguity), traffic may be divided into sub-demands and assigned in multiple path.



(a) 8-node network (b) DBN 13-node network (c) 14-node network (d) Toroidal network

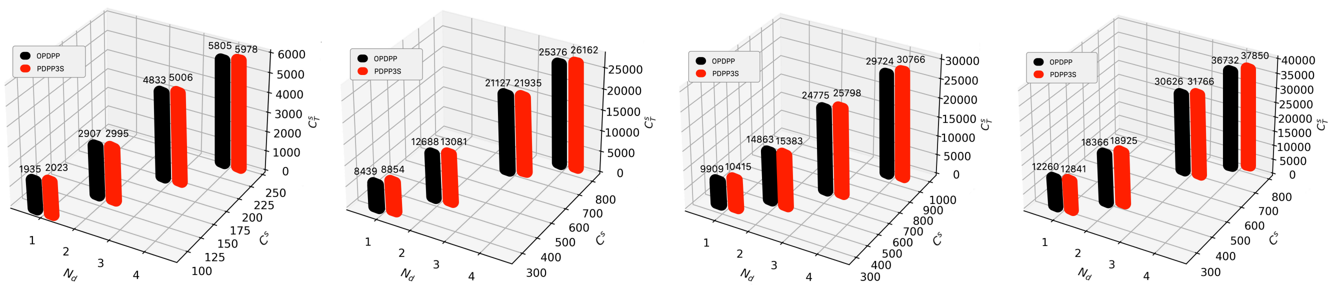
Figure 8: 4 physical topologies over study

Table 3: Analysis of four different topologies with $\beta_d^{max} = 0.2$ and h^d=100 Gb/s

Network id	Name	N (number of nodes)	L (links)	Nodal Degree (mean)	OPDPP					PDPP3S				
					$\overline{\beta^d}$	α_d	C^s	C^s_T	t	$\overline{\beta^d}$	α_d	C^s	C^s_T	t
(1)	8-node [43]	8	2x18	3.00	0.074	0.375	47	1164	0.48s	0.2	0.2	52	1296	0.062s
(2)	DBN 13-node [44]	13	2x26	4.00	0.069	0.375	154	5008	1.011s	0.2	0.2	164	5636	0.031s
(3)	14-node [45]	14	2x27	3.86	0.069	0.375	182	5898	1.14s	0.2	0.2	200	6624	0.031s
(4)	Toroidal [46]	16	2x32	4.57	0.0704	0.375	155	7236	2.25s	0.2	0.2	172	8112	0.047s

Table 4: Analysis of four different topologies with $\beta_d^{max} = 0.2$ and $h^d \in \{40, 100, 400$ Gb/s $\}$.

Network id	Name	N (number of nodes)	L (links)	Nodal Degree (mean)	OPDPP					PDPP3S				
					$\overline{\beta^d}$	α_d	C^s	C^s_T	t	$\overline{\beta^d}$	α_d	C^s	C^s_T	t
(1)	8-node [43]	8	2x18	3.00	0.12	0.307	89	1935	0.56s	0.2	0.2	89	2023	0.047s
(2)	DBN 13-node [44]	13	2x26	4.00	0.109	0.314	281	8439	1.14s	0.2	0.2	291	8854	0.032s
(3)	14-node [45]	14	2x27	3.86	0.11	0.312	312	9909	1.19s	0.2	0.2	319	10415	0.031s
(4)	Toroidal [46]	16	2x32	4.57	0.109	0.315	284	12260	1.48s	0.2	0.2	291	12841	0.063s



(a) 8-node network (b) DBN 13-node network (c) 14-node network (d) Toroidal network

Figure 9: Total used capacity (C^s_T) and maximum number of slots used over any link (C^s) in function of number of traffic demands per source-destination node pair (N_d).

Table 5: Running time from Fig. 9 for N_d=4.

Topology	OPDPP	PDPP3S
8-node	0.98s	0.03s
DBN 13-node	2.20s	0.09s
14 node	2.30s	0.09s
Toroidal	8.53s	0.09s

Additional resources such as transponders and/or guard-bands may be consumed with the increase in the number of split demands [16, 17, 40].

Concerning the enabling technologies that make the partitioning or split spectrum approach possible [47], there are some implementations regarding transponder architecture and utilization. For example, the bandwidth variable transponder (BV-TSP)-based and the multi-flow transponder (MF-TSP)-based implementations, [1, 48]. In the BV-TSP-based implementation, once the demand has gone through the splitting process, the resulting parts are transmitted using independent BV-TSPs. That is, as many BV-TSPs as parts into which the demand has been split are employed. For this reason, any allocation mechanism employing such an implementation has to carefully take into account this issue. On the other hand, this implementation does not impose additional hardware complexity with the sole split spectrum approach purpose, as it basically relies

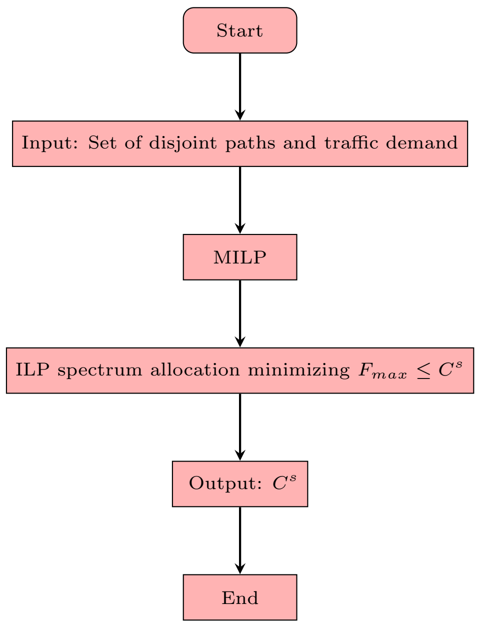


Figure 10: Diagram of the basic procedure for the step by step protection by diversity scheme

on the hardware already deployed in the network, keeping the capital expenditures (CAPEX) within reasonable limits [40, 48].

6.7. Redundancy

Usually the redundancy or spare capacity is defined as the ratio of total protection capacity to total working capacity in the entire network [49]. In this work the redundancy could be represented by α. Threfore, we can see in all simulations that OPDPP brings advantages but gets more redundancy than PDPP3. However, this excess traffic represents a reserved capacity on the combined lightpaths, which can be used by extra non-protected traffic [40].

6.8. Spectrum Fragmentation

RSA constraints, along with connection requests' establishment and release give rise to spectrum fragmentation, which is a common problem in EONs [10,11]. Fragmentation occurs whenever available contiguous frequency slots in each link in the path are misaligned or the number of available contiguous frequency slots does not meet the requested bandwidth requirement, which deteriorates the spectrum utilization and, consequently, the ratio of accepted connections.

However, there is a difference between analysing fragmentation under either static or dynamic network traffic conditions. This occurs because, while under static traffic conditions connection requests are known a priori and the network management can analyse the best way of establishing these connections (all at once and in an optimized way) in order to reduce/improve some desired aspect in the network; under dynamic traffic conditions, demands are totally unknown, i.e. connection requests arrive to and depart from a network one by one in a random manner. Therefore, fragmentation under dynamic traffic condition must be directly treated by any approach in the RSA process, whereas, under static traffic condition, fragmentation is mainly treated as a consequence of the minimization/maximization of the used metric in the objective function, as, for instance, the reduction in the number of used slots in the network, as also analysed in the paper. Please see [50, 51, 52] for details about fragmentation.

7. Concluding Remarks

In this study we proposed a novel MILP formulation for different protection schemes against single link failures in EONs, considering the distance the lightpath will travel and the probability of failure on that path. The proposed formulation is able to provide different protection levels, or SLA, with the squeezing flexibility which reduce the spectrum usage. The experiments demonstrated the effectiveness of our proposed OPDPP formulation. The present study makes several noteworthy contributions to the design of EONs with survivability, showing the advantages of OPDPP compared to traditional DPP and other symetrical protection methods.

A natural progression of this work is to examine more closely the relation between squeezing for protection and other different protection approaches against node failure, multiple failure etc. The solutions discussed in this paper may enhance the requirements on the nodal architecture at the optical level. In order to balance the efficient use of spectral resources with the tolerance requirements of the users, the combination of squeezing and partitioning among link-disjoint paths must be investigated. Over-partitioning may reduce the excess traffic required for protection, however, it may lead to deleterious effects in other network aspects such as: excessive differential delay between the paths and excessive use of both guard bands and transponders (BVTs, SBVTs, etc). Clearly there is a trade-off choice to be made in increasing the number of path partitioning. In this paper, we have limited the number of traffic splitting to the minimum value (i.e. three) that PDPP differs from DPP. The resulting performance gains are thus obtained from the enhanced exploration of the network connectivity at the cost of allowing for more space diversity, which may increase the demand for optical ports and spectrum-selective switches for the same amount of information, albeit at a reduced rate. The ongoing development of sliceable bandwidth variable transceivers should provide the required functionality, but more slices may be needed in highly connected networks, thus requiring more ports and more spectrum-selective switches, if the connectivity is fully explored. More detailed techno-economic studies of architectural solutions may then be warranted in order to assess the best compromise between cost and benefit in the exploration of the network connectivity.

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