Novel impairment-aware resource allocation scheme for elastic optical networks serving traffic with different service priorities

Kusala Munasinghe
Department of Electrical and Electronic Engineering
University of Sri Jayewardenepura
kusalakalani@gmail.com

M. Nishan Dharmaweera
Department of Electrical and Electronic Engineering
University of Sri Jayewardenepura
nishanmd@sjp.ac.lk

C. de Alwis
Department of Electrical and Electronic Engineering
University of Sri Jayewardenepura
chamitha@sjp.ac.lk

Uditha Wijewardhana
Department of Electrical and Electronic Engineering
University of Sri Jayawardenepura
uditha@sjp.ac.lk

***Abstract*—: In this research paper, we propose a novel impairment-aware resource allocation scheme that increases spectrum efficiency of an elastic optical network (EON), while satisfying the quality of transmission (QoT) requirements of traffic connections with different service priorities (i.e., high and low priority traffic). To demonstrate the validity and superiority of our algorithm, we compared the results of our proposed resource allocation scheme against a benchmark algorithm. The results were simulated for a 6-node network and a 14-node network. Compared to the benchmark algorithm, on average, our proposed scheme increases spectrum efficiency by an additional 20 % while ensuring a minimum latency for high priority traffic, causing minimum disruptions to existing low priority traffic, and blocking less than 1 % of the total connections.**

Keywords— Optical communication, Elastic optical networks, Network optimization, Resource allocation schemes, Network impairments, Service priorities

I. INTRODUCTION

To cater the rapidly increasing internet traffic, the traditional Wavelength Division Multiplexing based (WDM-based) backbone networks have to be gradually replaced with advanced Orthogonal Frequency-Division Multiplexing (OFDM) based Elastic Optical Networks (EONs) [1]. Traditional WDM-based internet networks impose stringent constraints on bandwidth allocation and, thus, leads to low resource utilization. As a result, OFDM-based EONs, which is scalable, flexible, resource-efficient, and better suited for dynamic traffic demands of the future, is accepted as the next evolution in optical fiber-based internet backbone networks [1]. To support this, the current ITU-T rigid grid has defined finer grids known as subcarriers by dividing the optical spectrum of each fiber into small bandwidths [3,4].

With the aim of improving the benefits (i.e, reduced cost and energy consumption) and performance (i.e higher throughput and resource utilization) of EONs, within the last decade, researches have come up with several Routing, Modulation, and Spectrum Allocation (RMSA) schemes [1]. However, the accuracy of such algorithms depends on the method they have used to estimate the Physical Layer Impairments (PLIs). While some have used accurate models to estimate the PLIs [2-7], others have opted for simple estimation methods based on transmission reach limits [2,8].

The need for high-speed, high-quality, and high-capacity internet traffic is greatly driven by the emerging bandwidth-intensive applications such as telemedicine, biomedical applications, online gaming, virtual and augmented reality applications, cloud services, and 5G data networks [9]. However, as the network traffic increases, the available capacity of the existing optical fibers becomes a limiting factor and, thus, may eventually lead to blocked or dropped connections. Furthermore, latency, which generally depends on propagation distance, can have a negative impact on applications that require real-time high-speed transmission. As a result, if a traffic connection of a certain application (e.g. remote medical surgery over the internet) is blocked/dropped, or re-routed along a much longer path (i.e., higher latency), it may produce a faulty outcome [10]

In such situations, it is important to prioritize certain traffic connections and give them the precedence over connections with relatively low importance (e.g. online gaming). Such prioritized traffic connections should maintain minimal latency. If incoming high priority connections can be accommodated using the shortest path by disrupting (i.e., re-routing, re-tuning, re-modulating) a minimal number of low priority connections, better performance can be expected.

When surveying the existing literature, several attempts have been taken to enhance the spectrum utilization in optical fibers [3-6]. Among them, [4] provides a heuristic that minimizes the maximum subcarrier index of the optical fibers which is corresponding to the maximum bandwidth thereby increasing the efficiency of resource allocation in EONs. Since there is a need for prioritizing certain traffic connections over the other internet traffic, an improvement for the existing resource utilization heuristics is required in a way that it is capable of handling internet traffic with different priority levels. This has not been addressed yet.

As its outcome, the research proposes a novel resource allocation scheme for EONs, which ensures the allocation of shortest low-latency path for high priority traffic while increasing the spectrum efficiency of the network and causing minimum disruptions to exiting low priority traffic. PLIs are taken into account when allocating the spectrum slots for a particular traffic connection and practical results have been obtained by applying the proposed resource allocation mechanism for 6-node and 14-node networks.

II. METHODOLOGY

A. Network model and PLI calculation

1) Model: This paper adopts the Gaussian noise based PLI model (GN model) in [4]. The noise model dictates that the signal quality degrades due to the accumulation of amplified spontaneous emission (ASE) noise and non-linear impairments (NLI) caused by self-channel interference (SCI) and cross-channel interference (XCI). Each link in the network has 2 fibers carrying traffic in opposite directions and each fiber has 320 subcarriers of 12.5 GHz width [4]. It is assumed that the traffic connections between different source-destination pairs arrive sequentially at random time intervals and stay infinitely. Among total traffic, p percentage is assumed to carry high-priority traffic. Each traffic connection has a bit rate requirement, a source and a destination, and the priority value allocated for it. The number of subcarriers required for a certain traffic connection based on the available 3 modulation formats ($x \in \{M_1, M_2, M_3\}$) is calculated and 3 shortest possible paths between any source and destination ($r \in \{r_1, r_2, r_3\}$) is found. In order to allocate a route, a modulation format, and a contiguous subcarrier band, the priority order of the traffic connection is considered in the first place and minimizing the maximum subcarrier index of the network is considered second.

2) PLI calculation: To calculate the impairments, the equations used in [4] are used as it is. A route r_i, a modulation format M_i, and a range of continuous and contiguous spectrum slots are allocated for an incoming traffic connection i if ;

- Signal to Noise Ratio (SNR) for connection i when using route r_i is satisfied.
- The SNR requirement of each previously allocated connection is not violated after allocating connection i on the selected route r_i, modulation format, and spectrum slots.

B. Proposed scheme

Given: the network model and the relevant parameters, quality of transmission (QoT) constraints, and the service priorities of incoming traffic, the proposed RMSA scheme aims to,

Maximize: spectrum efficiency and throughput of the network and **minimize** the disruptions caused to low priority connections while,

Adhering to: the following constraints: 1) serve all traffic connections, 2) ensure spectrum continuity and contiguity on transparent links for every connection, 3) perform non-overlapping spectrum allocation, 4) guarantee QoT performance, 5) and minimize latency for high-priority connections.

Flow diagram of the proposed scheme (i.e., algorithm) is summarized in Fig.1. In the proposed scheme, the traffic connections are served in the corresponding order they arrive. Initially, the maximum subcarrier index E is set to a small value (e.g. 10) and as shown in Diagram 1 of Fig.1, all the traffic connections are allocated the shortest possible path between its source and destination. The available continuous and contiguous slots in each link along the selected route are found and if the number of available continuous and contiguous slots is greater than the required number of subcarriers for the highest order modulation format, the PLIs of that particular traffic connection is calculated using Equation 1. As long as the SNR requirement is satisfied before and after allocating the selected slots, following Diagram 2 of Fig.1, the traffic connection is served using the selected route, selected modulation format and the selected spectrum slots. In situations where the SNR requirement fails, the other spectrum slots or the other modulation formats are tried. As shown in Diagram 4 of Fig.1, when a link is loaded with traffic connections and there is not enough space for a new connection along the shortest path, the incoming low priority (LP) connections are routed along alternative paths with enough spectrum and acceptable SNR values. If an incoming high-priority (HP) traffic connection cannot be served along the shortest path due to lack of spectrum, the blocked link and the blocked contiguous spectrum slots are identified by the algorithm shown in Diagram 3 in Fig.1. It checks whether the identified subcarrier range in the blocked link is already occupied with a LP connection and if so, that LP connection is removed (i.e., disrupted) and re-routed along a different path.

TABLE 1: THE SYMBOLS AND ABBREVIATIONS

Symbol	Meaning
i	Traffic connection
Mi	Modulation format Selected for connection i
fi	First Sub-carrier Index of connection i
φ_i	Last Sub-carrier Index of connection i
φ	Last subcarrier index of l
x	Modulation format considered ($x \in \{M_1, M_2, M_3\}$)
M_1	Highest Order Modulation format (16-QAM)
r_i	Selected route for connection i
r	Shortest possible paths considered ($r \in \{r_1, r_2, r_3\}$)
r_1	Shortest path
Tx_i	Required number of sub-carriers for connection i when it is assigned x
S_r	Set of available continuous and contiguous slots along r
Ω	State variable 1 ($\Omega=0$ when $S_r \neq [\,]$)
C_l	Cost of link l on route r
B	State variable 2 ($B=0$ when condition 1 is failed
BER	Bit Error Rate
A	State variable 3 ($A=1$ when BER is satisfied
Ly	Previously allocated LP connection on r_1 ($Ly \in L$)
L	Set of Ly on considered r_1
T_{xy}	Range of assigned sub-carriers for Ly
U_{max}	Maximum Subcarrier index
u	Spectrum slots required when M_1 is considered
LP	Low Priority Traffic connection
HP	High Priority Traffic connection
N_l	Number of spans on link l
G^0_{ASE}	PSD of ASE of a single span
G	Signal Power Spectral Density (PSD)
SNR_x	Signal to Noise Ratio threshold of modulation format x

The research is fully funded by National Research Council of Sri Lanka under the Grant Number (18-028)

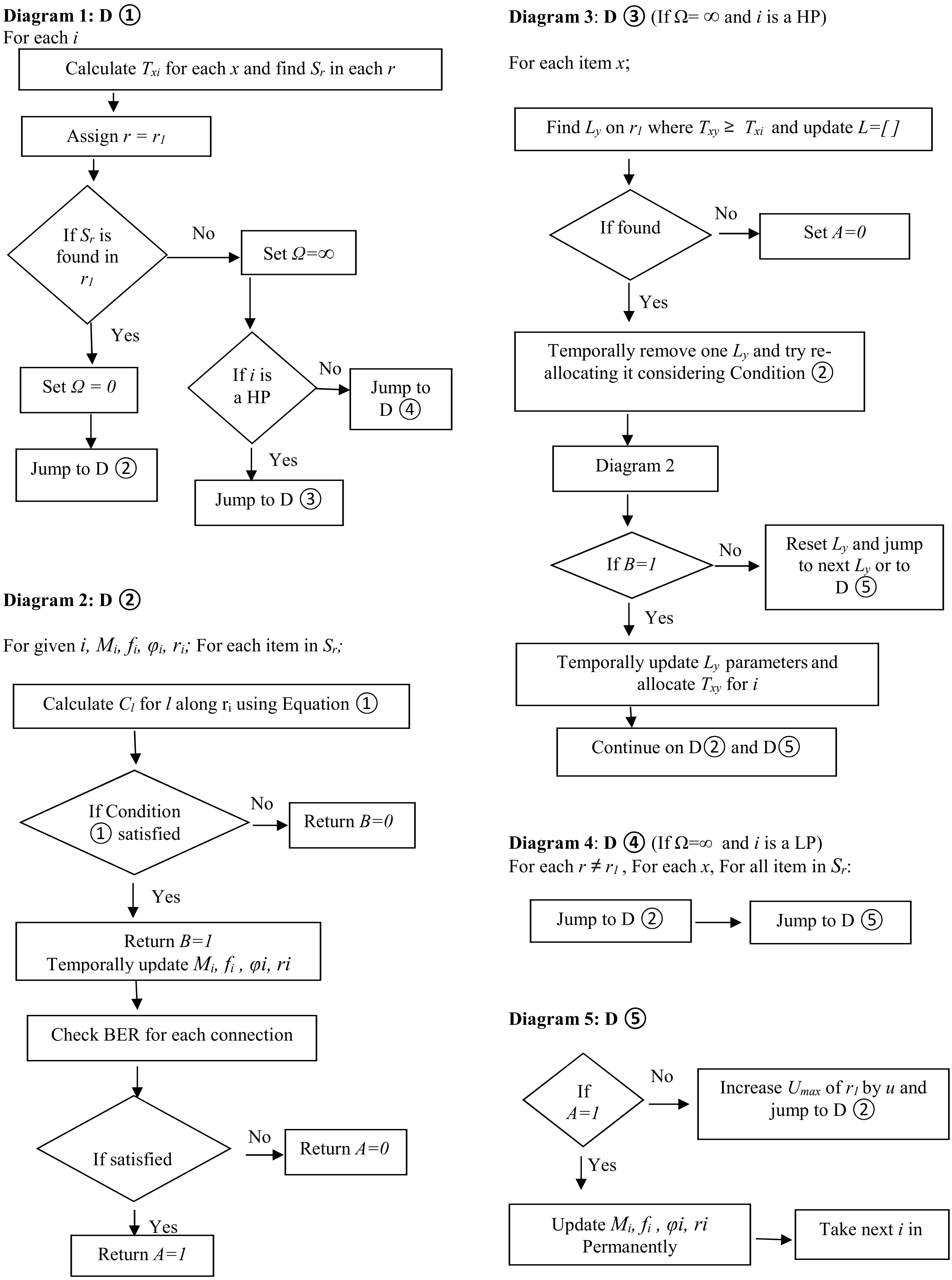

Fig. 1. The basic flowchart of the proposed algorithm

To minimize the need for re-tuning and re-modulating attempts are always made to find to accommodate a disrupted LP along an alternative route using the same modulation format and the same set of slots. However, if the adequate number of contiguous slots for the selected modulation format cannot be found in any alternative route, the LP traffic is re-tuned and then re-modulated.

Whenever there is an insufficient number of continuous and contiguous spectrum slots along the shortest path for HP connections even after considering the possibility of disrupting existing LP connections, E is extended by the minimum number of subcarriers required for the corresponding traffic connection (Diagram 5 of Fig.1). This process repeats for all the traffic connections.

The symbols and abbreviations used in Fig.1 are explained in Table 1. Equation 1, which is used to calculate the cost in terms of total impairments on a given link, and its respective values and notations were directly extracted from [4]. The set of conditions used for the assessment of SNR requirements, assignment of minimum subcarrier index, and minimizing LP connection disruptions are defined by Conditions 1 and 2.

$$C_l = \begin{cases} +\infty, \text{ if any subcarrier on } l \text{ from } f_i \text{ to } f_i + T_{xi} - 1 \text{ is unavailable} \\ N_l \left(G^0_{ASE} + \mu \operatorname{asinh}(\rho T_{xi}^2) + C_{l(\text{past})} + C_{l(\text{future})}\right) \text{ otherwise} \end{cases} \quad (1)$$

Condition 1

$$\text{If } \sum_{l \in r} \le G / SNR_x \quad \text{and} \quad T_{xi} + f_i - 1 \le \varphi \quad (2)$$

Condition 2

- Try to re-route L_y using T_{xy} (same spectrum-slots) and M_y (same modulation format).
- If failed: Try to re-route L_y using T_{xy} (same spectrum-slots), but with a different modulation format.
- If failed: Try to re-route L_y using different spectrum-slots and with a different modulation format.

C. Benchmark algorithm

To the best of our knowledge, an impairment-aware resource allocation scheme for EONs with different service priorities has not been presented in the existing literature. Therefore, the impairment-aware algorithm presented in [4], which has often been used as the benchmark in previous work [3,5,6] and has shown better performance over baseline algorithms with fixed guard bands, was selected as our benchmark. However, as different service priorities were not included in [4], the heuristic in [4] was slightly modified by adding the relevant constraints for HP connections. Since the simulations were performed on a dynamic network, a feasible Integer Linear Programming (ILP) based optimal solution could not be found for comparison.

III. RESULTS

A. Simulation Setting

As shown in Fig. 2 and Fig. 3, a 6-node network and the 14-node Deutsche Telekom (DT) network were used for the simulations. The label next to each link indicates the length in terms of spans. Each span was assumed to be 80 km in length. The parameters related to physical layer impairment calculations are taken from [4]. Three modulation formats have been used (Mi = 3): QPSK, 8-QAM, and 16-QAM.

For the small 6-node network and the 14-node network described above, the results of the proposed heuristic (indicated as Heuristic 2 in the graphs) and modified benchmark heuristic (indicated as Heuristic 1) are compared. Since the study intends to increase spectrum efficiency, the maximum subcarrier index is taken as the result in all simulations [3-6]. The number of blocked connections and disruptions are also recorded. The heuristics were run on a desktop computer with 6-core, i7 8700 CPU and 32GB RAM. The total running time for simulation is 3 hours and 16 minutes.

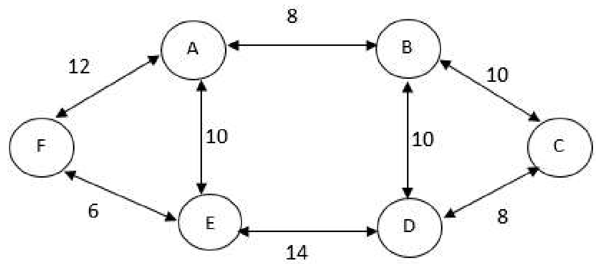

Fig. 2. Number of spans on each link of the 6-node network

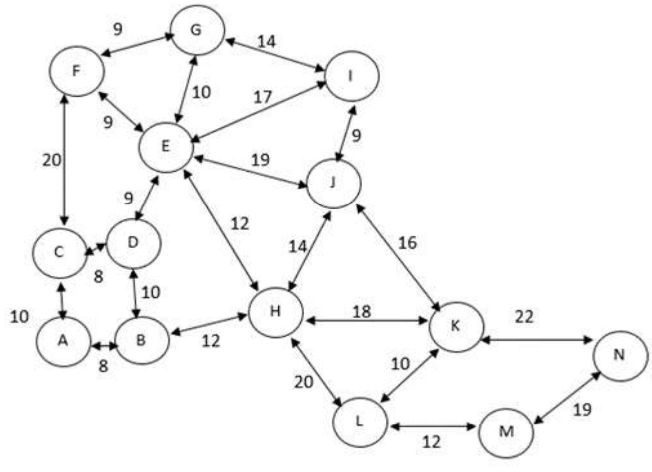

Fig. 3. Number of spans on each link of the 14-node network

Results have been obtained for varying network traffic loads. Each traffic load was generated by increasing the number of total connections entering the network. The bit rate and the arrival time of each traffic connection were generated randomly. For each traffic load, the experiments were repeated fifty times and the average result was taken. The results (i.e., maximum subcarrier index) were then plotted against the total network load.

The bit rate requirement of each connection was allowed to take any value between 300 Gbps and 500 Gbps. The power spectral density (PSD) was set to an optimum value of 0.02 W/THz [4]. Depending on the percentage of HP traffic entering the network, the results were depicted separately for the two networks.

TABLE 2 SIMULATION RUN TIME

Network	Run Time for Proposed Heuristic	Run Time for benchmark algorithm	Percentage difference of Run Time
6-node	25 minutes	22 minutes	12%
14-node	56 minutes	48 minutes	14.28%

B. Results for 6-node Network

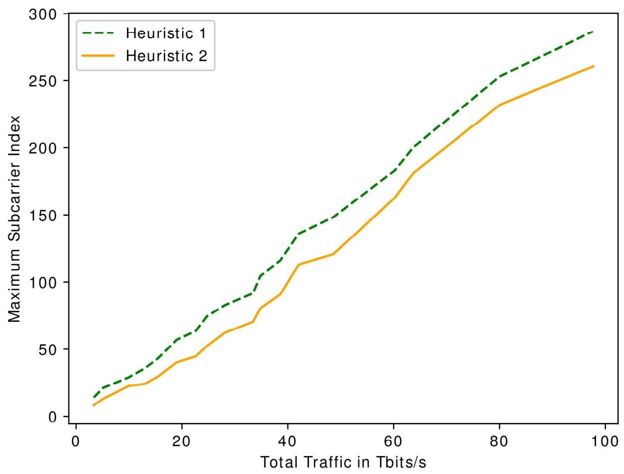

Fig. 4. 25 % of the total traffic is HP traffic

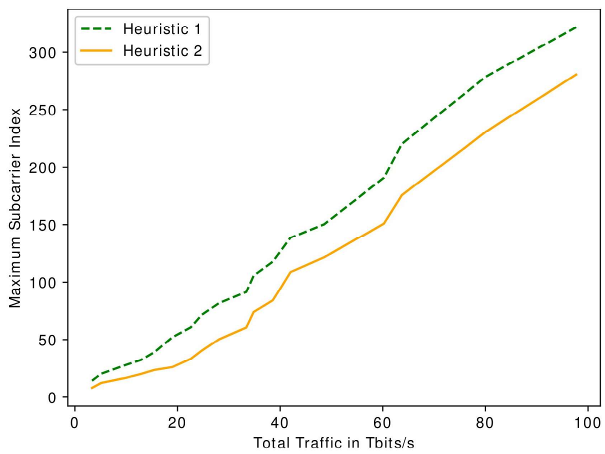

Fig. 5. 50 % of the total traffic is HP traffic

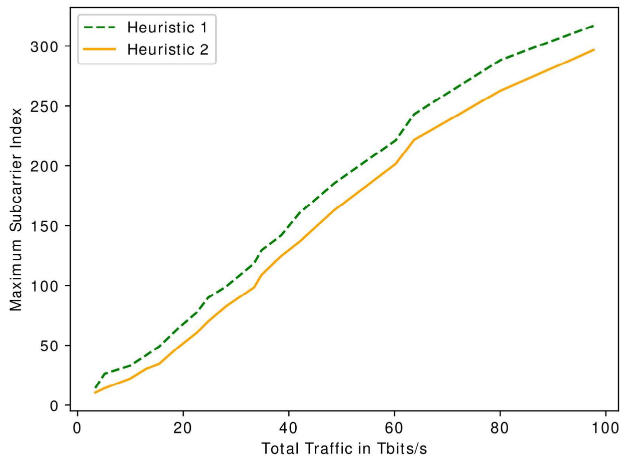

Fig. 6. 75 % of the total traffic is HP traffic

C. Results for 14-node Network

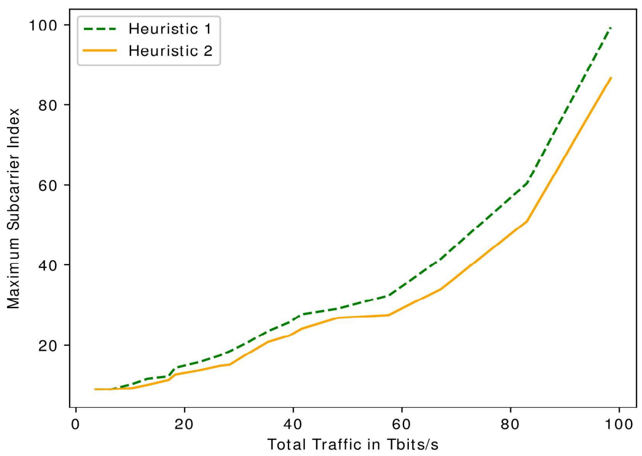

Fig. 7. 25 % of the total traffic is HP traffic

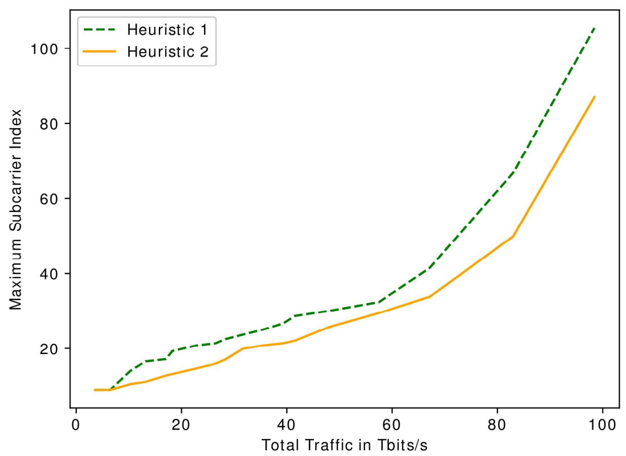

Fig. 8. 50 % of the total traffic is HP traffic

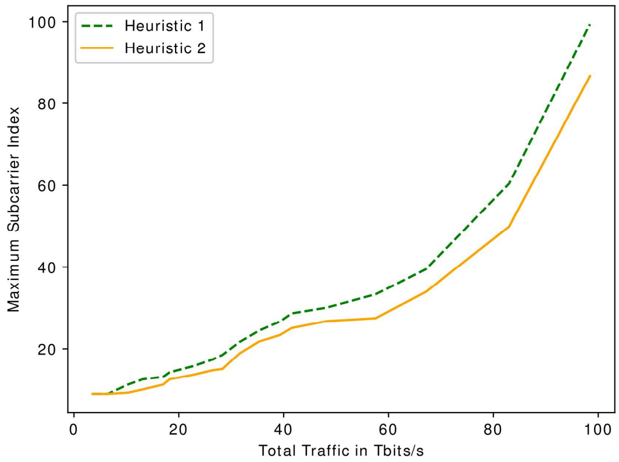

Fig. 9. 75 % of the total traffic is HP traffic

In figures Fig. 4 to Fig. 9, Heuristic 1 represents the results of the modified benchmark algorithm, and Heuristic 2 represents the results of the proposed algorithm. When there are only 25% of HP traffic, the probability of the required contiguous range for newly arrived HP traffic connection is being blocked by an already allocated LP connection is high. Hence, the percentage of re-routes is higher when compared with 50% and 75% HP traffic. Yet, the number of traffic connections to be re-routed is proportionate to the amount of HP traffic in the network and hence, it is less.

When the network is loaded with 75% of HP traffic, the number of HP traffic, which is blocked due to a LP traffic, is low and hence the chance of being re-routed is even less. The proposed heuristic shows the maximum efficiency when there is an equal amount of HP and LP traffic connections in the network. For the 6-node network, the percentage reduction of the maximum subcarrier index by Heuristic 2 when the network is loaded with equal amounts of HP and LP traffic is 27.31% at a cost of only 12.5% disruptions made to existing LP traffic connections. For the 14-nodes network, this value is 16.13% at a cost of 5.83% disruptions.

TABLE 3 SUMMARIZED RESULTS

Percentage of HP traffic connections in the network	**Percentage of blocked / dropped traffic connections**	**Percentage of disruptions to existing LP connections**	**Percentage increase in spectrum efficiency**
For 6-node Network			
25 %	HP traffic – null LP traffic – 1%	6.25%	18.75%
50 %		12.5%	27.31%
75 %		6.09%	17.09%
For 14-node Network			
25 %	HP traffic – null LP traffic – 1%	3.21%	8.38%
50 %		5.83%	16.13%
75 %		3.10%	8.13%

In the proposed method, the percentage of dropped HP connections is null and the percentage of dropped LP connections is nearly 1% of the total traffic. The comparison of Heuristic 2 against Heuristic 1 is summarized in Table 2. Comparing the results of table 2 and 3, it is observed that the spectrum efficiency improvement (on average over 16%) of the proposed algorithm comes at the expense of only a 13.14% increase in computation time.

IV. CONCLUSION

This paper proposed a novel impairment-aware resource allocation scheme for Elastic Optical Networks serving traffic with different service priorities. Our proposed algorithm increases spectrum efficiency, satisfies QoT constraints of high priority traffic, manages impairments efficiently, and reduces network disruptions. Furthermore, the computational complexity of the proposed algorithm is comparable to the benchmark algorithm. As per the simulation results, the proposed method increases the spectrum efficiency by nearly one-fourth when compared to the benchmark algorithms, while causing minimum disruptions to existing LP connections and traffic blocking.

ACKNOWLEDGMENT

This research is supported by the National Research Council of Sri Lanka under the Grant Number 18-028.

REFERENCES

[1] B. Chatterjee, N. Sarma and E. Oki, “Routing and Spectrum Allocation in Elastic Optical Networks,” *IEEE Communications Surveys & Tutorials*, vol. 17, no. 3, pp 1776-1800, 2015.

[2] G. Zhang, M. Leenheer, A. Morea, and B. Mukherjee, ”A survey on OFDM-based elastic core optical networking”, *IEEE Communication Surveys and Tutorials*, vol. 15, no. 1, pp. 65-87, 2013.

[3] S. Behera, A. Deb, G. Das, and B. Mukherjee, ”Impairment Aware Routing, Bit Loading, and Spectrum Allocation in Elastic Optical Networks”, *Journal of Lightwave Technology*, vol. 37, no. 13, pp. 3009-3020, 2019.

[4] J. Zhao, H. Wymeersch, and E. Agrell, "Nonlinear Impairment-Aware Static Resource Allocation in Elastic Optical Networks," *Journal of Lightwave Technology*, vol. 33, no. 22, pp. 4554-4564, 2015.

[5] M. N. Dharmaweera, L. Yan, M. Karlsson, and E. Agrell, "An impairment-aware resource allocation scheme for dynamic elastic optical networks," 2017 Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, CA, 2017, Th 2A. 19.

[6] K. Munasinghe, N. Dharmaweera, C. de Alwis, and U. Wijewardhana., ”Novel service-priority-aware resource allocation scheme for elastic optical networks”, in *26th Annual Technical Conference of IET-Sri Lanka Network*, 2019, pp. 104-108.

[7] M. Dharmaweera, J. Zhao, L. Yan, M. Karlsson, and E. Agrell, “Traffic-grooming- and multipath-routing-enabled impairment-aware elastic optical networks,” *Journal of Optical Communications and Networking*, vol. 8, no. 2, pp. 58–70, 2016.

[8] K. Christodoulopoulos, P. Soumplis, and E. Varvarigos, “Planning flexible optical networks under physical layer constraints”, *IEEE / OSA Journal of Optical Communications and Networking,* vol. 5, no. 11, pp 1296-1312, 2013.

[9] A. Ahad, M. Tahir, and K.A. Yau, “5G-Based Smart Healthcare Network: Architecture, Taxonomy, Challenges, and Future Research Directions”, in *IEEE Access*, vol. 7, pp. 100747-100762, 2019.

[10] E. Rothwell, L. Ellington, S. Planalp, and B. Crouch, “Exploring Challenges to Telehealth Communication by Specialists in Poison Information”, *Qualitative Health Research*, Vol. 22 no. 1, , pp 67-75, 2011.