Optimizing Resource Allocation in Filterless Elastic Optical Networks over C+L Band: QoT-Aware Approach

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ABSTRACT

Filterless optical networks (FONs) offer a cost-effective alternative to traditional networks by utilizing passive couplers/splitters. However, this approach leads to leakage signals and wasted spectrum. With the transition to elastic optical networks (EONs), which efficiently utilize spectrum, incorporating L-band alongside C-band offers expanded frequency resources. This paper proposes an approach to address quality of transmission (QoT)-aware tree selection, routing, modulation, and spectrum assignment (QTRMSA) in filterless EONs (FEONs) over C+L band. Heuristic algorithms are presented for complex large-scale networks, showing comparable performance in spectrum usage and modulation format. These algorithms highlight the impact of generalized signal-to-noise-ratio (GSNR) estimation methods on spectrum usage, blocking, and outage. Additionally, the proposed MX5 method ensures minimal outage or blocking up to a network throughput of 120 Tb/s over C+L band for large scale network (Telefonica region B network topology). These results provide insights for balancing performance metrics and optimizing resource allocation for FEONs over C+L band transmission.

Keywords: Filterless elastic optical network, Multiband optical networks

1. INTRODUCTION

Filterless optical networks (FONs) aim to cut costs by replacing expensive ROADM-based architecture with passive coupler/splitter nodes where authors in [1] demonstrated cost savings with FONs compared to traditional networks and they also introduced the initial tool for demand provisioning and routing in FONs. Elastic optical networks (EONs) offer superior efficiency over traditional wavelength division multiplexing systems, serving demands with optimal resource utilization. Using C+L band instead of conventional C-band transmission allows us to use almost double spectrum without deploying new fibers and causes to serving more demands. Beyond C-band, nonlinear interference, such as Kerr and inter-channel stimulated Raman scattering (ISRS) effects, deteriorate the Quality of Transmission (QoT) [2]. In terms of QoT-aware Routing, Modulation, and Spectrum Allocation (RMSA) for fixed-grid and flexible-grid EONs operating across multiple bands, the impact of noise, including nonlinear interference (NLI) such as ISRS and Kerr effects, as well as amplified spontaneous emission (ASE) noise from erbium-doped fiber amplifiers (EDFAs), is evaluated using either the generalized Gaussian noise (GGN) model as presented in [3], or a closed-form Gaussian noise (GN) expression as discussed in [2]. Finally, authors in [4], provided a comprehensive tutorial on FONs by considering all the aspects of FONs, e.g., protection in FONs, service provisioning in FONs, tree establishment problem, and so on.

In this paper, we offer a synopsis of the heuristic algorithms introduced in our previous work in [5] and assess their performance on a different network topology to ascertain the effectiveness of our proposed methods.

2. FILTERLESS ELASTIC OPTICAL NETWORK

In this section, we introduce the concept of Filterless Elastic Optical Networks (FEON) and outline the prerequisites involved. We present a method for determining the total noise within FEON, which allows for a direct calculation of the generalized signal-to-noise ratio (GSNR) by dividing the launch power by the total noise. The network topology is described by the graph $G(N,E)$, where N and E represent the set of nodes and unidirectional links, respectively. Demands, stored in $D(R_d,P^d)$, include the required bit rates (R_d) and candidate paths (P^d) that are pre-calculated from separate trees. These candidate paths are identified using Yen's k-shortest path algorithm [XXX], and leakage links are identified for each path. Additionally, we consider five modulation formats (MFs), including polarization-multiplexed (PM) binary phase shift keying (PM-BPSK), PM quadrature phase shift keying (PM-QPSK), PM 8-quadrature amplitude modulation (PM-8QAM), PM-16QAM, and PM-32QAM. Furthermore, both the C- and L-bands are utilized as spectrum resources, segmented into N = 916 frequency slot units (FSUs) with a granularity of Δ = 12.5 GHz for each FSU.

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In order to achieve filterless conditions, nodes consist of passive couplers and splitters. Consequently, the drop and continue process occurs at every intermediate or destination node along the chosen path for each demand [4]. Also, estimating GSNR is vital for QoT awareness. It involves evaluating NLI from the Kerr effect and ASE noise due to EDFAs. When assessing ASE noise, leaked signals from all the predecessor links must be considered [4]. In the provided filterless network topology shown in Fig. 1, comprising two fiber trees, the red and blue lines correspond to the first and second trees, respectively. To illustrate the idea of predecessor links, let us take the link from source node 1 to destination node 5. If a signal travels through link (2,1), (3,1), or (4,1), the resulting ASE noise from EDFAs leaks to link (1,5), establishing links (2,1), (3,1), and (4,1) as predecessors for link (1,5). Consequently, the total ASE noise generated by these four links could impact demands routed on link (1,5).

However, when calculating NLI noise for each demand, only the main links of the selected path are considered. Fig. 1 categorizes each FSU into three states: busy, wasted, and idle. FSUs assigned to a demand are marked as busy over the main links of its selected path, while those over links receiving the demand's leakage signal are considered wasted. Idle FSUs do not transmit main or leakage signals and can be allocated to future demands. For instance, consider demand 4→1 in Fig. 1, routed through the first FSU of link (4,1) and leaked onto links (1,2), (1,3), and (1,5). Consequently, the leakage signal renders the first FSU of links (1,2), (1,3), and (1,5) wasted. These links receiving the leakage signal of a demand are termed leakage links for that demand. It is important to highlight that while busy FSUs of different demands must adhere to the non-overlapping constraint, wasted FSUs of different demands can overlap.

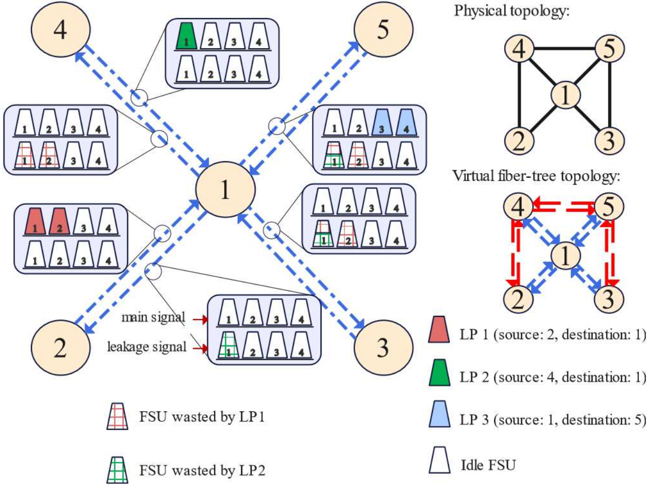

Fig. 1: Network topology with 2 fiber-trees. Reproduced from [5].

3. PROPOSED METHOD

This section presents a heuristic algorithm that considers QoT to tackle the tree, routing, modulation, and spectrum assignment (Q-TRMSA) issue in FEONs. The algorithm is called heuristic for FEON (HFEON). First of all, HFEON tries to find a solution for the tree establishment problem. It is worth noting that one of the established trees must be a spanning tree that ensures the connectivity between each node pair in the network. HFEON receives demands one by one then for each demand finds all available candidate paths on established trees and stores them in P^d. For each path in P^d, i.e., set of candidate paths for demand under test (DUT) d, HFEON tries to find the maximum index of used FSU and compute GSNR over that path. For this purpose, the algorithm computes the required number of FSUs (called N) by considering the largest available MF for demand d and then tries to find N idle and adjacent FSUs over main links and leaked links. It is worth noting that the main links and leaked links completely depend on the considered path. The algorithm selects the available spectrum using first-fit scheme. If a set of available FSUs is identified, HFEON calculates the GSNR as described in the following paragraph. However, if HFEON fails to find any available set of FSUs, it proceeds to the next path.

When calculating the GSNR for the provided DUT, it is necessary to take into account the status of the other demands. To ascertain the NLI noise, we need to calculate the self-channel interference (SCI) and cross-channel interference (XCI) terms for each main link along the specified path using equations (3) and (4) of [5], respectively. These values are then added up to determine the total NLI noise. The algorithm sequentially examines the main links of the candidate path, sorting the demands that include each link (either as a main or leakage link) in ascending order based on their required bandwidth. This prioritization stems from equation (4) of [5], which indicates that demands with lower required bandwidth contribute to higher XCI noise generation. Upon identification of the set of interfering demands, the system needs to ascertain their assigned FSUs and modulation formats. If an interfering demand (d') has been served in previous iterations, all its parameters (i.e., MF and FSUs) are known and factored into the SCI and XCI calculations. Conversely, if an interfering demand has not been addressed thus far (referred to as an upcoming interfering demand), its FSUs and MF must be temporarily estimated. To estimate the MF (m') for upcoming interfering demands, we introduce four modulation assignment methods: MX1, MX3, MX5, and conservative modulation (CM) assignment. For MX1, MX3, and MX5, the modulation (m') is set to 1, 3, and 5, respectively. For CM, the estimated m' is determined using a distance-adaptive method, where modulation is selected by comparing the path length and transmission reach of modulations. If the path length exceeds the transmission reach of the lowest MF (PM-BPSK), m' is assumed to be 1. Subsequently, to estimate the FSUs of each upcoming interfering demand, we determine the nearest FSUs to the candidate FSUs for the DUT available along the path of the upcoming interfering demand containing the considered link. After establishing the MF and FSUs of upcoming interfering demands, the SCI and XCI terms are computed using equations (3) and (4) of [5], respectively. Subsequently, the ASE noise for the DUT on the given candidate path is computed using equation (1) of [5], considering all predecessor links found for the last link of the current considered path. This process iterates over all main links of the candidate path. Finally, the algorithm calculates the GSNR and outputs it. Note that the GSNR is derived from $P/(P_{ASE} + P_{NLI})$, where P_{ASE} represents accumulated ASE noise over all predecessors of the final link of the path and P_{NLI} represents NLI noise terms computed over all links of the candidate path using by considering all interfering demands.

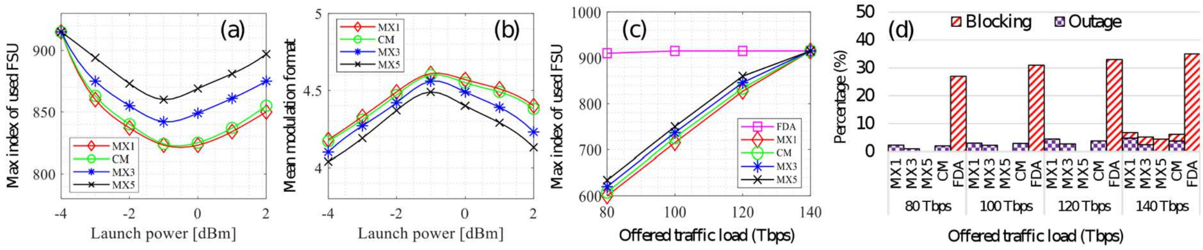

Fig. 2: Maximum used FSUs (a) and mean assigned modulation format (b) vs launch power, the effect of increasing offered traffic load on the assigned FSUs (c), and the percentage of blocking and outage (d).

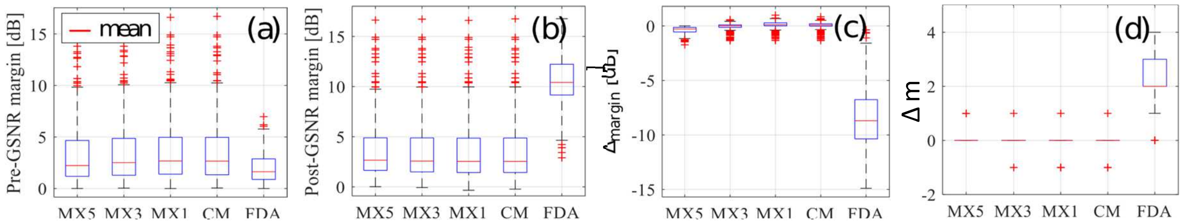

Fig. 3: Pre- and post-GSNR margin ((a), (b)), Δ_{margin} (c) and Δm (d) for -1 dBm launch power and 120 Tb/s throughput

4. EVALUATION

We examine the performance of the introduced HFEON algorithm in tackling the Q-TRMSA problem within FEONs operating in the C+L band. The HFEON algorithm processes input demands characterized by randomly selected source-destination pairs and variable bit rates. Its efficacy is then examined within a sizable metro-core network topology, specifically the Telefonica region B [7], configured as a filterless network. The maximum span length is equal to 70*km*, fiber attenuation is equal to 0.2*dB/km*, and fiber nonlinearity coefficient is equal to 1.2 1/*W/km*. After each span, an EDFA is considered for C-band and another one for L-band channels. Furthermore, we take into account GSNR thresholds for modulation formats ranging from $m = 1$ to $m = 5$, which are respectively set at 5.5 dB, 8.5 dB, 12.5 dB, 15.2 dB, and 18.2 dB, corresponding to a bit error rate (BER) of 10^{-3} as derived from [8].

We utilize the filterless distance adaptive (FDA) RMSA method [9] as a key benchmark to assess the performance of our algorithms. FDA is divided into three fundamental problems: routing, spectrum, and modulation assignment. To tackle the routing challenge within FDA, it selects a path from a variety of options across different fiber-trees, aiming to minimize the number of spans leaked to the final link of the chosen path. Spectrum assignment in FDA is managed using the first fit method. As for MF assignment, the MF selection depends on the number of leaked spans to the final link in the selected path, in comparison to the transmission reach of each MF. A higher MF is assigned when there are fewer leaked spans. The transmission reach for each MF, with an optimal power of -1 dBm, is set as follows: 3500 km, 1700 km, 700 km, 350 km, and 150 km for m = 1, 2, ..., 5, respectively, based on insights provided in [9].

In Fig. 2(a) and Fig. 2(b), we examine how adjustments in launch power per demand impact both the maximum index of utilized FSUs and the mean of assigned MF in C+L band, respectively. Optimal launch power settings for various scenarios can be deduced from Fig. 2(a) and Fig. 2(b), where the goal is to minimize the maximum index of utilized FSUs while maximizing the mean MF. Analyzing different scenarios reveals that the MX5 method exhibits the highest FSU utilization and lower mean MF, whereas the MX1 method shows the lowest FSU utilization and the highest mean MF among the various methods. The total traffic allocated is 120 Tb/s. The following scenarios consider the launch power settings close to optimal. Furthermore, Fig. 2(c) illustrates how augmenting the offered traffic load impacts the final index of utilized FSUs across the entire network. The findings indicate across all scenarios, it is evident that the MX5 method occupies a greater number of FSUs than other QoT-aware methods (i.e., MX1, MX3, and CM). As presented in Fig. 2(d), two parameters are reported to manifest the effect of traffic increment (from 80 Tb/s to 140 Tb/s). The first parameter is outage which is characterized as the proportion of demands whose actual GSNR, after servicing all demands, falls below the GSNR threshold associated with their assigned MF. The second parameter is blocking percentage which shows the proportion of demands that cannot be served in the network. In instances where the HFEON algorithm encounters blocking, the incidence of blocking is observed to be higher for the MX5 method compared to others. This can be attributed to two factors. Firstly, the MX5 method exhibits greater utilization of Frequency Slot Units (FSUs) than alternative methods, potentially leading to a lack of available FSUs for accommodating new demands. Secondly, the MX5 method tends to underestimate the GSNR, occasionally resulting in an estimated GSNR lower than the threshold for PM-BPSK modulation, thereby leading to demand blocking. Additionally, it is noted that the MX5 method does not encounter any outages across all scenarios, albeit at the expense of increased FSU utilization compared to the MX1, MX3, and CM methods.

Fig.3(a-c) present the pre- and post- GSNR margin, and Δ_{margin}, respectively. The concept of pre-GSNR margin is introduced, representing the disparity between the initial GSNR calculated during service of DUT and the GSNR threshold corresponding to its assigned MF. For the FDA method, the initial GSNR is calculated under the assumption that all FSUs are occupied by interfering demands with $m = 5$. Conversely, the post-GSNR margin reflects the difference between the actual calculated GSNR after servicing all demands and the GSNR threshold associated with its assigned MF. The actual GSNR computation considers the modulation format based on the current loading profile of each link. The Δ_{margin} metric denotes the difference between the pre- and post-GSNR margins for different methods. It is noteworthy that a negative Δ_{margin} indicates an underestimation of initial GSNR, ensuring the method avoids any outages under worst-case conditions for interfering demands. Conversely, a positive Δ_{margin} signifies GSNR overestimation, potentially leading to an outage. It is evident from the figure that in certain scenarios, the MX3, MX1, and CM methods exhibit negative post-GSNR margins for some demands, indicating potential outage occurrences for these demands. Conversely, both the MX5 and FDA methods consistently avoid outages across all scenarios. The FDA method demonstrates an exceptionally low Δ_{margin}, suggesting a significant underestimation of initial GSNR. Additionally, the FDA method generally yields higher post-GSNR margins compared to other methods, implying that it services demands with lower MF and consequently utilizes more FSUs in the network. On the other hand, the proposed MX5 method effectively reduces the post-GSNR margin without encountering any outages, thereby enhancing FSU usage efficiency. As can be inferred from Fig. 3(a-c), the pre-GSNR margin is approximately 2 dB for both the FDA and proposed HFEON algorithms in all scenarios. However, after applying the GSNR estimation algorithm, the post-GSNR margin is anticipated to be around 11 dB for the FDA algorithm and 2 dB for the proposed HFEON algorithm. This disparity suggests that the FDA algorithm significantly overestimates the level of interfering demands, resulting in a lower accuracy factor compared to the proposed HFEON algorithm.

To conclude our results, Fig. 3(d) illustrates Δm values for various methods, where Δm represents the difference between initially assigned and actual MF based on estimated and actual GSNR, respectively. Negative Δm indicates GSNR overestimation leading to higher MF assignment, while positive Δm signifies GSNR underestimation, resulting in reduced spectrum efficiency. The MX1, MX3, and CM methods encounter negative Δm in certain scenarios, while the MX5 method and FDA consistently exhibit positive Δm. Notably, the FDA shows high Δm, indicating extreme MF underestimation. Our proposed MX5 method effectively reduces Δm without experiencing outages, suggesting superior accuracy in MF assignment.

5. CONCLUSIONS

This study explored the QoT-aware tree selection, routing, modulation level, and spectrum assignment (Q-TRMSA) problem in Filterless Elastic Optical Networks (FEONs), considering ISRS, SCI, XCI crosstalks, and ASE noise. We proposed a heuristic algorithm for FEON (HFEON) with different MF assignment methods to handle largescale networks. Comparisons were based on FSU usage, assigned MF, outage, blocking, pre- and post-GSNR margins, and Δ_{m}. The MX5 method showed no outages, lower mean assigned MF, and Δ_{margin} compared to other methods, with higher usage of FSU. This suggests MX5's effectiveness that causes no outage and blocking up to 120 Tb/s throughput for Telefonica region B network topology.

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