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# Joint Fragmentation- and QoT-Aware RBMSA in Dynamic Multi-Band Elastic Optical Networks

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**ABSTRACT** Efficient utilization of fiber bandwidth is essential for reducing the total cost of ownership associated with deploying new fiber plants. One of the challenges in dynamic multi-band elastic optical networks (DMB-EONs) is spectrum fragmentation. It stems from the wavelength continuity constraint, the dynamic arrival and departure of service requests, and variations in quality of transmission (QoT) across the wavelength division multiplexing (WDM) channels. This study introduces a QoT-aware algorithm for routing, band, modulation format and spectrum assignment (RBMSA) that considers the spectrum fragmentation along each channel to reduce service blocking ratio (SBR) in DMB-EONs. Simulation results indicate that the proposed algorithm reduces SBR by up to 33.2% compared to a reference RBMSA algorithm that considers only QoT at the cost of increasing the average path length by 4.4%.
**Keywords:** Multi-band optical networks, spectrum fragmentation, quality of transmission.

## 1. Introduction

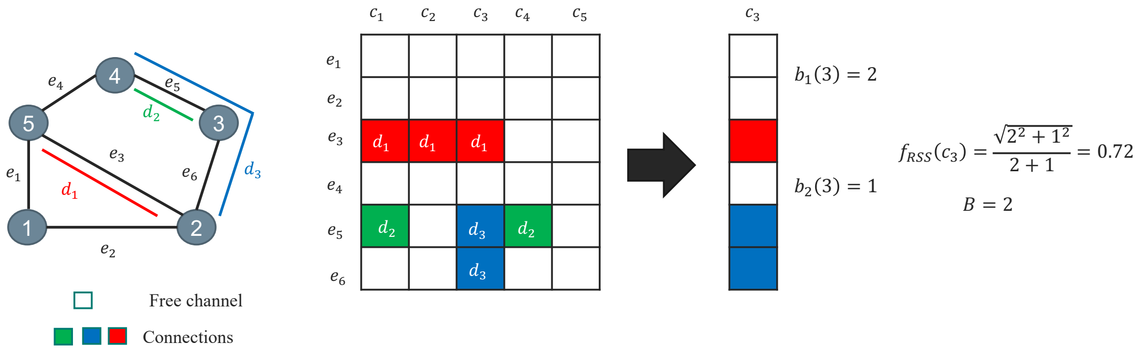
Traditional C-band elastic optical networks (EONs) face challenges in keeping pace with the data traffic surge triggered by the proliferation of high-bit-rate applications like video streaming, cloud computing, and internet of thing (IoT) devices [1]. Dynamic multi-band elastic optical network (DMB-EON) provide a cost-effective solution to enhance data transmission capacity by efficiently utilizing multiple wavelength bands across the optical spectrum, i.e., the L, S, E, O, and U bands [2].

One of the crucial challenges in EON is spectrum fragmentation (SF), where spectrum resources become divided into small, non-continuous, and non-contiguous idle chunks over the links due to the dynamic nature of service demands and wavelength availability [3]. SF can lead to inefficient use of network capacity and increased blocking probability for incoming service requests. SF-aware algorithms proactively utilize information on how spectrum resources are used to reduce the number of blocked service requests [4]. Moreover, the quality of transmission (QoT) of an optical connection (i.e., a lightpath (LP)) varies across different channels due to the inter-channel stimulated Raman scattering (ISRS) phenomenon, which results in power depletion from shorter to longer wavelengths in wavelength division multiplexing (WDM) systems using resources outside the C-band [5]. ISRS, together with the dynamic behavior of service requests with varying capacity requirements and the wavelength continuity constraint increases the SF in the network. Hence, the joint SF- and QoT-aware routing, band, modulation format and spectrum assignment (RBMSA) algorithm is crucial for DMB-EONs. The [6] uses Q-learning to address fragmentation and impairment-aware routing, modulation, and spectrum assignment (RMSA) in C+L band elastic optical networks. In this paper, for the first time, we propose a heuristic algorithm for the spectrum fragmentation- and QoT-aware (SFQA) RBMSA for C+L+S-band DMB-EONs. The proposed heuristic algorithm considers two different SF metrics and the generalized signal to noise ratio (GSNR) level of the channels available along different candidate paths. We conduct a comprehensive performance evaluation of the proposed algorithm and compare it to other heuristic algorithms from the literature, demonstrating that the SFQA algorithm outperforms the ones that consider only the QoT of the channels in the terms of service blocking ratio (SBR).

## 2. System Model and Physical Layer Assumptions

We consider a DMB-EON scenario in which service requests arrive and depart throughout the network's lifetime. Transmission is possible in multiple bands, utilizing pre-defined channels, each comprising six spectrum slots. For each service request, we must determine a path from the source to the destination node and a set of channels along that path that collectively meet the requested bit rate. Different channels may be allocated for the same service request, but they must all follow the same path. Additionally, the continuity constraint dictates that the channels assigned to a particular path must be the same across all links along the chosen path.

We assume that nodes are equipped with C+L+S-band bit-rate variable transponders (BVTs) and reconfigurable optical add-drop multiplexers (ROADMs). A BVTs utilizes flexible modulation formats, soft decision forward error correction, and variable bit rates [7]. The in-line amplifier sites are equipped with C-band erbium-doped fiber amplifiers (EDFA) for the C-band channels, L-band EDFAs for the L-band channels, and thulium DFA (TDFA) for the S-band. The amplified stimulated emission (ASE)-shaped noise is considered for the idle channels




(a) (b) (c)

*Figure* 1: An example with a subset of six network links supporting three services (a). The spectrum occupancy state (b). Calculation of the root of sum of squares (RSS) metric value for channel 3 (c).

to guarantee the power profile consistency [8], [9]. Moreover, the in-line amplifier sites are equipped with the digital gain equalizers (DGEs) to have the optimal launch power for each span based on the hyper-accelerated power optimization strategy proposed in [10].

Regarding the GSNR estimation, we apply a Gaussian noise (GN)/enhanced GN semi-closed form model to estimate the non-linear interference (NLI) noise power, including the Kerr effects and ISRS [11], [12]. This model was validated through field trials experiments [13]. According to the incoherent GN model for uncompensated optical transmission links [14], the end-to-end GSNR for a LP on channel $i$ can be derived as follows:

$$GSNR^i_{\mathrm{LP}}|_{\mathrm{dB}} = 10\log_{10}\left[\left(OSNR^{-1}_{\mathrm{ASE}} + SNR^{-1}_{\mathrm{NLI}} + SNR^{-1}_{\mathrm{TRx}}\right)^{-1}\right] - \sigma_{\mathrm{Flt}}|_{\mathrm{dB}} - \sigma_{\mathrm{Ag}}|_{\mathrm{dB}}, \quad (1)$$

where $OSNR_{\mathrm{ASE}} = \Sigma_{s\in S} P^{s+1,i}_{\mathrm{tx}}/P^{s,i}_{\mathrm{ASE}}$ and $SNR_{\mathrm{NLI}} = \Sigma_{s\in S} P^{s+1,i}_{\mathrm{tx}}/P^{s,i}_{\mathrm{NLI}}$. Moreover, $P^{s+1,i}_{\mathrm{tx}}$ is the launch power at the beginning of span $s+1$, $P^{s,i}_{\mathrm{ASE}} = n_{\mathrm{F}} h f^i (G^{s,i} - 1) R_{\mathrm{ch}}$ is noise power caused by the doped fiber amplifier (DFA) equipped with the DGE, and the NLI noise power ($P^{s,i}_{\mathrm{NLI}}$) is calculated from (2) in [11]. Moreover, $n_{\mathrm{F}}$, $h$, $f^i$, $G^{s,i} = P^{s+1,i}_{\mathrm{tx}}/P^{s,i}_{\mathrm{rx}}$, $S$, and $R_{\mathrm{ch}}$ are the noise figure of DFA, the Planck constant, channel frequency, center frequency of the spectrum, DFA gain, set of spans, and channel symbol rate, respectively. $P^{s,i}_{\mathrm{rx}}$ is the received power at the end of span $s$. $SNR_{\mathrm{TRx}}$, $\sigma_{\mathrm{Flt}}$, $\sigma_{\mathrm{Ag}}$ are the transceiver signal-to-noise ratio (SNR), SNR penalty due to wavelength selective switches filtering, and SNR margin due to the ageing. Hence, the GSNR for all potential connections from arbitrary sources to destinations in the network can be computed. Subsequently, the modulation format profiles of the $K$ shortest path-channel pairs are pre-calculated, employing GSNR thresholds for each modulation format as defined in the literature [15].

## 3. Proposed Spectrum Fragmentation- and QoT-Aware (SFQA) RBMSA

Various metrics have been introduced in the literature to measure SF in EONs, aiding network operators in monitoring and optimizing the utilization of optical spectrum resources [16]. Our proposed fragmentation-aware method utilizes two SF metrics that specifically consider fragmentation in the channels, i.e., number of cuts (NoC) and root of sum of squares (RSS). To illustrate how these metrics are calculated, Fig. 1 presents a snapshot of a simple network example with five nodes and six links, with each link having a capacity of 5 channels. The figure illustrates the current state of the network with three established services, denoted as $d_1$ to $d_3$. The spectrum allocation of each link is shown in Fig. 1b. The notation includes the following parameters: $e$ is the index of a link, $c$ is the index of a channel, $b_i$ is the size of the $i^{th}$ free block, and $B$ is the number of free blocks.

$$f_{RSS}(c) = \frac{\sqrt{\sum_{i=1}^{B}(b_i(c))^2}}{\sum_{i=1}^{B} b_i(c)} \quad (2)$$

Figure 1c illustrates the value for the RSS metric for the channel $c_3$ as defined in (2). To determine the value of NoC for each channel, an assessment of the state of all links within the designated channel is conducted. The NoC for a link with respect to a given channel corresponds to the instances where the state of the link is different from the state of its adjacent links within the same channel. The state of a link refers to whether it is occupied or unoccupied. In the example in Fig. 1b, link $e_5$ uses channel $c_3$. Looking at its neighbors we see that links $e_4$ is not using $c_3$ while $e_6$ does. So, there is a cut between links $e_4$ and $e_5$, and the NoC for link $e_5$ with respect to channel $c_3$ is 1. The NoC value for all the links with respect to $c_3$ can be calculated analogously. The value of NoC across the network for a given channel is equal to the summation of the NoC value of all the links, i.e., 10 with respect to $c_3$ in the example.

The pseudo-code of the SFQA algorithm for RBMSA of a service request is given in Algorithm 1. The basic intuition of this approach is to optimize the selection of paths and channels for service requests based on the available modulation format options and the fragmentation metric targets. The algorithm receives as input the service request $d$, the set of candidate paths between the source and the destination of $d$ as $P$, the complete set of channels that can be used across all frequency bands $C$, pre-computed modulation format tables for all paths and channels $MFT$, the channel occupancy matrix $COM$, and the desired fragmentation metric, denoted as $T$. The algorithm outputs a list of selected channels whose combined bit rate satisfies the requested bit rate; an empty list signifies that the service request is blocked.

The algorithm comprises two parts. The first part involves computing the fragmentation score (FS) for all potential paths and channels available for the service request. Meanwhile, the second part focuses on selecting the path and corresponding channels based on the calculated FS. Upon the arrival of the service request $d$, the algorithm is triggered and evaluates all candidate paths between the source and destination nodes. For each path, it assesses the free channels and retrieves their respective modulation formats, storing them in $M(p,c)$ (lines 2–5). Subsequently, it calculates the FS for each channel, considering a hypothetical scenario where the channel is selected to establish the service. This involves computing the difference between the SF value in the current spectrum state ($F_{current}$) and the hypothetical SF value ($F_{established}$) assuming the service is hypothetically established on the channel (line 6–9). If the metric of interest is RSS, the $F_{current}$ and $F_{established}$ are computed using (2). If NoC is considered, the $F_{current}$ and $F_{established}$ refer to the two corresponding values of NoC for channel $c$.

The second part of the algorithm aims to find the best path for the service request. The paths are sorted based on the best modulation format of their channels. If two paths have the same best modulation format, the FS is used to sort them (line 10). The algorithm proceeds by iteratively examining each path in $P_{sorted}$ (line 12) and sorting its available channels according to their modulation format. If multiple channels exhibit identical modulation formats, the algorithm prioritizes them based on their FSs (line 13). Finally, the algorithm iterates through the sorted channels, appending each channel to the list of selected channels, and evaluating the residual bit rate $r$ by considering the channel modulation format and the service request bit rate (line 16–17).

However, there is a chance that the selected path does not have sufficient channels to support the full bit rate requested. In such cases, the selected channels are reset, and the algorithm proceeds to examine another path (line 20). If none of the paths contain enough channels to accommodate the request, the algorithm returns $C_s$ with an empty value, indicating that the service $d$ is blocked.

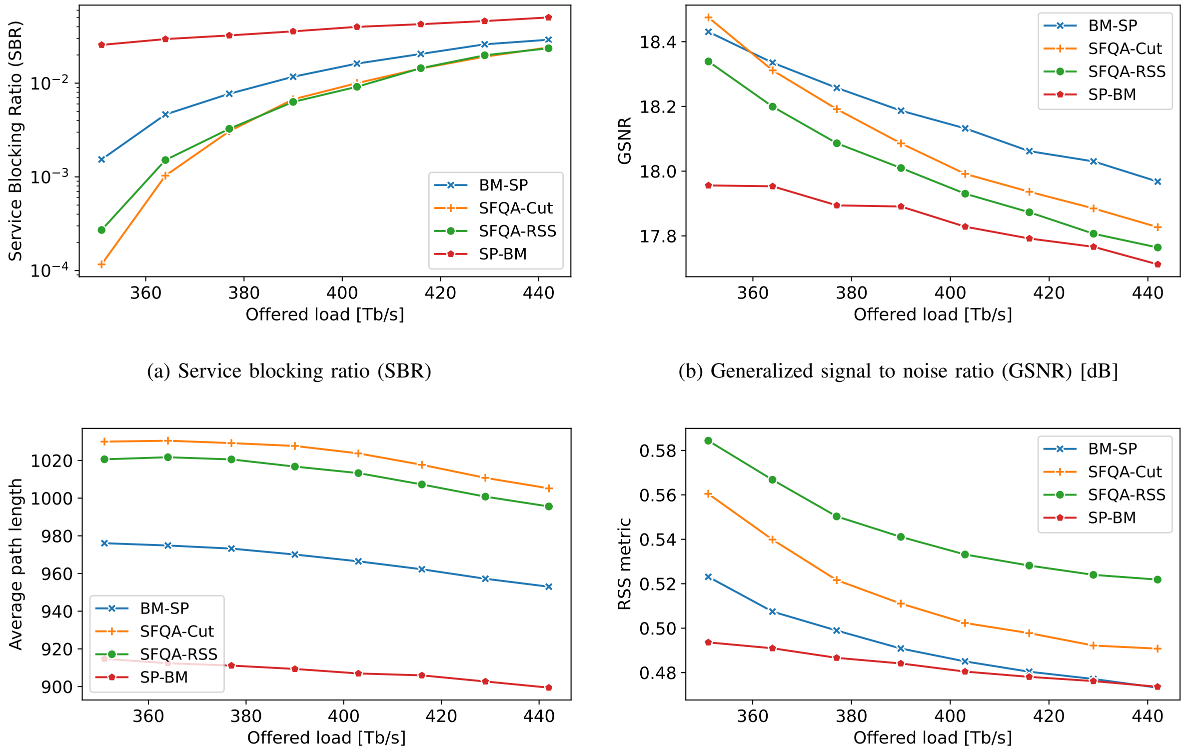
**Algorithm 1:** The spectrum fragmentation- and QoT-aware (SFQA) algorithm

**Input:** $d$, $P$, $C$, $MFT$, $COM$, $T \in [RSS, NoC]$,
**Output:** $C_s$

1 $C_s \leftarrow \varnothing$; `// channels selected for each service request`
2 **for** *each* $p$ *in* $P$ **do**
3     **for** *each* $c$ *in* $C$ **do**
4         **if** $c$ *is free on* $p$ *by checking* $COM$ **then**
5             $M(p,c) \leftarrow$ get modulation level using $MFT$
6             **if** $T$ *is* $RSS$ **then**
7                 $FS(p,c) \leftarrow F_{established}(p,c) - F_{current}(p,c)$
8             **else if** $T$ *is* $NoC$ **then**
9                 $FS(p,c) \leftarrow F_{current}(p,c) - F_{established}(p,c)$
10 $P_{sorted} \leftarrow$ sort the paths $P$ based on best $M(p,c)$ of their channels, and if two paths have the same best modulation format of their channels, sort based on the best $FS(p,c)$ of their channels
11 $br \leftarrow$ the bit rate of $d$
12 **for** *each* $p$ *in* $P_{sorted}$ **do**
13     $C_{sorted} \leftarrow$ sort the channels on path $p$ based on best $M(p,c)$, and if two channels have the same best modulation format, sort based on the best $FS(p,c)$
14     $r \leftarrow br$
15     **for** *each* $c$ *in* $C_{sorted}$ **do**
16         $C_s$ appends the channel $c$
17         $r \leftarrow r - 100 * M(p,c)$
18         **if** $r < 0$ **then**
19             **return** $C_s$
20     $C_s \leftarrow \varnothing$
21 **return** $C_s$

## 4. Simulation Settings and Results

This paper focuses on C+L+S-band EONs, where an aggregate bandwidth of 20 THz (6+6+8) is divided into 268 channels, each one with 75 GHz (6 * 12.5 GHz), considering a 400 GHz gap between adjacent bands.




(a) Service blocking ratio (SBR)

(b) Generalized signal to noise ratio (GSNR) [dB]

(c) Average path length [km]

(d) Root of sum of squares (RSS) metric

*Figure* 2: Performance of the RBMSA schemes for Japanese topology.

The simulations are conducted on the Japanese network topology with 14 nodes, 22 links [17], and a maximum span length of 80 km. Six modulation formats are evaluated, ranging from PM-BPSK to PM-64QAM at 64 Gbaud. Each channel can support bit rates spanning from 100 to 600 Gb/s when employing PM-BPSK and PM-64QAM, respectively. EDFAs with noise figures of 4.5 dB and 5 dB are employed for the C- and L-bands, respectively. A TDFA with a noise figure of 6 dB is utilized for the S-band. Standard single mode fiber with a zero-water peak is assumed, and spectrum continuity is enforced for channel assignment along a given path. A dynamic scenario is considered where the service requests are generated using a Poisson process, and an exponential distribution is assumed for the holding time of the services, with an average of 25 time units. The offered traffic load values are adjusted to achieve approximately 0.01% to 1% SBR for the proposed algorithms. The bit rate for service requests is selected randomly between 50 Gb/s and 600 Gb/s with a granularity of 50 Gb/s. Two million service requests are simulated, with the *SFQA* algorithm executed for each service request. The value of $K$ is set to 5. The proposed algorithm is developed in the Optical RL-Gym framework [18].

Two versions of the proposed heuristic algorithm are analyzed depending on the SF metric used: the one that uses the NoC metric is referred to as *SFQA-Cut*, and the one that uses the RSS metric is called *SFQA-RSS*. To evaluate the performance of the proposed algorithm, a comparison is made with two heuristic algorithms, namely *BM-SP*, and *SP-BM*. *BM-SP* selects a path with the best modulation format across its channels, favoring shorter paths in case of a tie in terms of best modulation format. Conversely, *SP-BM* favors path length minimization over modulation format efficiency. It always selects the shortest path first and then identifies the channel with the best modulation that is possible along the chosen path. Note that in all approaches, when confronted with identical modulation formats or fragmentation metrics for the channels along the same path, preference is given to the channel with the lowest frequency.

Figure 2 depicts the performance of the considered strategies as a function of the offered load. The *SFQA* algorithm demonstrates superior performance in terms of SBR as shown in Fig. 2a. More specifically, *SFQA-RSS* slightly outperforms *SFQA-Cut* and surpasses *BM-SP* and *SP-BM* algorithms by 33.2% and 74% on average across all loads, respectively. This highlights the advantages of incorporating occupancy state information into the path and the channel selection processes. This observation is further supported by Fig. 2b, illustrating the in GSNR levels across different scenarios. While the GSNR level of *BM-SP* surpasses the one of *SFQA*, its SBR performance suffers due to its lack of consideration for SF metrics. However, as can be seen in Fig. 2c, the benefit of *SFQA* in terms of SBR come at a cost of longer paths. More specifically, the *SFQA-RSS* algorithm exhibits (on average) paths 4.4% and 10.2 % longer than the ones from obtained with the *BM-SP* and *SP-BM* algorithms. To obtain a deeper insight into the network performance, Fig. 2d presents the network RSS metric values for different algorithms, The analysis shows that the network with greater fragmentation (lower RSS values) tend to experience higher SBR. Furthermore, Fig. 2d illustrates that the RSS metric decreases as load increases, indicating stronger fragmentation under higher loads.

## 5. Conclusion

This paper presents a heuristic algorithm for routing, band, modulation format and spectrum assignment (RBMSA) in dynamic multi-band elastic optical network (DMB-EON) that utilizes the QoT of the channels, and the spectrum occupancy information, measured by the number of cuts (NoC) and root of sum of squares (RSS) metrics. Simulation results demonstrate the effectiveness of the proposed algorithm in reducing SBR compared to benchmark algorithm by up to 33.2%, at the cost of increasing the average path length by 4.4%

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