# PLI-Aware Dynamic Routing in Software Defined Elastic Optical Networks (SD-EONs)

Arash Rezaee[†]
arash_rezaee@student.uml.edu

Ryan McCann[†]
ryan_mccann@student.uml.edu

Vinod M. Vokkarane[†]
vinod_vokkarane@uml.edu

[†]Electrical and Computer Engineering Department, University of Massachusetts Lowell, United States

***Abstract*—The ever increasing demand on the Internet leads to a growing desire for reliable connections more than ever. To this end, software-defined elastic optical networks need a comprehensive resource allocation method in their controllers that should be aware of load and physical layer impairments (PLIs). This paper proposes the PLI-Aware (PLIA) routing algorithm, which dynamically calculates all links' costs according to network states and PLIs. This algorithm reduces the request blocking probability due to awareness of congestion and lack of transmission quality.**

***Index Terms*—SDN, EON, RSA, PLIs, NLI, QoT, SD-EON**

## I. INTRODUCTION

Due to the Internet demand explosion, the efficient utilization of elastic optical networks (EONs) has become more critical in recent years. Also, this growth has led to the rise of the dynamic network load, indicating the critical role of control planes in network performance more than ever. Software-defined elastic optical networks (SD-EONs) as a fully centralized control plane have a more desirable performance compared to semi and fully-distributed control planes in terms of blocking probability and provisioning time [1]. The most crucial challenge of control planes is routing and spectrum assignment (RSA). Considering the quality of transmission (QoT) during RSA can result in realistic and reliable connections [2].

QoT of channels quantified by the signal to noise ratio (SNR), is affected by two types of physical layer impairments (PLIs): linear impairments (LIs) and non-linear impairments (NLIs) [3]. Several works have integrated the QoT into resource allocation, [4] proposes the effects of the PLIs in transparent EONs during the resource allocation step. For new and established requests, a margin for the SNR threshold is considered, leading to reduced blocking probability (BP). An impairment-aware resource allocation algorithm that minimizes power and spectrum wastage is presented in [5]. [6] considers a PLI, fairness, and fragmentation-aware algorithm that checks all possible available channels [6]. The main focus of [2] is QoT-aware spectrum assignment with load-balanced routing. Authors in [7] proposed a PLI-Aware RSA algorithm by considering a modulation level, links' unoccupied slots, optical reach, optical signal to noise ratio in routing, and a traffic balanced spectrum assignment for next generation EONs.

This work presents an algorithm that considers PLIs and the network load during its procedure. For PLIs, both linear and non-linear impairment effects of links as a weight that is calculated dynamically based on the network status. To the best of our knowledge, no other papers consider all of these metrics simultaneously in the routing step and as a link cost. The spectrum assignment is considered the same as the realistic methods introduced in [2]. Also, the conventional QoT-checked K-shortest path computation and realistic spectrum assignment (CQ-KSP), which were adopted from [2] and [7], are used as a benchmark.

## II. QOT-AWARE SD-EON CONTROL PLANE

Due to the convergence problem of distributed control planes in higher loads, SD-EON is presented as a fully centralized control plane with a logically centralized controller that separates the data plane from the control plane by means of the OpenFlow protocol to communicate between the control plane and infrastructures.

In the QoT-aware SD-EON, the controller collects the link states, PLI's information, and the network's physical topology for the accommodation of reliable connections. When a node sends a path computation request, the controller uses this updated data in order to allocate a path and a set of spectrum slots that meet the QoT constraints. Then, the controller communicates with the nodes of the computed path to reserve the assigned spectrum slots on their re-configurable optical add-drop multiplexer (ROADM) [2].

## III. PHYSICAL LAYER IMPAIRMENTS MODEL

Optical signals, which consist of several channels, are multiplexed and propagated on fiber and experience different types of impairments that degrade their quality. Amplifiers add incoherent photons spontaneously to amplify the optical signal, which leads to amplified spontaneous emission (ASE) noise. ASE is the most serious LI affecting optical reach and considers in this work. The power spectral density (PSD) of this noise is determined by:

$$G^{\text{ASE}} = (\exp(\alpha L_{\text{s}}) - 1) h\nu n_{\text{sp}}, \tag{1}$$

where $L_{\text{s}}$, $h$, $\upsilon$, and $n_{sp}$ are the fiber length per span, Planck's constant, light frequency, and the spontaneous emission factor, respectively.

The low complexity GN model estimates NLI, called the incoherent GN model (IGN), which includes self-channel interference, first term, cross-channel interference (XCI), and second term. Also, the polarization and channels assumptions are the same as [2], [3]. The generated NLI of spans is accumulated incoherently along a link. The loss of each span is compensated by an Erbium-doped fiber amplifier (EDFA),

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and all spans are identical. The IGN model calculates the PSD per polarization of the channel in each span by [3]:

$$\begin{aligned} {G_i}^{\mathrm{NLI}} =& \frac{3\gamma^2 G_i}{2\pi\alpha|\beta_2|}\left[{G_i}^2 \operatorname{arcsinh}\left|\frac{\pi^2|\beta_2|(\Delta f_i)^2}{2\alpha}\right|\right. \\ &\left. + \sum_{\substack{j=1 \\ j\neq i}}^{N_\mathrm{c}} {G_j}^2 \ln\left|\frac{|f_i-f_j|+\frac{\Delta f_j}{2}}{|f_i-f_j|-\frac{\Delta f_j}{2}}\right|\right], \end{aligned} \qquad (2)$$

where $\Delta f_i$, $f_i$, $G_i$ are the bandwidth, center frequency, and signal PSD per polarization of the $i^{th}$ channel, respectively. The SNR of channel $i$ is expressed by:

$$\mathrm{SNR}_i = \frac{G_i}{({G_i}^{\mathrm{NLI}} + G^{\mathrm{ASE}})N_\mathrm{s}}. \qquad (3)$$

The number of link spans and the number of channels in the fiber are denoted by $N_\mathrm{s}$ and $N_\mathrm{c}$, respectively. The rest of the parameters and launch power are the same as Table 1 and assumptions in [2]. For ensuring the QoT of channels, calculated SNR should be more than $\mathrm{SNR}_{\mathrm{th}}$. The $\mathrm{SNR}_{\mathrm{th}}$ is considered for the quadrature phase shift keying (QPSK) modulation format with a $4 \times 10^{-3}$ bit error rate with $\approx 1.5$ dB margin, which is equal to 8.5 dB.

## IV. PLI-AWARE DYNAMIC ROUTING ALGORITHM

This work considers transparent elastic optical networks that dynamically satisfy spectrum continuity and contiguity constraints. Resource allocation involves two phases, routing and spectrum assignment. We propose a new PLI-aware routing algorithm as described below:

### A. Routing

PLI-aware (PLIA) routing considers both LI and NLI values of each link to dynamically calculate the least-impaired path between every source-destination pair. In order to balance the physical distance or hop-count of the route, we introduce a weighted link metric in conjunction with the PLI.

The available frequency slots vector (ASV), adopted from [2], is represented for link $\ell$ of the network by $\mathrm{ASV}_\ell = \{(S_{\mathrm{L(i)}}, S_{\mathrm{U(i)}}) \mid 1 \leq i \leq N_\ell\}$, where $S_{\mathrm{L(i)}}$, $S_{\mathrm{U(i)}}$, $N_\ell$ are the start and end slots of window $i$, and the number of $\mathrm{ASV}_\ell$, respectively. Indeed, window $i$ represented by pair $(S_{\mathrm{U(i)}}, S_{\mathrm{L(i)}})$, contains $S_{\mathrm{U(i)}} - S_{\mathrm{L(i)}} + 1$ slots (the number of required frequency slots) which satisfies the contiguity constraint. To satisfy continuity constraints, the intersection of the ASVs of path links defines the ASV of the path.

The PLIA algorithm illustrates a PLI-Aware routing trying to minimize the LI and NLI simultaneously while tracking link loads by means of NLI. We have considered two policies for the proposed algorithm. In the first policy of this method, for each network link, the ASV is calculated according to the required slots. If a free channel exists, the NLI of each channel is estimated by the XCI part of Eq. 2, and the cost of the link is calculated with length, the worst case NLI, and the mean of ASV members' NLIs (using Eq. 4). Otherwise, the cost of the link is considered infinity. If the costs of all links are equal to infinity, the request is blocked. Otherwise, Dijkstra's algorithm finds the shortest path. The first term of the equation, by considering the length, attempts to reduce the distance, which leads to reducing the ASE noise. This algorithm, in two steps, considers the load, first after calculating the ASVs and second in the NLI part of the link cost. If the load increases, the NLI cost will increase. The worst-case NLI is the NLI of the middle channel when a span is fully occupied, and the maximum number of channels are used. The cost of link $\ell$ is calculated by:

$$C_\ell = \beta \times (\frac{d_\ell}{d_{max}}) + (1-\beta) \times (\frac{NLI_{mean,\ell}}{NLI_{worst}}), \qquad (4)$$

where $d_\ell$, $d_{max}$, $NLI_{mean,\ell}$, $NLI_{worst}$ and $\beta$ are the length of link $\ell$, the maximum length of network links, the mean of NLI of available channels on the link, the worst case NLI and weight of length in link costs, respectively. In the second proposed PLI-aware policy, link length is replaced by hop count, and the first term of Equation 4 is changed to $\beta \times (1)$.

### B. Spectrum Assignment

We incorporate the realistic algorithm from [2]. The realistic algorithm uses the first-fit spectrum allocation and checks the estimated SNR of the first available channel using Eq. 3. If the estimated SNR is above the threshold, the request is established. Otherwise, it is blocked.

## V. SIMULATION RESULTS

Comprehensive numerical simulations have evaluated the performance of the introduced approaches in Section IV in the SD-EON control plane. All of the simulations were implemented in the OMNET++ simulator. The simulations are performed on the Pan-European network, which is adapted from [2], including 27 nodes and 55 bidirectional links with 256 frequency slots of a 12.5 GHz bandwidth.

The generated traffic is uniformly distributed among node pairs. Inter-arrival times are considered with a Poisson distribution in the simulated EONs. The supported bit rates for lightpaths are 100 and 400 Gbps, which need three and ten slots for the QPSK modulation format. The inter-arrival and holding times of requests follow the exponential distribution, and the average holding time equals $3,600$s for all simulations. The average blocking probability results plotted in this section meet either a $90\%$ confidence interval or the maximum number of independent trials (5,000 seed values).

Figure 1(a) illustrates the lightpath blocking probability versus network load in the SD-EON control plane, for the proposed PLIA routing and realistic SA under different $\beta$ values for the two policies. In the legend, $\beta$ values followed by *d* refers to minimum distance policy and *h* refers to minimum hop policy. Growing network load leads to an increase in the blocking probability; in the higher loads, due to lack of resources, the blocking probability is increased; on the other hand, in the lower loads, the network's resources are vacant and the blocking is less likely. The second point, which is demonstrated in this figure, is the effects of decreasing the $\beta$ coefficient on the blocking chart. If $\beta$ equals one, distance is

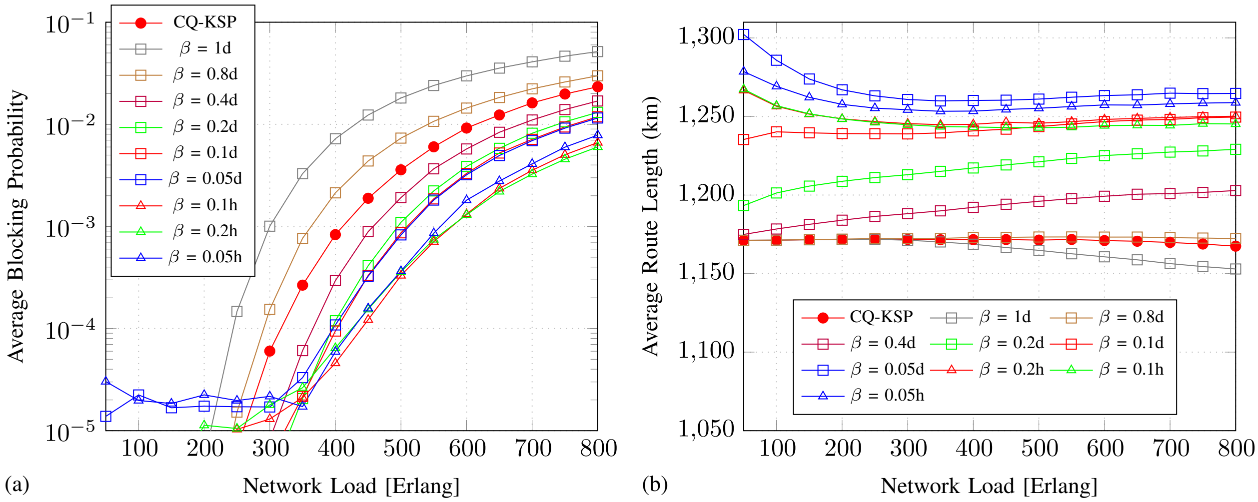

Fig. 1. PLIA routing with realistic SA algorithm in SD-EON control plane, (a) average lightpath blocking probability, (b) average established route length.

only considered as a cost and the algorithm works like the shortest distance path; decreasing $\beta$ shows that the algorithm increases the effect of NLI on links' costs and results in lower blocking probability. When $\beta = 0$, the algorithm ignores the distance (and LI effects), only focuses on reducing the NLI effects, and converts to the NLI-decreasing greedy algorithm. This assumption results in higher blocking at lower loads because most of the network's resources are empty, and this method tries to route the lightpath through longer paths with vacant links. Therefore, the signal experiences more LI effects, causing lower SNR and a higher blocking probability. For this reason, $\beta = 0$ doesn't lead to valid results and is eliminated from the figures. To improve the readability, we have also removed $\beta = 0.6$ plot, as it is identical to the BP behavior of CQ-KSP. The results show that the best $\beta$ value for reducing the blocking probability is either 0.1 or 0.2, which has more rational behavior and better performance for different network loads. The improvement is significantly higher at low loads. On average, the PLIA algorithm for $\beta = 0.2$ reduces the blocking by about $58\%$ compared to CQ-KSP across all loads. The second policy, due to using the hop for the cost of links, uses a lower number of spectrum slots than length. For this reason, blocking probability decreases even further, especially in higher loads. For $\beta = 0.2$, the second policy presents a more than $45\%$ decrease in blocking probability for higher loads compared to the first policy.

Fig. 1(b) depicts the average length of successful lightpath versus network load. We observe that the average path distance of lightpaths is about 1,170 $km$ for all beta values. At higher loads, when the $\beta$ is decreased, the average length increases as the distance portion in the links' costs is lowered. The lightpaths are longer for $\beta$ equal to zero, particularly between 50-150 Erlang. The algorithm attempts to reduce the NLIs greedily and results in using more vacant links. The average established path length for CQ-KSP is constant for all loads. According to the simulation results, the mean hop of established lightpaths for all loads and $\beta$s and CQ-KSP are about 4.1, excluding the Erlang for $\beta = 0$. For Erlang 50 and $\beta = 0$, the mean hop is about 4.8. In the second policy, the established lightpath mean hop is reduced to about four, but the distance average is increased to about 1,250 $km$. The average route calculation time takes about 7 $ms$ for PLIA, while CQ-KSP takes less than 1 $ms$.

## VI. CONCLUSION

To conclude, we consider the load and PLI-Aware routing algorithm in the SD-EON controller. This algorithm decreases the request blocking caused by link congestion or linear and nonlinear impairments. Numerical results illustrate that the PLIA algorithm offers the lowest blocking probability for $\beta$ equals 0.2 and improves the blocking probability by $43\%$ in Erlang 800 compared to the benchmark. Finally, implementation of the presented algorithm in other networks and the modulation level adaptive routing algorithms and using other spectrum assignment methods are left for future research.

## REFERENCES

[1] A. Giorgetti et al., "Dynamic Restoration With GMPLS and SDN Control Plane in Elastic Optical Networks," *J. Opt. Commun. Netw.*, vol. 7, no. 2, pp. A174–A182, Feb 2015.

[2] A. Rezaee et al., "Quality of transmission-aware control plane performance analysis for elastic optical networks," *Computer Networks*, vol. 187, p. 107755, 2021.

[3] P. Johannisson et al., "Modeling of nonlinear signal distortion in fiber-optic networks," *Journal of Lightwave Technology*, vol. 32, no. 23, pp. 4544–4552, 2014.

[4] A. Fontinele et al., "An efficient ia-rmlsa algorithm for transparent elastic optical networks," *Computer Networks*, vol. 118, pp. 1–14, 2017.

[5] K. K. Munasinghe et al., "Joint minimization of spectrum and power in impairment-aware elastic optical networks," *IEEE Access*, vol. 9, pp. 43 349–43 363, 2021.

[6] H. Khanahmadzadeh et al., "Joint Fairness, Fragmentation, and Physical Layer Impairments Aware Routing, Spectrum and Modulation Level Allocation in Elastic Optical Network," in *2022 30th International Conference on Electrical Engineering (ICEE)*, 2022, pp. 1039–1044.

[7] H. Beyranvand et al., "A quality-of-transmission aware dynamic routing and spectrum assignment scheme for future elastic optical networks," *Journal of Lightwave Technology*, vol. 31, no. 18, pp. 3043–3054, 2013.