

Performance Evaluation of Survivability Strategies for Elastic Optical Networks under Physical Layer Impairments

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Abstract

This paper carried out a performance evaluation study that compares two survivability strategies (DPP and SM-RSA) for elastic optical networks with and without physical layer impairments. The evaluated scenarios include three representative topologies for elastic optical network, NSFNET, EON and USA. It also analyzes the increase of blocking probability when the survivability strategies are evaluated under the realistic scenario that assumes physical layer impairments. For all studied topologies under physical layer impairments, the survivability strategies achieved blocking probability above 80%.

Keywords: elastic optical network, survivability, physical layer impairment.

1 Introduction

The growth in the number of Internet users and the appearance of new applications require the improvement of optical transport network. Recently, the optical network based on Orthogonal Frequency Division Multiplexing (OFDM) has been considered one of the main vehicles to undertake this evolution. With OFDM technology, the optical spectrum is divided into frequency slots that are 12.5 GHz wide, and a different number of slots can be allocated for each circuit [1]. Therefore, an OFDM optical network can allocate a spectrum for an optical circuit based on bandwidth requirements. This new generation of optical transport networks is called elastic optical networks (EON) due to the flexible allocation of bandwidth achieved by OFDM. The EON uses the optical spectrum more efficiently when compared to Wavelength Division Multiplexing (WDM).

The problem of Routing and Spectrum Assignment (RSA) must be solved to establish an optical circuit in an EON [2]. The RSA problem consists in defining a route for a given source-destination node pair. Then, the RSA solution should choose a free spectrum range (i.e., set of slots of contiguous frequency) within the defined route to establish the optical circuit.

Links in EON networks have high transmission capacity, therefore a link failure represents the loss of a large amount of data. A failure affects all circuits that traverse the failed link. A failure in EON may imply a loss of large amounts of data and interruption of critical services. Thus, an EON network must implement strategies to guarantee that failures can be quickly and efficiently recovered. The ability of EON to survive after the occurrence of failures is known as optical network survivability.

Several papers were proposed to improve the performance of EON [2] [3] [4]. In a relevant number of those papers new RSA algorithms are proposed. In other works, the RSA problem is studied under physical layer impairments. The problem of survivability in EON also is studied in related literature. As far as we know, no work has ever been done analyzing the optical survivability strategies considering physical layer impairments. In a more realistic context, the RSA algorithms should be compared considering the failures probability and the physical layer impairments. In this paper we carried out a performance evaluation study that compares two survivability strategies under physical layer impairments by computer simulation. In this study we analyze the performance of survivability strategies considering three different network topologies.

The remaining sections of the paper are organized as follows. Section 2 presents the elastic optical networks. Section 3 discusses some important concepts of survivability in EON and related studies. The physical layer model that is used to compute the physical impairments is described in Section 4. In Section 5 a performance evaluation study comparing the survivability techniques is made. Finally, Section 6 presents some conclusions.

2 Elastic Optical Network

In an elastic optical network the optical spectrum is subdivided in frequency intervals of 12,5GHz. A set of slots must be allocated in each link of the selected route for the establishment of an optical circuit. Figure 1 illustrates a simple example of slots division in optical fiber.

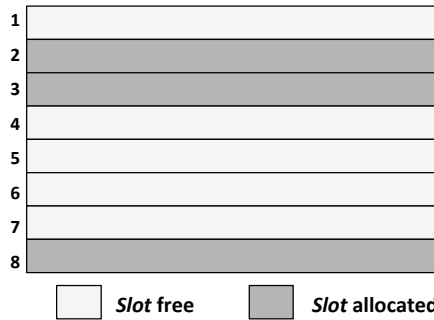


Figure 1: Simple example of the slots division in an optical fiber

Figure 1 presents an optical fiber with 8 slots. Each slot has an index (1 to 8). Each slot can be used separately for different optical circuits or aggregated in a single circuit to provide a larger bandwidth.

In order to establish an optical circuit between a source node and a destination node, it is required to define a route and to assign a spectrum (i. e. set of slots) to each link of the route. This is known as the Routing and Spectrum Assignment (RSA) problem. It is required that the assigned frequency slots be the same along the whole optical circuit. These frequency slots must also be adjacent to each other to satisfy the constraint of spectrum contiguity.

The RSA problem can be solved by using two distinct approaches: sequential or integrated. In the sequential approach, the resources are allocated in two steps. First the route is selected by a routing algorithm. In the second step, the frequency slots are allocated in the links of a selected route. In this case, a routing algorithm and another algorithm are used to allocate the frequency slots. In the integrated approach, the route and the frequency slots are selected in a single step, using only one algorithm.

Some of the most cited spectrum assignment algorithms in literature are First Fit, Exact Fit and Last Fit [2]. The First Fit algorithm chooses the frequency slot (a set) available with lower index. The Exact Fit algorithm tries to allocate the set of available slots with an amount of slots equal to the optical circuit request. If there are no sets of slots equal to the amount of slots requested, the Exact Fit algorithm selects

the set of slots with an approximate amount of slots to establish the optical circuit. The Last Fit algorithm tries to allocate the set of slot at the end of the optical spectrum.

The amount of frequency slots used in each optical circuit depends on the modulation format adopted [2]. The modulation is the way that the digital information is represented in optical channels [5]. A given modulation format can transport more bits per symbol than others. For example, 32QAM format transports more bits per symbol than BPSK format. On the other hand, the BPSK format reaches higher distances than 32QAM format. In this way, there is a relationship between the numbers of bit per symbol and the reached distance [6].

3 Survivability in Elastic Optical Networks

In an EON, the quantity of data transported is high. A single fiber can be transported between 10 to 100 Tbps [7]. Therefore, a failure in such kind of network may imply in loss of large amounts of data and interruption of critical services. For example, the Gartner Research Group lost about 500 million dollars in 2004 due to network failure [8]. In this way, the high availability is an important requirement that must be taken into account during the planning of the network. Thus, survivability strategies must be used to improve the network availability after failure occurs [9], [10] [11].

Optical survivability is typically classified as protection or restoration strategies [2]. Protection strategies consist in reserving redundant resources (i.e. before the failure happens) that in a possible failure will replace the failed ones. In restoration strategies, redundant resources are not allocated. Restoration tries to find disjoint resources in order to recover the failure.

Besides, protection and restoration survivability strategies can be applied to a link or path [12]. In the link protection/restoration, the strategy tries to bypass just the failed link. In the path protection/restoration, the strategy changes the entire path that contains the failed link (a disjoint path is then used).

The protection can also be classified as dedicated or shared. Two disjoint routes (primary and backup) are assigned for each circuit request in the dedicated protection. The former is called primary route, and it is used in the absence of failure. The latter, backup route is used if any resources of the primary route fail. The resources of backup route are dedicated and exclusive to bypass some failure of the primary route. Alternatively, in the shared protection, the resources of backup route are shared among other requests with disjoint routes. Figure 2 illustrates an example of dedicated path protection for A6NET topology.

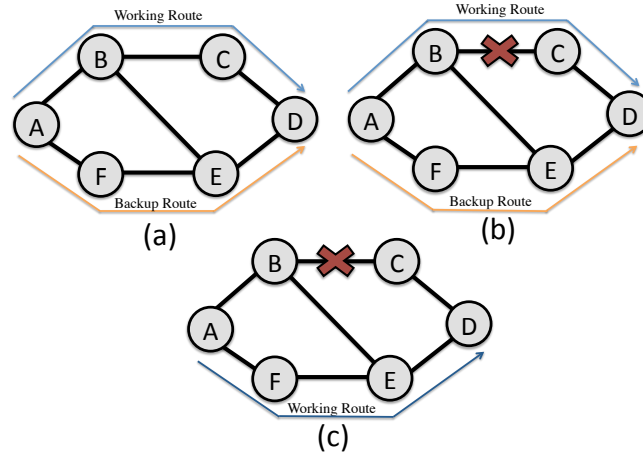


Figure 2: Example of dedicated path protection.

Figure 2 (a) shows the allocation of two disjoint routes to respond to a circuit request with source-destination node *pair*(A, D). The primary route is A – B – C – D and the backup route is A – F – E – D. In Figure 2 (b) the link B – C fails and the dedicated path protection strategy works to change the optical signal to backup route. In this way, the connection (A,D) survives the failure of link B – C.

Unlike protection, the restoration strategy is a reactive approach that tries to bypass the failure after it happens. The restoration can be classified as dynamic restoration or pre-computed restoration. In the former, the backup route is computed after the failure occurs; take into account the state of the network. In the latter, the backup route is previously computed but the resource are allocated only after the failure occurs. It is important to note that the restoration strategy does not guarantee that the resources will be

available in the backup route after the failure occur. Figure 3 shows an example of dynamic restoration for A6NET topology.

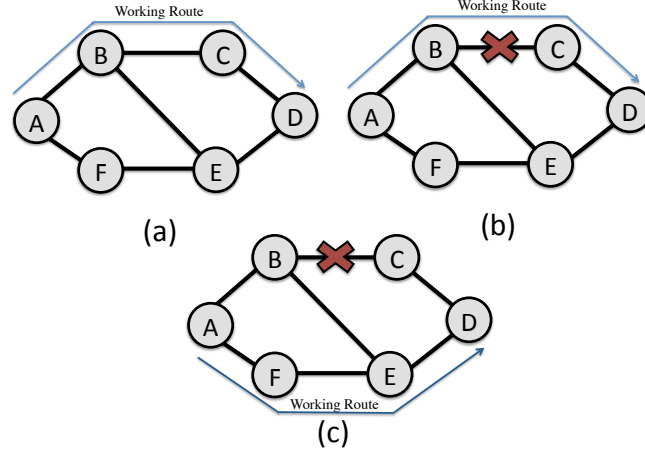


Figure 3: Example of path dynamic restoration.

Figure 3 (a) shows the use of the primary route $A - B - C - D$ to connect the nodes A and D. Before failure occurs, none backup route is computed or allocated. The dynamic restoration just compute the backup route after the control plan signals that a failure occurred (Figure 3 (b)). The connection cannot be restored if there are no free resources in the backup route. Figure 3 (c) presents the backup route computed ($A - F - E - D$) by dynamic restoration to survive the connection between the nodes A and D.

Other survivability strategies have been proposed in literature as alternatives to classic strategies. The authors of [13] propose a survivability strategy based on multipath. In this strategy a connection can use different optical paths to transport the data. This solution is named Survivable Multipath Routing and Spectrum Allocation (SM-RSA). The SM-RSA transports the data using N disjoint routes. Its aim is to reduce the impact of spectrum fragmentation. Besides, the SM-RSA improves the survivability of the connection because the data is transport using a different path. Only a part of the data is lost if a failure occur. In the SM-RSA strategy, a request is represented by $r = (s, d, B, q)$, where s and d are the source and destination nodes, B is the bandwidth requirement, and q is the survivability level requirement ($0 \leq q \leq 1$), indicating qB bandwidth must be available after any single link failure. In accordance to [13], to accommodate a connection request $r = (s, d, B, q)$ using multipath provisioning, it is required to find $N \geq 2$ link-disjoint paths between s and d and allocate capacity on each of the N paths so that the total capacity on the N paths is at least B , and the total capacity on any group of $N - 1$ paths is at least qB . Figure 4 illustrates the use of RSA-MS strategy to attend request $R_1 = (s_1, d_1, B=10, q=0.3)$ (Fig 4a) and $R_2 = (s_2, d_2, B=10, q=0.7)$. (Fig 4b).

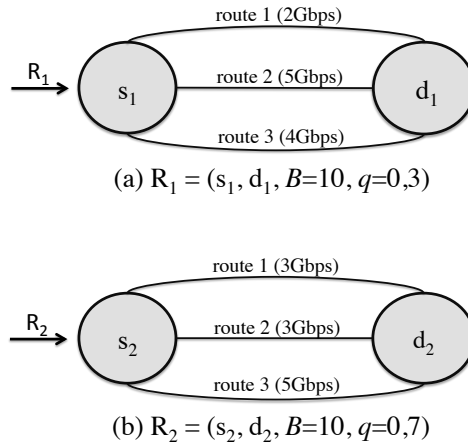


Figure 4: Example of algorithm SM-RSA.

The request R1 requires 30% of survivability ($q=0.3$) and 10 Gbps of bandwidth ($B = 10$). The solution illustrated in Figure 4a) uses 3 routes ($N=3$) and together they meet the bandwidth requirement ($B=10$ Gbps). Under a single failure scenario, if one link of a route 1 fails, route 2 + route 3 guarantee 9 Gbps (90% of survivability). If one link of a route 2 fails, route 1 + route 3 guarantee 6 Gbps (60% of survivability). In case of failure in route 3, route 1 + route 2 guarantee 7 Gbps (70% of survivability). Therefore, for all cases of single failure, the solution of SM-RSA (Fig. 4a) respects the requirements of the $R1=(s1,d1,B=10,q=0.3)$.

For the request $R2 = (s2, d2, B=10, q=0.7)$ illustrated in Figure 4b), under a single failure scenario, the requirement of bandwidth is respected, but the survivability level is disrespected. The solution also uses 3 routes ($N=3$) and together they meet the bandwidth requirement ($B=10$ Gbps). However, if one link of a route 3 fails, route 1 + route 2 just guarantee 6 Gbps (60% of survivability). In this case, the solution of SM-RSA (Fig. 4b) does not respect the requirements of $R2=(s2,d2,B=10,q=0.7)$. Therefore, the R2 request must be blocked because its requirement cannot be attended.

In [13] the SM-RSA strategy presents better performance when compared to other survivability strategies based on single-path. In general, SM-RSA obtains greater efficiency in terms of blocking probability when values lower than q are used. However, the choice of reduced values of q decreases the survival of the algorithm.

4 Physical Layer Impairment

Naturally, there is a degradation of the quality of the optical signal during its transmission. This is due to physical layer effects. Degradation occurs both on the devices on the network nodes and on the links. The literature agglutinates such degradations in two classes: Linear Impairments (LI) and Nonlinear Impairments (NLI) [14]. Linear Effects are those independent of signal power. Chromatic Dispersion (CD), Amplified Spontaneous Emission (ASE) and Fiber Attenuation are effects of this category. Nonlinear effects are dependent on the power of the optical signals and can cause interference both in the circuit itself and in its neighbors. Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four-Wave Mixing (FWM) are examples of nonlinear effects.

During the transmission of a signal, the greater the distance traveled from the fiber, the greater the signal power attenuation. This occurs in such a way that it generates a need to amplify the optical signal so that it reestablishes its power and thus can be detected at the destination. Usually, optical amplification is performed by the Erbium Doped Fiber Amplifier (EDFA) amplification equipment. EDFA amplifiers naturally introduce ASE noise [15]. This work considers ASE noise.

In addition, the effects of SPM, XPM and FWM are considered. SPM occurs because the refractive index of the fiber has an intensity-dependent component. This causes an induced phase shift that is proportional to the pulse intensity and causes different parts of the pulse to suffer different phase shifts [16]. The XPM is the phase shift of a signal caused by the intensity fluctuations of other channels that share the same fiber at different optical frequencies. This effect may be reduced by increasing the spacing between the circuits or by causing circuits to operate at different bit rates [15]. Finally, the FWM occurs by the non-linear action between three optical frequencies that give rise to a fourth frequency. If the fourth frequency is equal to or close to one of the other three, this signal will interfere with the circuit bandwidth [15]. Considering these four effects are in line with what literature deals with. For this work we will use the physical layer model proposed in [17, 18].

In an elastic optical network, such physical layer effects may impact the quality of the optical signal, as its Bit Error Rate (BER) may become intolerable. In this sense, if BER reaches high levels, Quality of Transmission (QoT) will be impacted. Thus, it can generate a block by QoT [19]. The optical receivers have a performance curve that associates the Signal to Noise Ratio (SNR) directly with the BER, so the SNR can be used as the physical layer QoT criterion of an optical circuit.

According to [17, 18] the calculation of the SNR for circuit i using route r_i is expressed by:

$$SNR_i = \frac{I}{I_{ASE} + I_{NLI}}. \quad (1)$$

The variable I is the Power Spectral Density (PSD), where $I = P_{TX}/\Delta_f$, in which P_{TX} is the power of the signal and Δ_f is the bandwidth of the circuit. The PSD of the ASE noise is given by:

$$I_{ASE} = \sum_{l \in r_i} N_l I_{ASE}^0, \quad (2)$$

where N_l is the number of spans of the link l and $I_{ASE}^0 = (G_{AMP} - 1)Fh\nu$. The variable F is the spontaneous emission factor, which is equal to half of the Noise Figure (NF) of the amplifier [19], h is Planck's constant,

v is the light frequency and G_{AMP} is the gain of the optical amplifier. Equation 3 shows the PSD of the noise of nonlinear effects Nonlinear Impairments (NLI):

$$I_{NLI} = \sum_{l \in r_i} N_l I_{NLI}^l, \quad (3)$$

where I_{NLI}^l is the PSD of the NLI noise in a single span of the link l and is expressed by [18]:

$$I_{NLI}^l = \frac{3\gamma^2 I^3}{2\pi\alpha|\beta_2|} \left(\operatorname{arcsinh} \left(\frac{\pi^2 |\beta_2|}{2\alpha} B_i^2 \right) + \sum_j \ln \left[\frac{\left(\Delta_{f_{ij}} + \frac{B_j}{2} \right)}{\left(\Delta_{f_{ij}} - \frac{B_j}{2} \right)} \right] \right), \quad (4)$$

where j is another circuit using link l ; B_i and B_j are, respectively, the bandwidths for circuits i and j ; $\Delta_{f_{ij}}$ is the spacing from the central frequency between circuits i and j ; γ is the non-linear coefficient of the fiber; β_2 is the dispersion parameter of the fibre; and α is the power attenuation caused by the fiber.

If the QoT levels are not adequate, the request can be blocked by QoTN (QoT in the new circuit) or QoTO (QoT in other already established circuits)[20]. The QoTN is the blockage suffered if the new request does not reach the appropriate levels of QoT. Even if a new request meets this requirement, it may still be blocked if the establishment of the new request impacts the QoT of the already established circuits, thus causing the QoTO. These two types of block are considered in the performance evaluation of this paper.

5 Performance Evaluation

This section presents a study to evaluate the performance based on simulations of discrete events. Simulations were carried out using SLICE Network Simulator (SNetS), a simulation tool that was developed to evaluate the performance of OFDM elastic optical networks.

In order to validate the results obtained through simulations with SNetS, a comparison with simulation results presented in [21] was performed. All parameters used in this validation study are in accordance to the model presented in [21]. In this validation study we compare the blocking probability of K Shortest Path (KSP) considering $k=1, 2, 4$ for NSFNet topology. We assume modulation level (m) of 2 and 4 bits per signal. Figure 5 shows the simulation results obtained by SNetS and in [21], respectively.

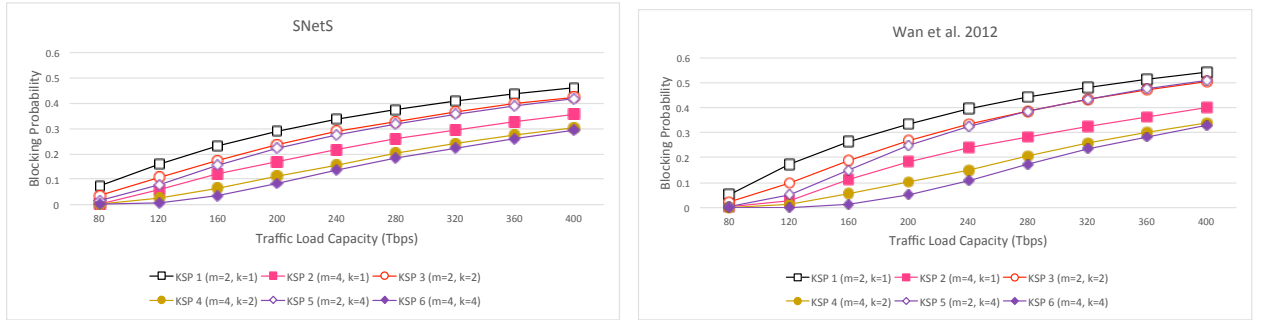


Figure 5: Blocking probability of KSP obtained by SNetS and [21]

One may observe from the curves that SNetS provides blocking probability results with similar behavior to those results presented by [21].

In this section, the performance of Survivable Multipath Routing and Spectrum Allocation (SM-RSA) and Dedicated Path Protection (DPP) strategies are compared under physical layer impairments. The blocking probability of both survivability strategies is analyzed for NSFnet, EON and USA network topologies, shown in Figure 6. The value shown on each link of the topology indicates the link distance in km.

The performance evaluation study considers the network without and with physical layer impairments. In the network without physical layer impairments, the modulation is calculated based on the maximum reach of the transmission, in accordance to [2], [13]. It is important to note that such assumption is not realistic. Therefore, in this paper our main contribution is to study the performance of survivability strategies under physical layer impairments. In this more realistic context, the modulation is calculated taking into account the QoT of each optical circuit. Such approach is in accordance to [19]. For the selected route the QoT achieved to each modulation format is verified. After that, the most efficient modulation format that respects the threshold required by the network is chosen.

Following the more realistic modeling approach, we can decompose the overall blocking probability of the network into three components: (i) blocking by the Lack of Available Slot (LAS); (ii) OSNR Inadequate

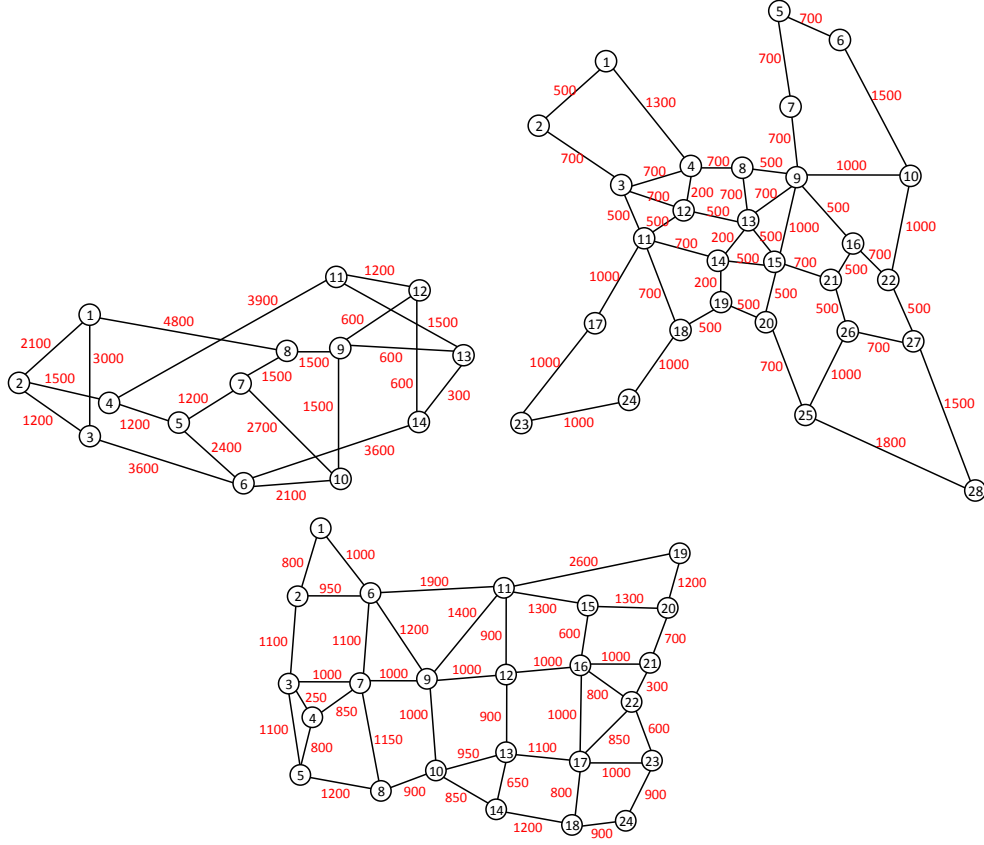


Figure 6: NSFNet, EON and USA topologies.

to the New optical circuit (OIN) and (iii) OSNR is Inappropriate for some of the Other optical circuits (OIO) already active in the network. In this paper, OIN and OIO blocking are related to QoTN and QoTO blocking, respectively.

The physical layer model presented in Section 4 was implemented in SNetS to assess the impact of the effects of the physical layer in optical circuits. All of the network links are bidirectional and have bandwidth of the spectrum divided in 400 frequency slots. The frequency slots have bandwidth of 12.5 GHz and the guard bands have bandwidth of 6.25 GHz [16]. The gains of the amplifiers were designed to compensate for the losses. Others parameters used in the simulations are listed in Table 1.

Table 1: Physical layer parameters used in the simulations.

Description	Value
Signal power spectral density	-17 dBm/GHz
Power attenuation	0,2 dB/km
Length of each span	16 ps ² /km
Fiber nonlinearity coefficient	1,3 (Wkm) ⁻¹
Length of each span	100 km

A dynamic traffic model was used in the simulations, where connection requests arrive at each node following a Poisson process with an average rate λ . The load is distributed uniformly for all nodes. The holding time of connections is distributed exponentially with an average $1/\mu$. The network load is $\rho = \lambda/\mu$. A total of 100,000 requests are generated for each replication. For each simulation, 10 replications are performed with different random variable generation seeds. In all of the results presented in this paper, a confidence level of 95% was considered.

We studied the SM-RSA performance under the following different values q (0.6; 0.7; 0.8; 0.9 and 1.0). Such values of q mean survivability levels of 60%, 70%, 80%, 90% e 100% respectively. The number of routes assumed was $N = 2$. Therefore, each optical request must be attended using 2 disjoint routes. The bit rate requirements for each requested circuit can be 10, 40, 80, 100, 160, 200 and 400 Gbps. The modulation formats considered in this study were BPSK, QPSK, 8QAM, 16QAM, 32QAM and 64QAM, and their respective SNR thresholds are 6, 9, 12, 15, 18 and 21 dB [19].

Figures 7, 8, 9 present the blocking probability for a NSFNET, EON and USA topologies, respectively. In Figures 7 (a), 8 (a), 9 (a), the blocking probability is compared in both scenarios, with and without physical layer impairments. We use the PLI notation to indicate that the specific results were carried out under physical layer impairments. In the Figures 7 (b), 8 (b), 9 (b), the results are presented without PLI, for better visualization.

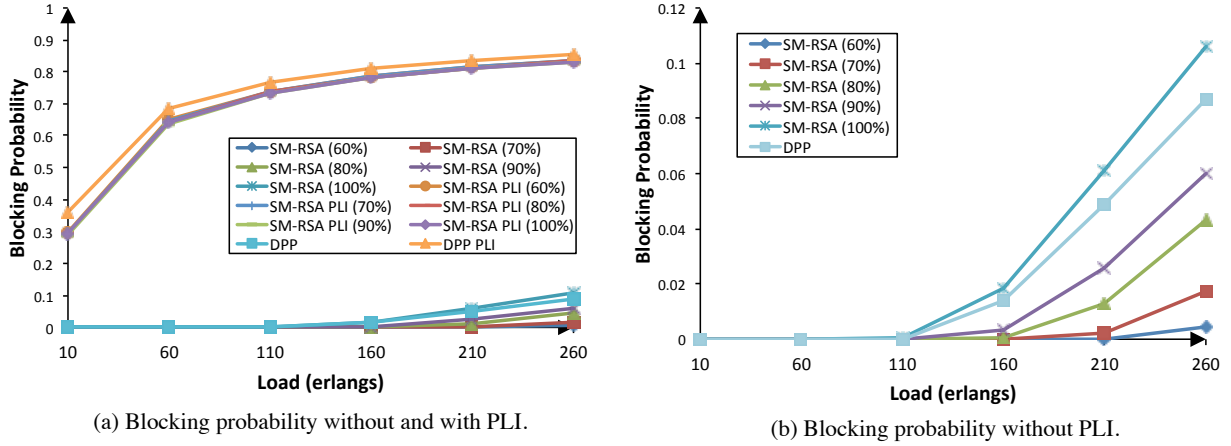


Figure 7: Blocking probability for NSFNet.

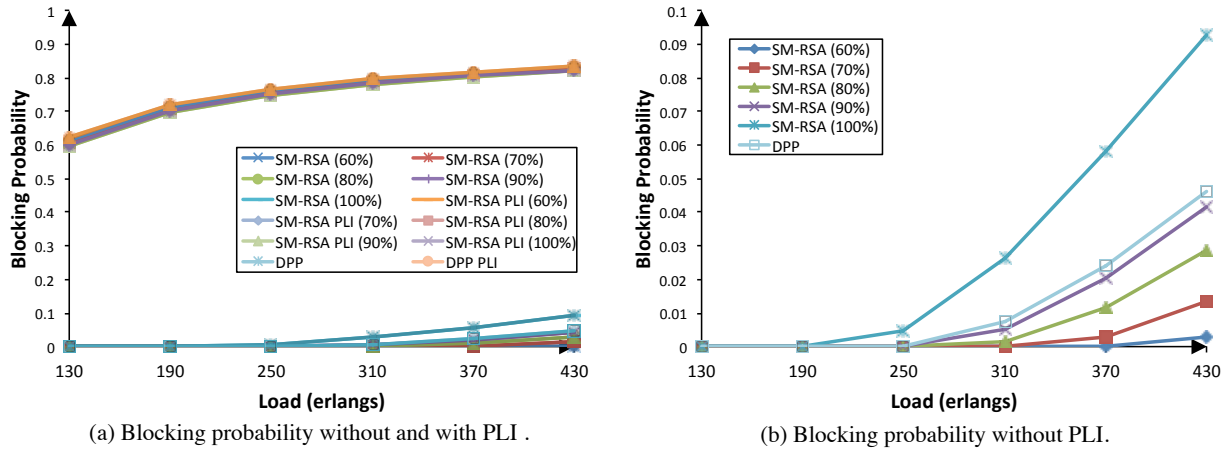


Figure 8: Blocking probability for EON.

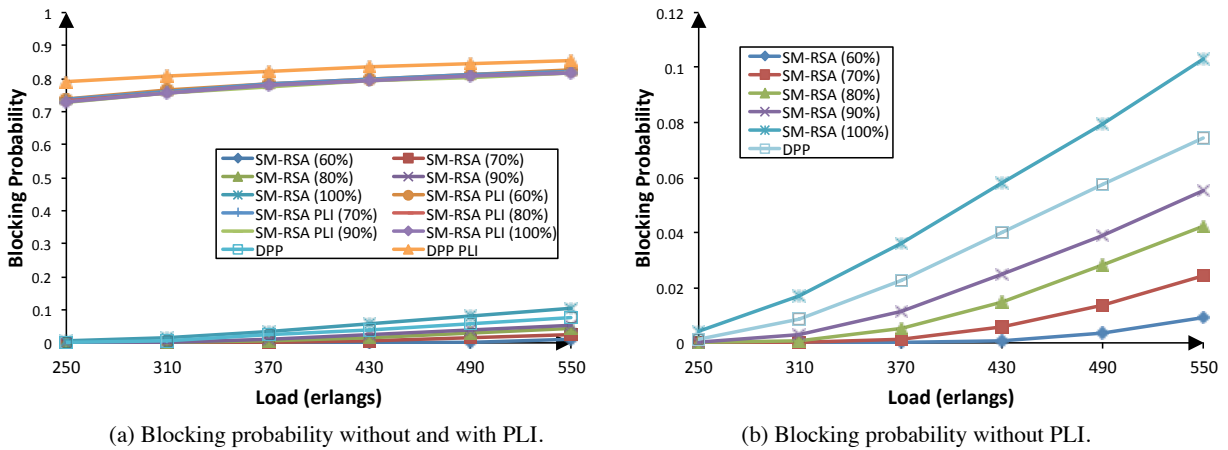
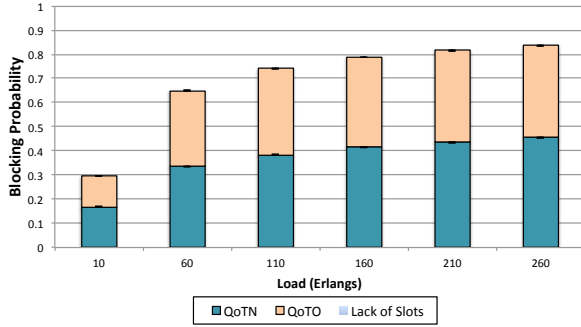


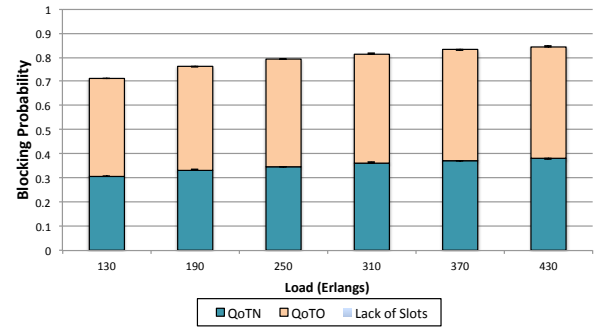
Figure 9: Blocking probability for USA.

From Figures 7(a), 8(a), 9(a), one observes that blocking probability is significantly higher under PLI when compared to a scenario without PLI. In the higher traffic load, the survivability strategies achieved blocking probability above 80% under PLI for three topologies studied. In general, the DPP present the worst performance when the physical layer impairments is assumed. For all topologies studied under the higher traffic load, the increase of blocking probability of network considering PLI when compared to the network without considering PLI is at least 500% for all survivability strategies. Such behavior indicates that it is important to consider the physical layer impairments when planning survivability of the elastic optical network.

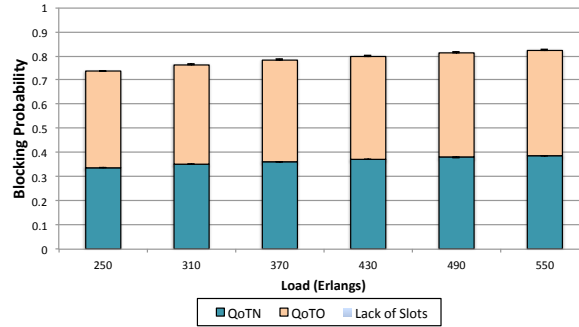
Figures 10a, 10b and 10c show the three components of blocking probabilities when the SM-RSA ($q=0.6$) is used for NSFNET, EON and USA topologies with PLI, respectively. This value of q was chosen because it was the one that obtained the highest relative increase of blockade probability, when compared to its scenario without PLI.



(a) Blocking probability composition for the SM-RSA algorithm with 60% survival in the NSFNet topology.



(b) Blocking probability composition for the SM-RSA algorithm with 60% survival in the EON topology.



(c) Blocking probability composition for the SM-RSA algorithm with 60% survival in the USA topology.

Figure 10: Blocking probability composition for the SM-RSA algorithm with PLI and 60% survival in the NSFNet, EON and USA topology.

From Figures 10a, 10b and 10c, one may observe that QoTN and QoTO blocks are the main responsible for high levels of blocking probability. Under the higher traffic load, the SM-RSA($q=0.6$) achieved 46% of QoTN and 38% of QoTO in NSFnet topology, 38% of QoTN and 46% of QoTO in EON topology, 39% of QoTN and 44% of QoTO in USA topology. The impact of PLI is high for all topologies, therefore there is not blocking due to Lack of Available Slot (LAS).

As seen, the algorithms proposed in literature do not take into account physical layer impairments. Thus, in the evaluation of performance of these algorithms, an increase in the probability of blocking is observed when inserting physical layer impairments. This shows the need to develop strategies considering more realistic scenarios.

6 Conclusion

This paper presented a novel study that compares the performance of survivability strategies with and without considering physical layer impairments in Elastic Optical Networks. As far as we know, no work has ever been done analyzing the impact of the physical layer impairments in the blocking probability of survivability strategies proposed to elastic optical network.

For all topologies studied, the SM-RSA and DPP survivability strategies obtained high blocking probability rates due to the physical layer impairments. The DPP and SM-RSA strategies achieved blocking probability above 0.80 for NSFNet, EON and USA topologies.

In future works, we intend to study a large number of survivability strategies only under physical layer impairments. We also intend to evaluate the performance of survivability strategies in translucent elastic optical network by using some regenerators to reduce the blocking probability due to physical layer impairment. Besides, we will study survivability strategies considering traffic load that achieved up to 1% of blocking probability.

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