Heuristic Approaches for Dynamic Provisioning in Multi-band Elastic Optical Networks

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***Abstract*—Multi-band elastic optical networks are a promising alternative to meet the bandwidth demand of the ever-growing Internet traffic. In this letter, we propose a family of band allocation algorithms for multi-band elastic optical networks. Employing simulation, we evaluate the blocking performance of 3 algorithms of such a family and compare their performance with the only heuristic proposed to date. Results show that the three new algorithms outperform the previous proposal, with up to one order of magnitude improvement. We expect these results to help advance the area of dynamic resource allocation in multi-band elastic optical networks.**

***Index Terms*—Elastic Optical Networks, Multi-band, Band Allocation.**

I. INTRODUCTION

BY extending the operation of elastic optical networks beyond the C-band to the L, S, E, and O bands, multi-band elastic optical networks (MB-EONs) are a promising alternative to meet the ever-growing Internet traffic [1]. MB-EONs offer the advantage of a significant increase in network capacity avoiding the costs associated with multiple fibers operating in the C-band or laying multi-core fiber solutions [2].

Previous research in multi-band networks have focused on:
Mitigating physical impairments: Stimulated Raman Scattering (SRS) becomes relevant when propagating optical signals in a multi-band optical network environment [3] and the imperfections of multi-band transceivers might also degrade the quality of the signal [4]. In this line, research has focused on achieving good quality of transmission across the bands. For example, proposing non-linearity compensation techniques [5] and signal power optimization methods [6], [7].
Designing new devices: Amplifiers, wavelength selective switches, and transceivers mainly operate in the C band, with some commercial devices operating in the L-band. An extensive summary on the challenges and advances on multi-band devices can be found in [4].
Designing a new control plane: Including new bands requires extended capabilities in the control plane. One of the most relevant tasks here is implementing efficient resource allocation algorithms that consider how different bands affect the quality of the transmission of optical signals. In [8] a first resource allocation algorithm was proposed to operate in the C+L+S+E scenario, whilst in [9] a deep reinforcement learning agent - which did not outperform the algorithm in [8] - was proposed.

This letter focuses on novel band allocation algorithms for MB-EONs and explores the impact of solving the band allocation task in different stages of the resource allocation task. A family of band allocation algorithms is presented, and the blocking performance of 3 variants is evaluated employing simulation. Results show that the three variants outperform the only algorithm proposed so far [8] for MB-EONs. We expect these results to help the research community devise better solutions for resource provisioning in MB-EONs.

II. MODELS

A. Physical layer model

We consider an elastic optical network where the spectrum of each link is divided in frequency slot units (FSUs) of 12.5 GHz each. The network can operate in any of 3 different scenarios:

- **C+L**: C and L bands are active, equipped with 344 and 480 frequency slots, respectively.
- **C+L+S**: C, L and S bands are active, equipped with 344, 480 and 760 frequency slots, respectively.
- **C+L+S+E**: C, L, S and E bands are active, equipped with 344, 480, 760 and 1136 frequency slots, respectively.

The O band is not considered due to the enhancement of nonlinear interactions and the reduced accuracy of the Gaussian noise (GN) model in that region, as well as the poor performance exhibited in core networks [8].

Following the methodology from [10], the worst-case optical reach of the scenarios described was calculated considering four modulation formats. For each configuration, the signal-to-noise ratio (SNR) was computed for every FSU at optimum signal power using the Interchannel Stimulated Raman Scattering Gaussian Noise (ISRS GN) model and assuming dual polarization (DP) signals [11]. To determine the optical reach, a minimum SNR was defined for each

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modulation format under study. The minimum SNR is related to a fixed bit error rate threshold to be met as a parameter of quality of transmission. The optical reach was defined as the maximum distance that can be reached with a modulation format without presenting a bit error rate higher than that determined by the minimum accepted SNR. For each band, the FSU with the lowest SNR defined the optical reach.

Table 1 shows the optical reach (in km) for different band configurations and modulation formats assuming a bit error rate threshold of $4.7 \cdot 10^{-3}$ before Forward Error Correction. As the number of bands increases, nonlinear interactions due to SRS reduce the maximum transmission reach.

TABLE I: Optical reach [km] for different multi-band scenarios and modulation formats.

Active bands	**Modulation Formats**			
	DP BPSK	***DP QPSK***	***DP 8-QAM***	***DP 16-QAM***
C+L	C:19700 L:16700	C:9900 L:8400	C:5400 L:4600	C:2400 L:2200
C+L +S	C:17400 L:16700 S:14800	C:8700 L:8400 S:7400	C:4700 L:4600 S:4100	C:2300 L:2200 S:2000
C+L +S+E	C:13000 L:14400 S:10200 E:3100	C:6500 L:7200 S:5100 E:1500	C:3500 L:3900 S:2900 E: 900	C:1700 L:1900 S:1400 E:400

The number of frequency slots, $f_{src,dst}$, required by a connection request defined by the triplet (src, dst, b) is given by $f_{src,dst} = \lceil b/FSU_m \rceil$, where src and dst are the source and destination nodes of the connection request, respectively; b is the requested bitrate, and FSU_m is the bitrate achieved by a frequency slot unit for a given modulation format, m. FSU_m is equal to those reported in Table 3 in [10]: 23, 46, 69 and 92 Gbps for DP BPSK, DP QPSK, DP 8-QAM, and DP 16-QAM, respectively.

A connection request cannot be established in more than one band (e.g., part of the FSUs allocated in one band and the rest in an adjacent band). This situation allows for a physical layer implementation based on discrete amplifiers (such as EDFA) that operate separately in each band, where guard-bands are used to allow signal splitting and combining.

B. Network and traffic models

The network topology is represented by graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ is the set of network nodes and $\mathcal{L}$ is the set of unidirectional links, with cardinality N and L, respectively. All links are equipped with the same capacity. The connection request arrival is modeled as a Poisson process, with the average arrival rate denoted by λ. The holding time of each connection request follows an exponential distribution, with a mean value denoted by $1/\mu$. The network traffic load is given by λ/μ. The source and destination nodes of a connection request are randomly selected, following an uniform distribution, whilst the bitrate is uniformly selected from B different values. Thus, the set of connection requests, each defined by the triplet (src, dst, b), is made of $N \cdot (N-1) \cdot B$ elements.

III. A FAMILY OF BAND ALLOCATION ALGORITHMS

In this section we focus on the band allocation problem, given that the algorithms for routing, modulation format, and spectrum allocation (RMSA) are very well studied [12]. We propose a family of band allocation algorithms: depending on how the configuration parameters are chosen, different algorithms (variants) can be obtained. The family of algorithms can be described in terms of an off-line stage (in charge of data pre-processing) and an online stage (that determines the next band to be attempted), as follows:

A. Off-line stage

This stage is executed once, before network operation starts.

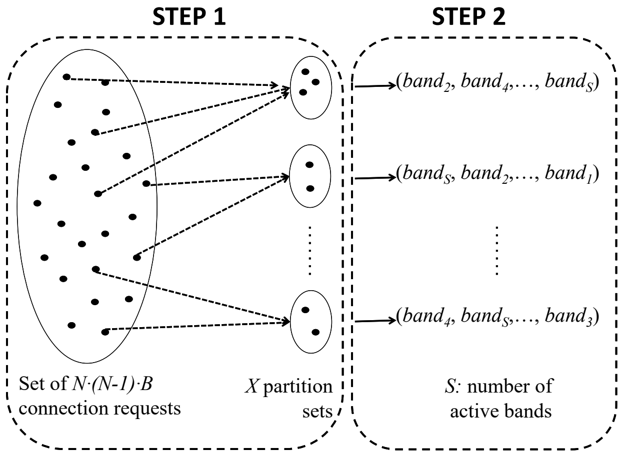

Fig. 1: Family of band allocation algorithms: Off-line stage

STEP 1: Partition the set of connection requests in X sets - as shown in the left part of Fig. 1 - such that each connection request belongs to one partition only. Examples of partition criteria are route length, route number of hops, or bitrate.

STEP 2: Associate each partition set with an ordered list of bands, where S is the number of active bands of the considered scenario (as described in Section II.A). For example, the uppermost partition set in the left part of Fig. 1 is associated with the ordered list ($band_1$, $band_2$,..., $band_S$). The list defines the order in which bands will be attempted to establish resources for the associated connection request. The order can be established by applying criteria such as band capacity, optical reach or balanced selection of bands.

B. Online stage

When a connection request (src, dst, b) is received, the main resource allocation algorithm is called. This algorithm, in turn, calls the function $Band()$ that determines the next band to be attempted. The function is described in Algorithm 1.

Variable $curr\_band$ identifies the current band being considered. Functions $last()$ and $next()$ receive as input argument $bands(src, dst, b)$ which is the ordered list of bands associated to request (src, dst, b) (defined in the offline stage) and return

Algorithm 1 Band allocation function

```
function BAND($curr\_band, src, dst, b$)
    if $curr\_band = last(bands(src, dst, b))$ then
        return $-1$
    else
        $curr\_band \leftarrow next(curr\_band, bands(src, dst, b))$
        return $curr\_band$
    end if
end function
```

the last and next band in such list, respectively. The function Band() checks whether the current band is the last band in the list. If so, it returns the value -1 signaling that no more bands can be attempted. Otherwise, it returns the identification of the next band to be attempted.

This family of band allocation techniques is flexible enough to generate different variants of algorithms by changing the number and type of partitions and the criteria used to build the ordered lists. Additionally, the function $Band()$ can be easily inserted in any resource allocation for MB-EONs.

IV. NEW ALGORITHMIC PROPOSALS

As a case study, we present three variants of the family of band allocation algorithms described in the previous section. The three variants are built using the criteria of path length or bitrate to define the partitions and capacity, optical reach and band balancing to build the ordered lists of bands. The variants are:

Variant 1 (V1): Connection requests are partitioned into $X = 2$ sets. The partition criterion is the length of the shortest routes (in km). Let M be the median value of the shortest route lengths of all network node pairs, and $r_{src,dst}$ the length of the shortest route between nodes src and dst. Partition sets are built as follows:

- Set_1: requests such that $r_{src,dst} < M$
- Set_2: requests such that $r_{scr,dst} \geq M$

The ordered lists of bands are built using a single criterion: optical reach of bands. Thus, Set_1 is associated to the ordered list of bands (E,S,C,L) and Set_2 to (L,C,S,E). This algorithm attempts to allocate connections with longer/shorter routes to the bands with longer/shorter optical reach values first.

Variant 2 (V2): Connection requests are partitioned into $X = 4$ sets. The partition criterion is the length of the shortest routes (in km). Let LR be the length of the longest shortest route in the network and $r_{src,dst}$ the length of the shortest route between nodes src and dst. Connection requests are allocated to partition sets as follows:

- Set_1: requests such that $r_{src,dst} \leq LR/4$
- Set_2: requests such that $LR/4 < r_{src,dst} \leq LR/2$
- Set_3: requests such that $LR/2 < r_{src,dst} \leq 3 \cdot LR/4$
- Set_4: requests such that $3 \cdot LR/4 < r_{src,dst} \leq LR$

The ordered lists of bands are built using two criteria: optical reach of bands and balanced selection of bands. The ordered list of bands for partition sets 1, 2, 3 and 4 are (E,S,C,L), (S,C,L,E), (C,L,E,S) and (L,E,S,C), respectively. This algorithm is similar to V1, but uses a finer granularity to partition the connection requests whilst attempting to balance the use of bands (using a Round-robin approach, such that each partition has a different preferred band).

Variant 3 (V3): Connection requests are partitioned into $X = 2$ sets. The partition criterion is the bitrate. Let M_b be the median value of the available bitrates. Partition sets are built as follows:

- Set_1: requests such that $b_{src,dst} < M_b$
- Set_2: requests such that $b_{scr,dst} \geq M_b$

The ordered lists of bands are built using three criteria: band capacity, optical reach and balance across bands. Set_2 is associated to the ordered list of bands (E,L,S,C). Thus, requests with higher bitrates (and thus, higher FSU requirements) are attempted first in the band with the highest capacity (band E in Set_2). The second priority is a band with a longer reach (band L in Set_2), just in case a high bitrate request also has a long path. Finally, to balance band selection, Set_1 is associated to the ordered list of Set_2 in reversed order. That is, the list (C, S, L, E).

The main difference between the variants here presented and the band allocation used in the algorithm proposed in [8] lies in the number and types of partition sets and the different orders used to attempt the bands. In [8] X is equal to 1, while our variants use 2 or 4 partitions. In [8] all connections attempt the bands in the same order, in our variants this order changes with the characteristics of connections and bands.

V. SIMULATION RESULTS

A C++ simulator was used to evaluate the bandwidth blocking probability (BBP: defined as the relationship between the blocked traffic (in Gbps) the total traffic offered to the network [13]) of the three variants just described and two baseline algorithms.

For the 3 variants, we used the RBMSA algorithm described in Algorithm 2 as the main allocation algorithm. That is, the algorithm performs band allocation (B) immediately after the routing task (R) and before the modulation level (M) and spectrum allocation (SA) tasks. For the routing task, we pre-computed the shortest path. The function $msa(curr\_band, route)$ selects the modulation format requiring the lowest number of FSUs whose optical reach is equal to or greater than the length of $route$ (data from Table I), and the spectrum assignment is First-Fit in $curr\_band$.

For comparison purposes, we included two baseline algorithms: B1 and B2. B1 is the RBMSA algorithm described above (Algorithm 2) using the band allocation presented in [8]. That is, $X = 1$ and the same order of bands, (C,L,S,E), is attempted for all connections. The comparison with B1 allows to evaluate the impact that the band allocation step alone has on the BBP. B2 is the RMBSA algorithm proposed in [8], with the use of values from Table I to determine the feasibility of route, modulation and band choices. The main differences between B2 and the RBMSA algorithm using the proposed variants is the order in which the routing, modulation level, band and spectrum allocation problems are solved (RMBSA in B2 and RBMSA in our algorithms), the modulation format allocation step (most efficient first and others are tried later if

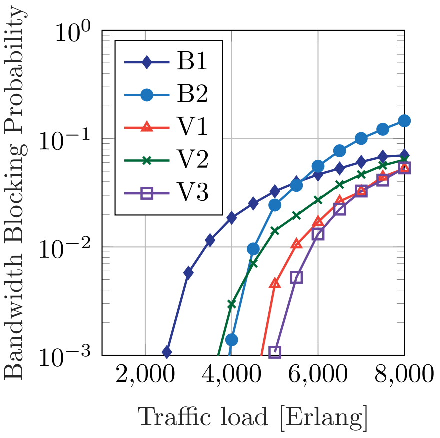

Fig. 2: C+L+S+E scenario

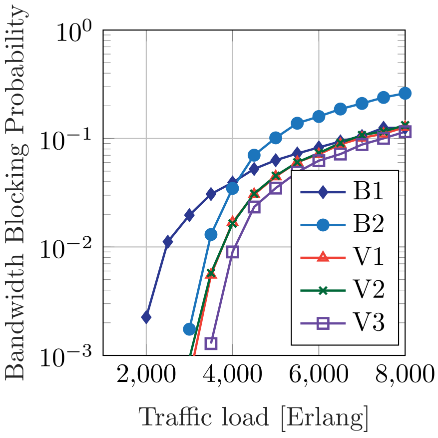

Fig. 3: C+L+S scenario

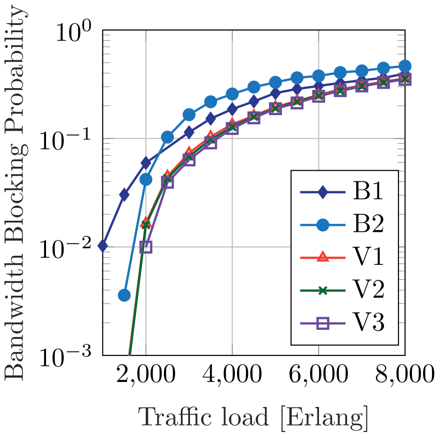

Fig. 4: C+L scenario

Algorithm 2 RBMSA algorithm

```
function RBMSA($src, dst, b$)
    route ← shortest_path()
    $curr\_band \leftarrow 0$
    while $TRUE$ do
        $curr\_band \leftarrow$ band($curr\_band, src, dst, b$)
        $result \leftarrow$ msa($curr\_band$,$route$)
        if $result = success$ then
            allocate_resources()
            return REQUEST_ALLOCATED
        end if
        if $curr\_band = -1$ then
            return REQUEST_REJECTED
        end if
    end while
end function
```

the selected one does not work in [8] vs. the most efficient with enough optical reach here) and the band allocation algorithms used. The comparison against B2 will allow to evaluate the performance of our proposals against the state-of-the art.

Notice that as different MB-EONs algorithms are proposed by the research community, they might solve the routing, modulation level, band and spectrum allocation problems in different orders and use different algorithms for each step. What combination yields the best results is an open problem.

We tested the algorithms in the COST239 network (N=11, L=52) [14]. The mean holding time of all connections was set to $1/\mu = 500$ s. The mean inter-arrival rate of connections was varied between 2 connections/s and 16 connection/s to generate the same traffic loads used in [8]. The set of B bitrates is $\{10, 40, 100, 400, 1000\}$ Gbps.

Fig. 2 shows the BBP of the three variants and the two baseline schemes for different traffic loads for the C+L+S+E scenario. Additionally, although V1, V2, and V3 were designed for a 4-band scenario, we also tested their performance in the C+L+S and C+L multi-band scenarios (by simply deleting the corresponding bands from the lists generated for the 4-band scenario). These results are shown in Fig. 3 and Fig. 4, respectively. Table II shows the BBP increase (in number of times) of the baseline algorithms with respect to the variants for selected traffic loads for all scenarios.

Two main trends can be observed: First, the proposed variants outperform the baseline algorithms in all scenarios and traffic loads. When evaluating the performance of the band allocation task only (B1 vs. V1-V3), all variants outperform the baseline, highlighting the fact that associating different band orders to different connections improves blocking performance. When evaluating the performance of the resource allocation algorithms (B2 vs. V1-V3), the proposed variants implemented in a RBMSA algorithm also outperform B2, except for V2 at traffic loads lower than 4500 Erlang in the C+L+S+E scenario. When disaggregating the blocking, we observed that only 400 and 1000 Gbps connections were blocked and that blocking occurs due to the lack of available slots. By way of example, Table III shows the percentage of blocked requests for a traffic load of 5000 Erlang. By having a slightly more balanced band usage, as shown in Table IV where the percentage of connections successfully established in each band by the different algorithms is shown for a traffic load of 5000 Erlang, the proposed variants can accommodate more 400 and 1000 Gbps requests in the different bands. Hence, we can conclude that allocating bands considering the features of connections and bands leads to a better performance than not doing it (B1 and B2 approaches). V3 exhibits a clear better performance for the scenario for which it was initially designed (C+L+S+E) and slightly better performance for the 3 and 2-band scenarios, suggesting that bitrate-based partitions might perform best. Second, the impact of decreasing the number of bands on the BBP varies for the different algorithms. The performance of B1 and B2 is not significantly affected when eliminating band E because this is the lowest-priority band for these algorithms. Thus, this band has the lowest number of connections established, as shown in Table IV. Instead, V1-V3 increased their blocking to a greater extent than the baselines, since they relied on band E to establish a higher percentage of connections (ranging from 16% to 74%). When further eliminating another band (band

TABLE II: BBP increase (number of times) of each baseline with respect to V1-V3.

Traffic load [Erlang]	C+L+S+E scenario			C+L+S scenario			C+L scenario		
	V1	***V2***	***V3***	***V1***	***V2***	***V3***	***V1***	***V2***	***V3***
4000	B1: 18.6 B2: 1.4	B1: 6.3 B2: 0.5	B1: 18.6 B2: 1.4	B1: 2.3 B2: 2.1	B1: 2.4 B2: 2.1	B1: 4.4 B2: 3.9	B1: 1.4 B2: 1.9	B1: 1.5 B2: 2.0	B1: 1.5 B2: 2.1
6000	B1: 2.8 B2: 3.3	B1: 1.7 B2: 2.0	B1: 3.5 B2: 4.2	B1: 1.2 B2: 2.2	B1: 1.1 B2: 2.2	B1: 1.3 B2: 2.6	B1: 1.2 B2: 1.5	B1: 1.2 B2: 1.5	B1: 1.2 B2: 1.5
8000	B1: 1.3 B2: 2.8	B1: 1.1 B2: 2.3	B1: 1.3 B2: 2.7	B1: 1.0 B2: 2.1	B1: 0.9 B2: 2.0	B1: 1.1 B2: 2.3	B1: 1.1 B2: 1.3	B1: 1.1 B2: 1.3	B1: 1.1 B2: 1.3

TABLE III: Percentage of 400 and 1000 Gbps requests rejected for different multi-band scenarios (5000 Erlang)

Algorithm	C+L+S+E scenario				C+L+S scenario			C+L scenario	
	C	***L***	***S***	***E***	***C***	***L***	***S***	***C***	***L***
B1 400	0.0	0.0	0.0	0.5	0.0	0.0	1.3	0.0	8.7
B1 1000	0.0	0.0	0.0	2.7	0.0	0.0	4.9	0.0	14.4
B2 400	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	2.8
B2 1000	0.0	0.0	0.0	0.8	0.0	0.0	3.1	0.0	9.1
V1 400	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.4	1.0
V1 1000	0.0	0.1	0.0	0.0	0.0	1.0	0.4	1.6	3.8
V2 400	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.6
V2 1000	0.3	0.0	0.1	0.0	0.5	0.0	0.6	1.4	4.2
V3 400	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0
V3 1000	0.0	0.0	0.0	0.0	1.1	0.0	0.0	5.3	0.0

TABLE IV: Percentage of connections successfully established in each band for different multi-band scenarios (5000 Erlang)

Algorithm	C+L+S+E scenario				C+L+S scenario			C+L scenario	
	C	***L***	***S***	***E***	***C***	***L***	***S***	***C***	***L***
B1	61.7	20.7	11.0	3.4	61.6	20.8	11.3	50.6	23.1
B2	69.5	17.6	8.8	3.4	73.3	14.8	8.7	73.5	14.6
V1	2.3	22.5	4.8	70.4	4.4	23.3	70.9	60.6	32.5
V2	14.3	29.4	39.9	16.0	29.9	14.5	54.2	71.1	22.2
V3	60.0	5.0	2.1	32.9	70.8	20.8	7.3	61.9	32.0

S), all algorithms are affected similarly, but the baseline's BBP remains higher than that of the proposed variants. The fact that the variant's blocking performance gets closer to each other and the baselines as the number of bands decreases suggests that an algorithm designed for a 4-band scenario might need a tailored ordered list of bands for a 3 or 2-band scenario instead of simply eliminating the corresponding band from the list.

VI. CONCLUSION

This letter presented a family of band allocation algorithms for dynamic MB-EONs. Simulation results on different scenarios (C+L+S+E, C+L+S, and C+L) and traffic loads showed that 3 variants from this family outperformed the current state-of-the-art algorithm for up to one of order of magnitude. Results also highlight the fact that allocating bands taking into account the features of the connections (e.g. route length or bitrate) and bands (e.g. capacity, reach, band balancing) is key for improved performance. Further work will focus on studying different variants. For example, variants using mixed criteria to partition the set of connections requests (e.g., a combination of route length and bitrate) or variants that change the order in which bands are attempted depending on the specific bands available.

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