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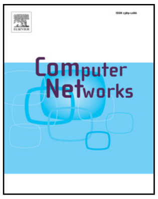

Leveraging adaptive modulation with multi-hop routing in elastic optical networks

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ABSTRACT

The technology used for data transmission in optical networks is going through significant changes in response to the rapid growth of Internet traffic and emerging high performance applications, boosting research on how to satisfy the increasing demands with the available resources. In this scenario, the elastic optical networks paradigm enables improved provisioning through flexibility and scalability in spectrum assignment. This work proposes data and optical grooming and the use of spectral modulation control as a solution to the Routing, Modulation Level, and Spectrum Allocation problem in a dynamic traffic context. The proposed algorithm obtains the greatest spectrum aggregation possible using higher modulation levels through multiple hops in the virtual topology. Experiments show that this approach results in reduced blocking without impacting the use of the network's resources.

1. Introduction

Internet traffic has been growing exponentially and tends to continue doing so due to emerging applications such as high definition TV, cloud computing, multimedia applications, and real-time networks [1]. Current optical networks, which are based on the *Wavelength Division Multiplexing* (WDM) paradigm, can establish connections with a fixed bit rate (10Gb/s, 40Gb/s, or 100Gb/s) where the channels are modulated in a single format and equally spaced by 50 GHz [2].

Currently, Internet traffic demands increasingly different granularity levels with more flexible bit rates and unpredictable geographical transit patterns [3]. The conventional optical transmission technology is unable to satisfy these growing demands since it has physical limitations which impose fixed transmission rates in each wavelength, hindering the use of the network resources [4]. Additionally, new researches show that the WDM networks are approaching their limits due to the increase in traffic and growing mobility of its sources [5].

Adapting this technology to the recent demands is one of the challenges of the Future Internet. These issues require scalable optical network infrastructure and efforts to increase the network transport capacity, improving its efficiency using the resources, and allowing traffic with different granularities and flexible bit rates.

An *Elastic Optical Network* (EON) can dynamically adjust resources, such as optical bandwidth and modulation format, according to the requirements of each demand [6]. This flexibility is mostly due to the *Orthogonal frequency-division multiplexing* (OFDM), especially in wireless networks (802.11a/g *Wi-Fi*, 802.16 *WiMAX*, and *LTE*) [7]. OFDM improves efficiency of spectral resources via super-channels which provide an adaptable bit rate to ideally satisfy the band requirements, creating channels with the bandwidth required by the data flows to be transmitted.

The allocation strategies for satisfying the call requests determine the resources usage. In WDM, this is the *Routing and Wavelength Assignment* (RWA) problem, and the goal is to allocate the best pairing of route and wavelength for a given traffic demand. In EON, it is the *Routing and Spectrum Assignment* (RSA) problem, and the objective is to find a path and give it a contiguous amount of spectrum slots [2]. This problem has evolved into the *Routing, Modulation Level, and Spectrum Allocation* (RMLSA) problem [8], which includes the attribution of the modulation format to be used. These are NP-Hard problems [8,9] to which several algorithmic solutions for elastic networks have been successfully applied [2].

Similar to WDM technology, the EON networks also allow flow aggregation onto one optical channel through (electrical) traffic grooming [10]. This technique results in higher spectral efficiency since it enables low capacity demands to be grouped and, at the same time, minimizes guard band usage by electrically aggregating traffic [11].

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To further improve flexibility, EON technology provides support for optical grooming [2], which enables transport from a single source to different destinations without having to establish more than one optical channel, using only one transponder at the source [12]. This dispenses guard bands between optical paths with identical routes, resulting in better spectral efficiency. Additionally, traffic grooming and distribution can be done directly in the optical layer [13], which significantly increases spectral efficiency and reduces the network operational costs.

Several works approach traffic and optical grooming concepts for handling the RSA problem, but these have not yet been fully investigated in the RMLSA context, especially in a scenario with dynamic traffic, in which it also important to explore multi-hopping routing in a virtual topology [12].

Considering the current state-of-the-art and unanswered questions related to this problem, this works proposes a solution for RMLSA in dynamic traffic scenario by using spectral modulation control and traffic and optical grooming. The idea behind joining these techniques is to better exploit the optical network resources to provide greater bandwidth by obtaining greater optical grooming using higher modulation levels through multiple hops in the virtual topology. Simulation results show reduced blocking, with gains up to 81%, with no impact on the use of the network resources.

The rest of the paper is organized as follows. Section 2 introduces elastic optical networks architectures and their elements. Section 3 presents the algorithms, techniques, and the state-of-the-art in EON literature. Section 4 shows the proposed approach for solving the RMLSA problem. Section 5 presents numerical results for applying the proposal in standard tests. Finally, concluding remarks are given in Section 6.

2. Elastic optical networks

EONs based on OFDM are characterized for dividing spectral resources into frequency *slots* as subcarriers, allowing multiple modulation formats and different data rates and spectra sizes. An EON's goal is to allocate a demand to an optical path with bandwidth of adequate size, so the optical path can be expanded or contracted as needed, according to traffic fluctuations or new connection demands [14].

Fig. 1 illustrates the differences between optical paths with fixed and flexible grids. In a fixed grid, a single frequency bandwidth of the spectrum is used, regardless of the client's demand; in a flexible grid, the bandwidth adapts to the demand. The architecture of an EON based on OFDM is composed of *bandwidth-variable transponders* (BVTs) and *bandwidth-variable Wavelength Cross-Connects* (BV-WXC), which enable lightpaths in flexible grids to be established.

Several OFDM subcarriers can be joined into a superchannel, transporting data without any guard bands. So the BVTs create the lightpaths with flexible bandwidth, allowing the resources to be adjusted to the current demand [7]. Since an elastic lightpath is allocated as required, it can transmit multiple bit rates, as illustrated in Fig. 1 where the use of a fixed grid's fiber's spectral resources are adapted to a flexible grid. The figure also presents gain with this spectrum variation.

The BV-WXCs are responsible for establishing an end-to-end path with enough bandwidth to accommodate the spectral resources defined by the BVTs. When the BVTs increase traffic, each BV-WXC in the route must expand its switching window, allowing a variable data rate in each lightpath [7]. This OFDM based EON architecture is illustrated in Fig. 2, where the BVTs are located in the network's edge and the BV-WXCs in its core [14].

The modulation format used in each subcarrier of EONs also allows flexible adjustment of bandwidth. Since every lightpath is composed of an arbitrary number of OFDM subcarriers, each can be individually modulated (with a different BVT) for a transmission [15]. For example, single bit per symbol *binary phase shift keying* (BPSK), QPSK (2 bits per symbol), 8QAM (3 bits per symbol) or 16QAM (4 bits per symbol). The number of subcarriers and the modulation format are adjusted to the amount of traffic and optical reach requested [7]. The choice of modulation level should consider the *quality-of-transmission* (QoT) and, consequently, the *optical signal-to-noise ratio* (OSNR) [7,8].

Even though physical impairments, such as crosstalk, affect OSNR and thus, the QoT [16,17], in EON literature the transmission distance of the lightpath is claimed to be the most relevant factor in QoT [18–20]. Therefore, given the size of the path, the modulation level that provides the best spectrum efficiency without hindering the QoT can be found. This allows shorter paths to use higher modulation levels, as illustrated in Fig. 3.

An important issue is the choice of the spectral and capacity characteristics of the subcarriers. As per the International Telecommunication Union's Recommendation G.694.1, conventional fixed grid networks channel spacings of 50 GHz on a fiber [21], but EONs have more flexibility, using a spectrum granularity of 12,5 GHz per subcarrier [2]. The passband is, therefore, closely related to the size of the spectrum allocated by each OFDM subcarrier and its modulation format. This is represented by Eq. (1),

$$B = \frac{C}{log_2 M} \tag{1}$$

where B is the subcarrier's spectrum capacity in GHz, C is the data rate in Gbps, and M is the modulation level being used, *Quadrature Amplitude Modulation* (QAM) or *Phase-Shift Keying* (PSK) [7]. In other words, M is the number of phases used for coding a number of bits per symbol, so the higher the modulation level, the greater the subcarrier's passband and the shorter its reach (according to the QoT factor).

This kind of lightpath with flexible spectrum bandwidth cannot be found by traditional RWA algorithms, commonly used in conventional optical networks [7,8], so new mechanisms for routing and spectrum allocation are needed. In usual RSA algorithms, subcarriers in the same optical path must be routed contiguously using the same spectrum band throughout the route, and distinct lightpaths must be spaced by a guard band to attend OFDM restrictions.

These RSA limitations are illustrated in Fig. 4, which considers an EON with four nodes and the arrival of a request for connection with bit rate equivalent to three OFDM subcarriers (shown as slots). Assuming this request source is node a and its destination is node d, the connection cannot be established through the shortest path (via nodes a–c–d) because links 1 and 2 do not have three contiguous slots which are continuous along the links. These requirements, however, are met by a connection through the a–c–b–d route using slots 5, 6, and 7 through links 1, 3, and 4.

The complexity of the RSA problem can be deduced by reduction of the RWA problem. If the number of OFDM subcarriers in the channel is equal to the number of wavelengths in the fiber, the creation of a new lightpath in the RWA algorithm is equivalent to that in the RSA algorithm, i.e. for conventional optical networks, the RSA problem is a reduction of the RWA problem [8]. Since this reduction is done in polynomial time, the RWA problem has a solution if and only if the RSA is solvable; thus, the RSA problem is also of the NP-Hard class [9].

One of the issues of RSA algorithms is satisfying traffic demands with low bit rates. A connection requested bandwidth can be much lower than the capacity of a lightpath, and two lightpaths that go through one or more common fiber links must be separated by at least one guard band to avoid severe interference [11]. Though BVTs can dynamically adjust the offered bandwidth in an EON, if

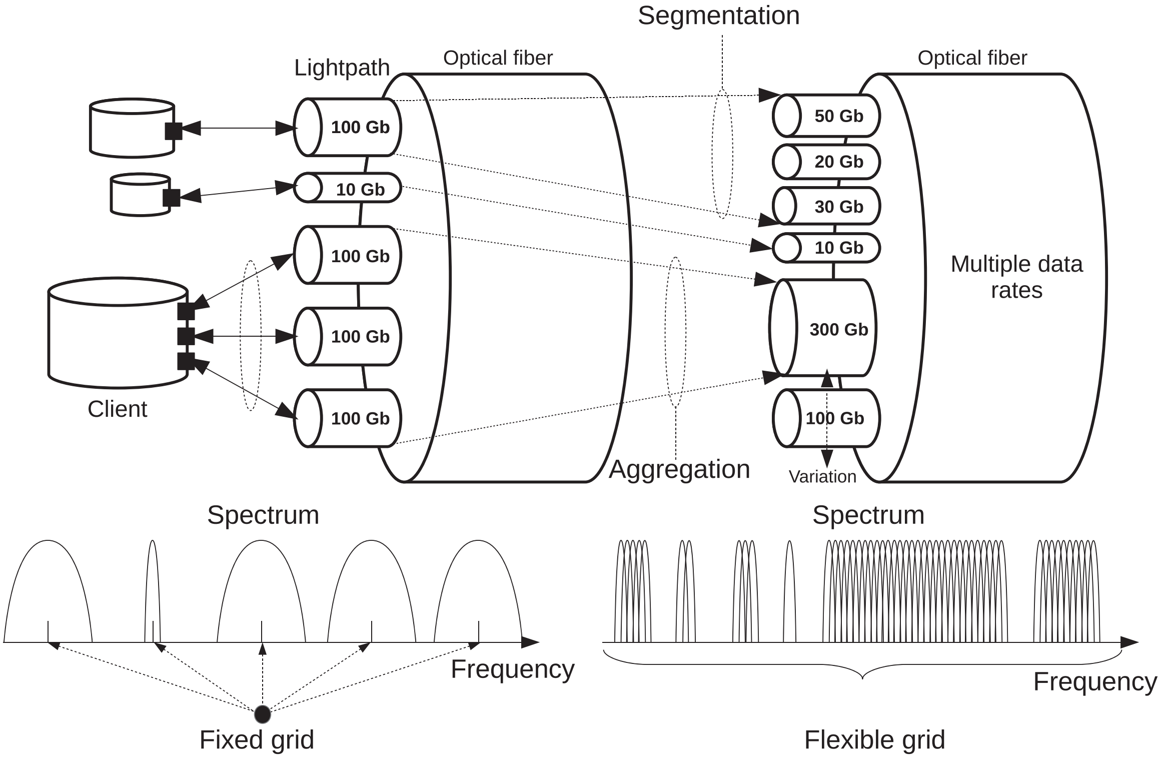


Fig. 1. Comparison of lightpaths with fixed and flexible grids.

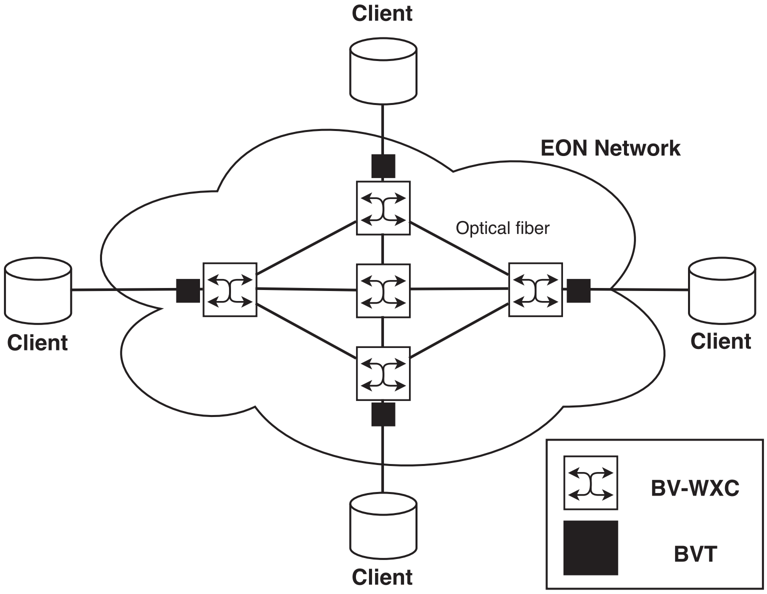


Fig. 2. Architecture of an EON based on OFDM.

the demand needs less bandwidth than the available in the OFDM subcarrier, the spectrum will be underused. Additionally, several such demands might produce a significant amount of guard bands, leading to squandering of the spectrum. This can be addressed in EON by (electrical) traffic grooming [10], as has been successfully done in conventional WDM networks [22].

Traffic grooming requires the traffic to belong to the same lightpath, i.e. to have the same source and destination BVTs; when different destinations are concerned, more than one lightpath must be established. Therefore, it is necessary to have guard bands between adjacent lightpaths and several BVTs, one for each path.

Though traffic grooming enables better exploitation of the spectrum, the flexibility obtained by using BV-WXC provides even more [14]. The basic idea behind this is to aggregate multiple lightpaths in a single BVT and transmit them through the BV-WXCs [13]. This process is called optical grooming [12], and the grouping of lightpaths is an optical tunnel [13]. The optical grooming eliminates electrical processing by offloading parts of the grooming function to the optical layer at the same time that it improves transponder usage and reduces guard band usage [12].

The optical tunnel is composed of lightpaths with the same BVT as source and, since no guard bands are required between

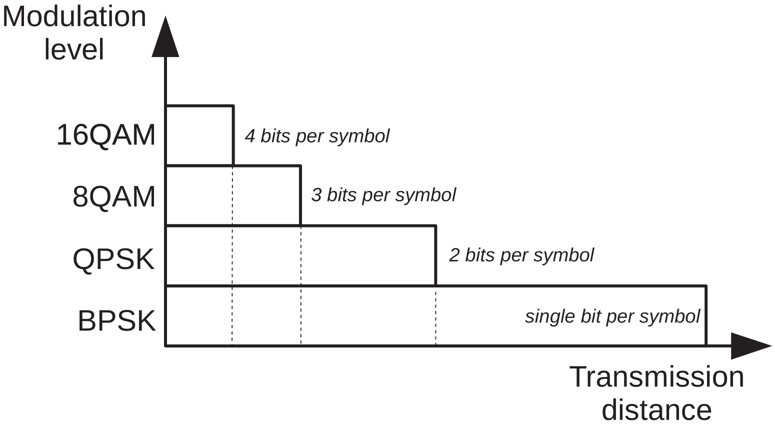


Fig. 3. Modulation level according to transmission distance.

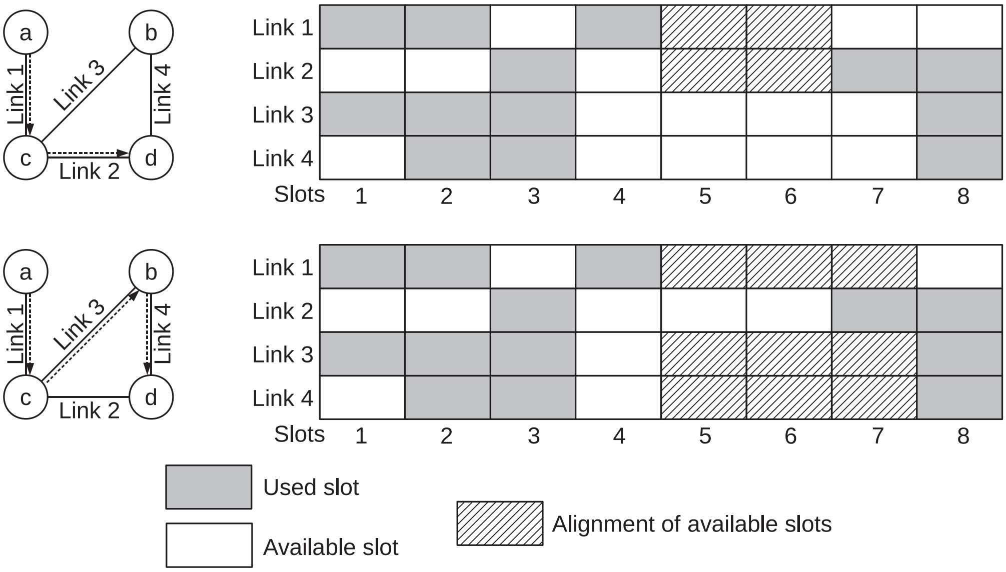


Fig. 4. Example of the RSA problem.

them, it achieves significantly better efficiency using the spectrum [12,13]. Additionally, by using more of the spectrum in each BVT, less of such devices are needed to satisfy the same traffic demand, decreasing the network's operational costs. Despite enabling less transponders, this approach does not impact on the number of receivers because traffic from different source-destination pairs need to be received separately [13].

As the Internet traffic grows and applications change, EONs provide several advantages such as: (i) support to different levels of traffic demand (Gb/s to Tb/s); (ii) efficient use of spectrum through allocation of flexible optical paths on demand; (iii) support to variable band rate with spectral expansion/contraction via number of subcarriers or modulation format; (iv) efficient energy consumption by disconnecting OFDM subcarriers according to traffic demand; and (v) adaptive restoration in case of network failures by adaptive spectrum allocation and modulation format optimizations.

3. Related works

Research on solutions for routing and spectrum allocation in elastic optical networks has been growing recently. The RSA problems are investigated in static and dynamic traffic scenarios, considering modulation and adaptive distance of the channel.

Three heuristics for solving the RSA problem in a dynamic scenario were proposed in [17]. The first is a two-step approach which initially applies Yen's algorithm for computing single-source *K-shortest paths* (KSP) that are then processed in an attempt to allocate the demand to one of them. The second applies a *Modified Dijkstra Shortest Path* (MSP) to search for the shortest route. The last is the *Spectrum-Constraint Path Vector Searching* (SPV) algorithm which applies a breadth-first search to create a tree that represents the candidate paths and finds, within the options that provide the demanded spectrum, the shortest one. The results presented in this work show significant decrease in blocking compared to traditional RWA in WDM networks.

The authors of [8] introduced the use of adaptive modulation in the RSA problem, considering the modulation format in the fiber and, thus, expanding it to the Routing, Modulation Level, and Spectrum Allocation problem. This was investigated in [23], where the authors analyzed the effects in the algorithms proposed in [17] when using adaptive modulation. To this end, they proposed the *m Adaptive RSA algorithms, mAdap*, (illustrated in Fig. 5), which iterates in decreasing order through possible modulations, applying the RSA algorithm until a solution is found. Experimental results for this work show significant reduction in blocking and spectral usage.

The authors of [10] introduced traffic grooming in EONs, increasing spectrum efficiency by eliminating guard bands between demands smaller than the bandwidth in a subcarrier. In their

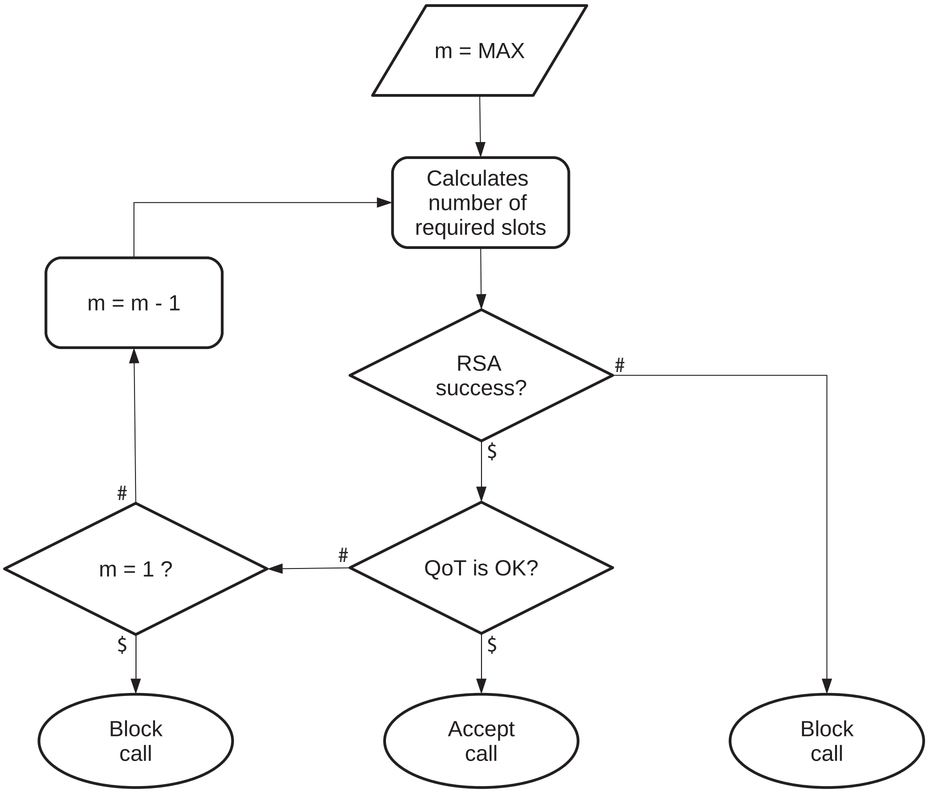


Fig. 5. m Adaptive RSA (*mAdap*) flowchart.

approach, several low-speed connection requests are groomed in elastic lightpaths through electrical layer multiplexing. Results of a *mixed integer linear program* (MILP) formulation showed spectral economy between 8% and 24% in an EON with static traffic scenario.

The traffic grooming problem in the dynamic traffic EON scenario was investigated in [11]. This work proposes the use of an auxiliary graph for implementing grooming policies, and spectrum reservation for future traffic demands. Results showed that there are different trade-offs between policies, which should be adopted according to the network's circumstances and goals, and that there was significant reduction in operational costs (by using less BVTs, for example).

Optical grooming was introduced in [13], in a proposal that does not require the use of guard bands or multiple light sources in BVTs. An *integer linear program* (ILP) was proposed for a static scenario, and two heuristic algorithms used for solving the RSA problem in an optical grooming context. It demonstrated that significant savings can be achieved in terms of transponders and spectrum. The algorithms were validated with the ILP and compared to approaches without optical grooming. Results showed that this aggregation enables between 25% and 80% economy in BVT usage and 5–15% greater efficiency in spectrum usage.

The *First-Possible Aggregating* (FPA) algorithm for optical traffic grooming in a dynamic network scenario was proposed in [24]. It maximizes the use of the a BVT by aggregating multiple lightpaths in one transponder. Additionally, FPA improves spectrum usage by decreasing the number of guard bands between lightpaths that share a route. These resources can be readily used in additional connections through the network with fewer transponders per node. Results showed that this approach brings significant improvements in blocking compared to other algorithms.

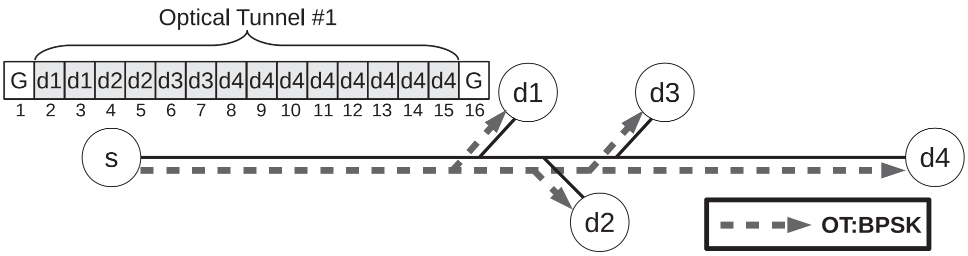
The authors of [25] introduce the MPH-SRNP algorithm, which use optical grooming techniques and a different approach to spectrum reservation with the auxiliary graph (AG) proposed in [11] to obtain better results. Grooming policies are compared regarding bandwidth blocking ratio, number of transponders, and number of hops in the virtual and physical topologies, and results also showed that there are trade-offs between them, so the choice depends on the objectives of the network operator.

The proposals in [23] consider adaptive modulation, but not traffic grooming techniques and, contrariwise, the ones in [10,11,13,24,25] do consider traffic grooming techniques but not the adaptive modulation scenario. The first to join these issues were the authors of [26], where the *Distance-adaptive and Fragmentation-aware optical Grooming* algorithm (DFG) algorithm was presented. It optically groups traffic demands that share the link and have the same source, and commutes them through the link with no guard bands while considering the modulation in use in the optical tunnel. Results showed that optical grooming is not always efficient because the length of a lightpath in a tunnel might be too great and hinder its modulation as a whole, as illustrated in Fig. 6. The algorithm FPA satisfies 4 demands with 14 slots and 2 guard bands (using 16 slots in total) in Fig. 6a, while DFG uses a different modulation level in nodes *d1, d2*, and *d3*, using a higher modulation level through another *optical tunnel* (OT), to use 14 slots in the same scenario, as in Fig. 6b.

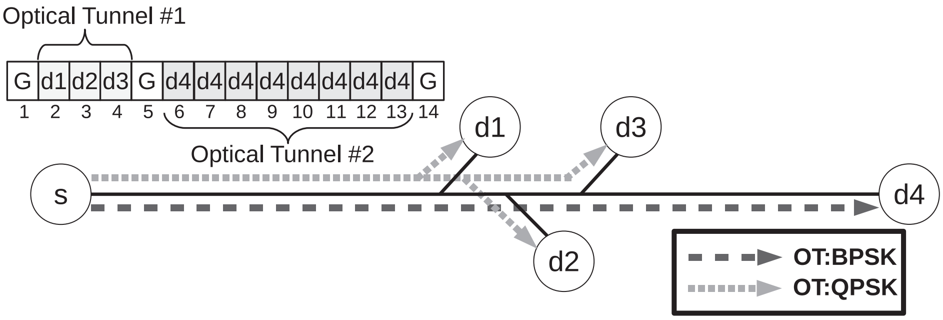
The work presented in [26] does not, however, consider dynamic traffic in the network nor investigate the use of multi-hop routing in the virtual topology, both issues that have shown interesting results. To address them, this work proposes the *Maximize the use of Best Modulation format* (MBM) algorithm. The characteristics of the all works discussed so far are summarized in Table 1.

4. Maximizing the use of best modulation format

This work considers all the most important aspects from previous approaches in a dynamic traffic in EON scenario: (i) traffic



(a) Maximum possible spectrum aggregation, FPA algorithm.



(b) Conscious spectrum aggregation, DFG algorithm.

Fig. 6. Adaptive distance problem with spectrum aggregation.

Table 1
Approaches to the RSA/RMLSA problem.

	Network scenario			Grooming	
Proposal	Traffic	Routing	Modulation	Traffic	Optical
KSP, MSP, SPV [17]	Dynamic	Single-Hop	Static	No	No
RMLSA Approach [8]	Static	Single-Hop	Dynamic	No	No
TG-Approach [10]	Static	Single-Hop	Static	Yes	No
LB-SR [11]	Dynamic	Multi-Hop	Static	Yes	No
MTG [13]	Static	Single-Hop	Static	No	Yes
FPA [24]	Dynamic	Single-Hop	Static	No	Yes
MPH-SRNP [25]	Dynamic	Multi-Hop	Static	Yes	Yes
DFG [26]	Static	Single-Hop	Dynamic	Yes	Yes
MBM (our proposal)	Dynamic	Multi-Hop	Dynamic	Yes	Yes

grooming for better usage of the channel's resources; (ii) optical grooming for more efficient use of the resources; and (iii) adaptive modulation for reducing the use of the network's spectral resources.

The proposed Maximize the use of Best Modulation format algorithm aims at the greatest optical grooming possible through multi-hop routing, using higher modulation levels. To this end, an optical transmission between two distant nodes must be composed of several shorter paths that satisfy the required QoT factor, allowing less spectral resources to be consumed by using more *optical-electrical-optical* (OEO) conversions, i.e. there is a trade-off between using less spectrum and using more transponders. Additionally, this approach benefits from the use of multi-hopping, which enables new entry points for traffic and optical grooming, as discussed below.

The algorithm is illustrated in Fig. 7, in the same scenario presented in Fig. 6. Node *d4* is too far from the source (*s*) and only satisfies the QoT requirements through BPSK modulation, as shown in Fig. 6. Nodes *d1, d2*, and *d3*, on the other hand, can be reached through more efficient modulations, such as QPSK. The DFG approach (Fig. 6(b)) observes this and splits the optical tunnel, gaining spectral resources, but the farther demand (*d4*) is sent throughout the entire path in the same modulation level (BPSK).

Differently, MBM uses multi-hopping for shorter lightpaths with higher modulation levels, effectively consuming less resources (13 slots compared to DFG's 14), as shown in Fig. 7. As with DFG, the demands to nodes *d1, d2* e *d3* are sent through the QPSK modulation, but the demand to *d4*, which requires 8 slots, is handled in two hops. First it is sent through QPSK modulation, by optical grooming to node *d3*. There, an OEO occurs and a different transponder, the one with the highest modulation level possible (in the example, 8QAM modulation), is used to send it to its final destination. The advantage is that MBM uses less slots than DFG for satisfying the same demands.

Proposed algorithm

MBM was designed to take advantage of the *mAdap* approach but it does not follow the same steps to solve the RMLSA problem. The proposal is described in Algorithm 1, where *TG* represents traffic grooming, *OG* is optical grooming, *s* and *d* are, respectively, the connection's source and destination nodes, and *b* is the requested bandwidth of a connection request.

The MBM algorithm is based on three steps for accepting a request *r*: a single-hop for traffic and optical grooming (lines 4–14); a multi-hop step for the same goals through multiple hops in the

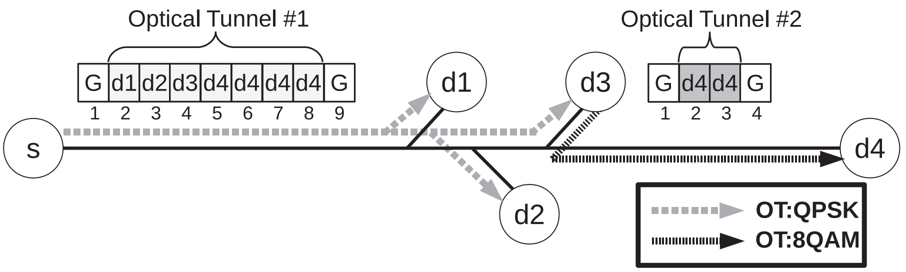


Fig. 7. MBM algorithm example.

virtual topology (lines 15–44); and a final single-hop step (without grooming) based on the KSP algorithm [17,23] (lines 45–50).

Initially, it creates two structures composed by *k*-shortest paths through an off-line procedure (lines 1–2), thus the value of the constant *k* is also an input. Then, for each request, the MBM algorithm searches for a lightpath in the network to do *TG* using *least used* policy (line 4).

If end-to-end *TG* is not possible, the algorithm gets the *k*-shortest edge-disjoint paths from *s* to *d* (line 7) and tries to do *OG*. The algorithm searches for the lightpath originating from *s* sharing the most links with *Paths*[*i*] (lines 8–10), then checks if this lightpath has optical grooming capacity. If it does, *OG* based on FPA [24] approach is done (line 11).

If no acceptable lightpath is found, the algorithm advances to the multi-hop step. It gets the *k*-shortest paths (line 15) and checks if either *TG* or *OG*, in this order, is possible in *Paths[i]* by multi-hopping in virtual topology (lines 16–35). After the *while* loop, the algorithm tries to create a new lightpath with the appropriate modulation level, according to the lightpath's size (lines 36–44).

Finally, if no grooming with the request *r* was possible, the algorithm executes the KSP algorithm with the highest possible modulation level using a single-hop approach (line 45). If a new lightpath cannot be created, the request is blocked (line 49).

The *TG* and *OG* procedures are described as follows. The *TG*(*r, s, d*) requires that there is at least one established lightpath in the network with source *s* and destination *d*. If there is such lightpath, it verifies if there is enough spare space to allocate the bandwidth requested *r*. The *OG*(*r, s, d*) procedure also requires an established lightpath (lp_a) in the network, however, it only requires that the source is *s*. If there is such lightpath, the *OG* creates a new lightpath (lp_b), which is contiguous to lp_a (disregarding guard bands), with destination *d* and capacity equal or greater to the requested *r*. This requires that there are enough slots (along lp_a) for the expansion of the communication channel (optical tunnel). Moreover, the lp_b lightpath must satisfy all constraints (RSA/RMLSA) and the sum of the slots in the optical tunnel must not exceed the capacity of the transmitter.

Note that the MBM multi-hop step, associated with the *mAdap* approach, always tries to use the highest possible modulation level according to the lightpath size. In other words, the MBM algorithm leverages the adaptive modulation by using the highest modulation levels supported on the network in order to save spectrum.

Complexity analysis

The time complexity of the off-line computation phase is analyzed as follows. The *k*-edge-disjoint path algorithm does *k* executions of Dijkstra's algorithm, thus the time complexity is $O(k*(|E|+|V|log|V|))$, where *E* is the set of bidirectional links and *V* the set of nodes in the network. The space complexity is *k* times Dijkstra's space complexity, which is $O(k*|V|^2)$. For the *k*-shortest path, Yen's algorithm is employed, thus the time complexity is $O(k*|V|(E+|V|logV))$, and the space complexity is $O(|V|^2+k*|V|)$ [27]. Note that all the above computations are performed for each node pair, thus they should be multiplied by $O(|V|^2)$.

The time complexity of the on-line algorithm is analyzed as follows. The first step (lines 4–14) is dominated by two procedures: (*i*) if traffic grooming is possible (line 4); and (*ii*) if optical grooming in *k*-paths is possible (lines 8–13). The maximum number of lightpaths allocated in a network is $|E|*|S|$, where *S* is the set of slots in each link. Thus, the time complexity of first step is $O(|E|*|S|)$. Analogously, the second procedure follows similar steps for *k* paths, so the time complexity is $O(k*|E|*|S|)$. Therefore, the first phase has a time complexity of $O(k*|E|*|S|)$.

The second step (lines 15–44) has two costly procedures: (*i*) a loop (lines 19–35) checking the possibility of traffic grooming (line 23) and/or checking the possibility of optical grooming (line 26); and (*ii*) the KSP algorithm (line 39). As before, the grooming has time complexity of $O(|E|*|S|)$, which gives a complexity of $O(|V|*|E|*|S|)$ for the first procedure. The second procedure has complexity of $O(k)$ since the paths are already available after being computed off-line [23]. Both procedures are executed *k* times, so the complexity of the multi-hop step is $O(k*|V|*|E|*|S|+k^2)$.

The last step (lines 45–50) simply applies the KSP algorithm ($O(k)$). Considering all three steps, it is clear that the second one dominates the others, so the MBM algorithm has a time complexity of $O(k*|V|*|E|*|S|+k^2)$.

5. Numerical results

Simulations were performed using the ONS network simulator [28]. To assess the MBM algorithm's performance, it was compared to 5 other related algorithms: KSP, MSP, SPV, FPA, and MPH-SRNP. For every algorithm, each simulation was run five times using the independent replications method, and results are presented with confidence intervals with 95% reliability. For each simulation, 10^5 connection requests are generated with 15 levels of granularity varying from 12.5 Gb/s to 100 Gb/s (with a 6, 25 Gb/s step), all with the same probability of arrival. This process follows a Poisson distribution where source and destination are uniformly distributed for all communicating pairs in the network.

The network topologies considered here are USANet (24 nodes and 43 bidirectional links) and PanEuro (27 nodes and 81 bidirectional links), shown in Figs. 8 and 9, respectively, with distances in kilometers. For these experiments, the following are considered: the bandwidth for each slot is 12.5 GHz and each link has 120 slots for capacity (1.5 THz); one guard band has two slots (25 GHz); each node has 15 transponders; and each of those has a maximum capacity of eight slots.

The modulations are BPSK, QPSK, 8QAM e 16QAM with 1, 2, 3, and 4 bits per symbol, respectively, as specified in [8]. Each modulation's reach follows the half distance law [19], and, considering signal regenerators, the maximal distances are 8000, 4000, 2000, and 1000 km, in the same order. For all algorithms, $k=3$ and the chosen policy for solving the RSA problem is *First Fit* (FF),

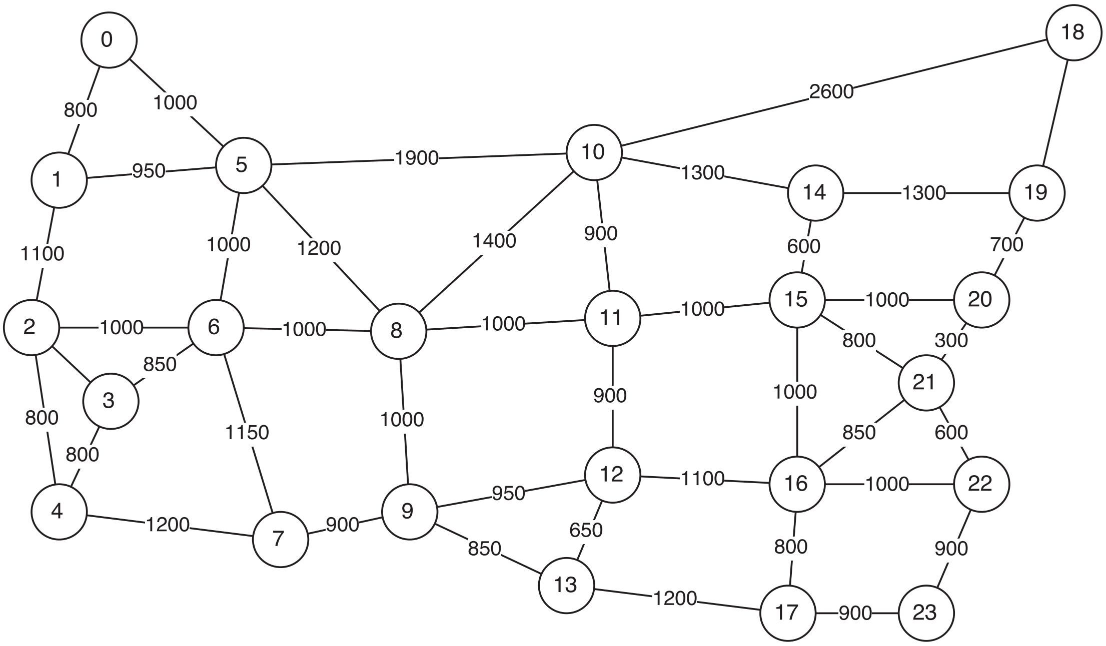


Fig. 8. USANet topology.

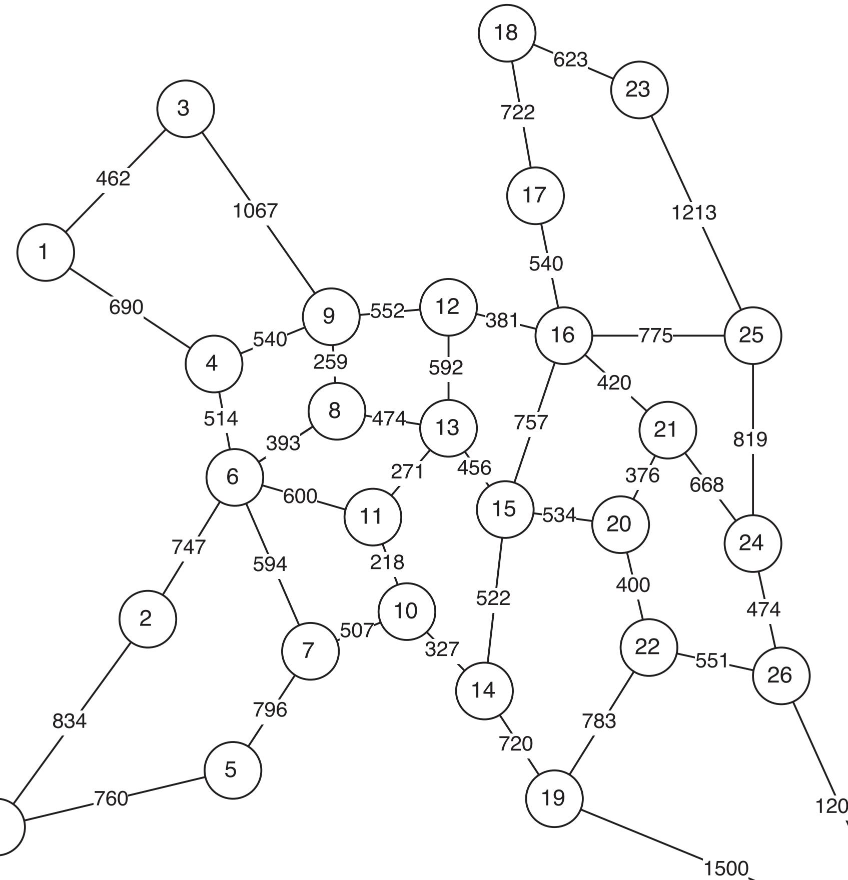


Fig. 9. PanEuro topology.

Algorithm 1 *Maximize the use of Best Modulation format* - MBM

```
$kDPaths \leftarrow$ all k-shortest edge-disjoint paths (off-line)
$kSPaths \leftarrow$ all k-shortest paths (off-line)
while a connection request $r(s, d, b)$ arrives do
    if $TG(r, s, d)$ is possible then                          ▷ (single-hop step)
        accept request $r$
    else
        $Paths[] \leftarrow kDPaths(s, d)$
        for $i$ do1$k$
            Search for an allocated lightpath in the network originating from $s$ which shares the most links with $Paths[i]$
            if found and $OG(r, s, d)$ is possible then
                accept request $r$
            end if
        end for
    end if
    $Paths[] \leftarrow kSPaths(s, d)$                          ▷ (multi-hop step)
    for $i$ do1$k$
        $s' \leftarrow s$
        $d' \leftarrow s$
        while $d' \neq d$ do
            Search for an allocated lightpath in the network originating from $s'$ which shares the most links with $Paths[i]$
            if found then
                $d' \leftarrow$ last shared node in the lightpath
                if $TG(r, s', d')$ is possible then
                    $s' \leftarrow d'$
                else
                    if $OG(r, s', d')$ is possible then
                        $s' \leftarrow d'$
                    else
                        break the loop
                    end if
                end if
            else
                break the loop
            end if
        end while
        if $s' = d$ then
            accept request $r$ ▷ Continue to next connection arrival
        else
            Create a new lightpath from $s'$ to $d$ using KSP with the highest possible modulation level
            if created then
                accept request $r$          ▷ Continue to next connection arrival
            end if
        end if
    end for                                                    ▷ (single-hop step)
    Create a new lightpath from $s$ to $d$ using KSP with the highest possible modulation level
    if created then
        accept request $r$
    else
        block request $r$
    end if
end when
```

which packs existing connections into a smaller number of spectrum slots, leaving slots available for future use [12,29]. For the MPH-SRNP algorithm, according to [25], it was considered the use of eight sub-transponders per transponder with capacity of four slots per sub-transponders.

In order to have a fair comparison of all algorithms' performances solving the RMLSA problem, they were evaluated in a *mAdap* approach (see Fig. 5) considering the metrics described in the following subsections.

It is important to note that the metrics regarding the use of network resources are evaluated to show gains related to the mechanisms implemented in the MBM algorithm in comparison with the literature. In addition, traffic engineering solutions that lead to reduced use of resources installed on the network, contribute to the reduction of the network exhaustion probability. Moreover, we do not evaluate operational cost metrics, such as the energy saving obtained by disabling transmission equipment [9], which is considered out of the scope of this work.

5.1. Bandwidth blocking ratio

BBR reflects the ratio of blocked bandwidth, higher values meaning more bandwidth is being blocked, so lower values are desirable. Fig. 10 shows the BBR of the algorithms for different traffic loads in both topologies. It is clear that the MBM algorithm has a lower BBR than the others, being about half of that of the KSP, MSP, and SPV algorithms.

Considering FPA and MPH-SRNP, the MBM gain varies from 81% in lighter loads to 43% in heavier ones. This is a consequence of MBM having more options for satisfying demands by considering multiple hops in the virtual topology because it alleviates the continuity requirements. Though MPH-SRNP also incorporates multi-hopping, it avoids hops in the physical layer, resulting in routes with larger distances which leads the *mAdap* approach to use lower modulation levels.

Fig. 11 focus on the load range from 150 to 200 Erlangs for both topologies. We observe that MBM has a lower BBR than the others in PanEuro, almost no blocking. In the UsaNet topology the results MBM are a little worse than SPV, however, as the traffic load grows the difference reduces rapidly.

5.2. Ratio of available transponders

The ratio of available transponders reflects their usage, higher values mean more transponders are available to handle increasing traffic (in the future). Fig. 12 shows the results for the algorithms for different traffic loads in both topologies. MBM is slightly worse at this than FPA, around 6% in UsaNet and 12% in PanEuro, and significantly better than the others, up to 59%. This increased use of transponders in MBM, due to multi-hopping, indicates the resources are being better used in this algorithm. More importantly, the additional cost for this has little impact on BBR results, as can be seen by comparing MBM's to MPH-SRNP's results in Fig. 10.

5.3. Average transponders per request

The number of transponders relates to the operational cost of the network, since they are considered more expensive than spectral resources [25], lower values mean the transponders' capacities are being better used. Fig. 13 shows the average number of transponders used per connection, in both topologies. It is clear that the ratio is less than 1.0 for FPA, MPH-SRNP, and MBM, an obvious effect of their traffic grooming aspect, where multiple connections share a single transponder.

The multi-hop algorithms (MPH-SRNP and MBM) have the best results, as expected since this technique helps enabling new entry

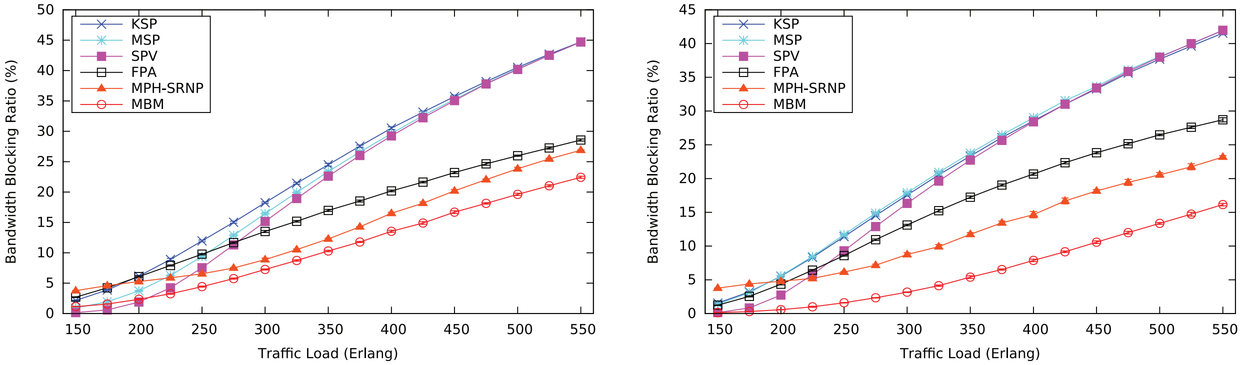


Fig. 10. BBR for USANet (left) and PanEuro (right).

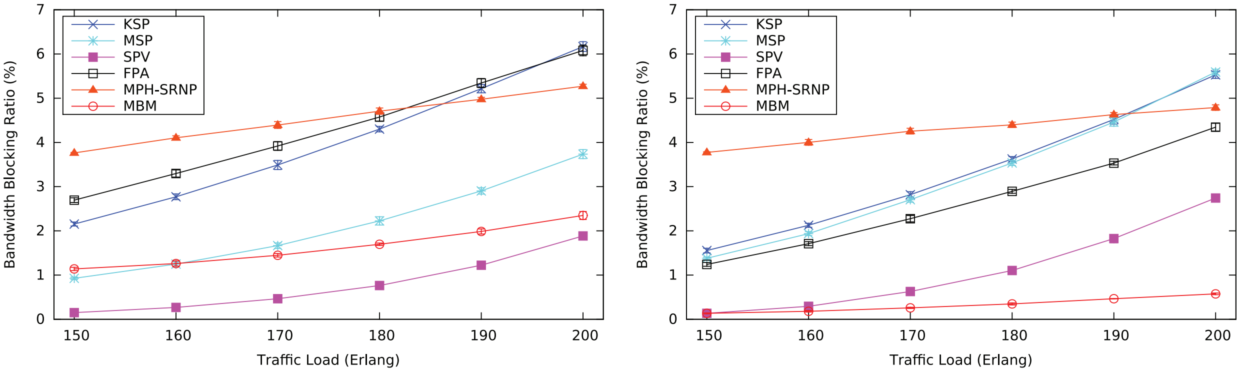


Fig. 11. BBR (150–200 Erlangs) for USANet (left) and PanEuro (right).

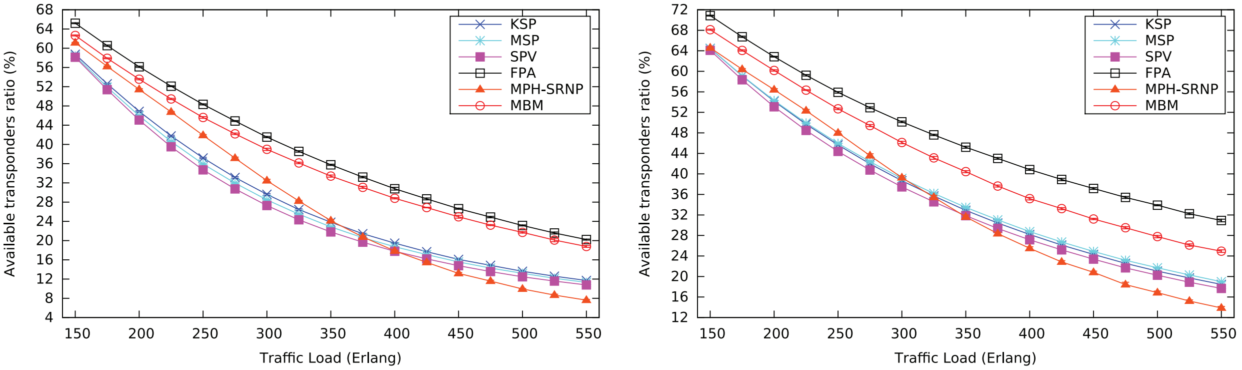


Fig. 12. Average ratio of available transponders for USANet (left) and PanEuro (right).

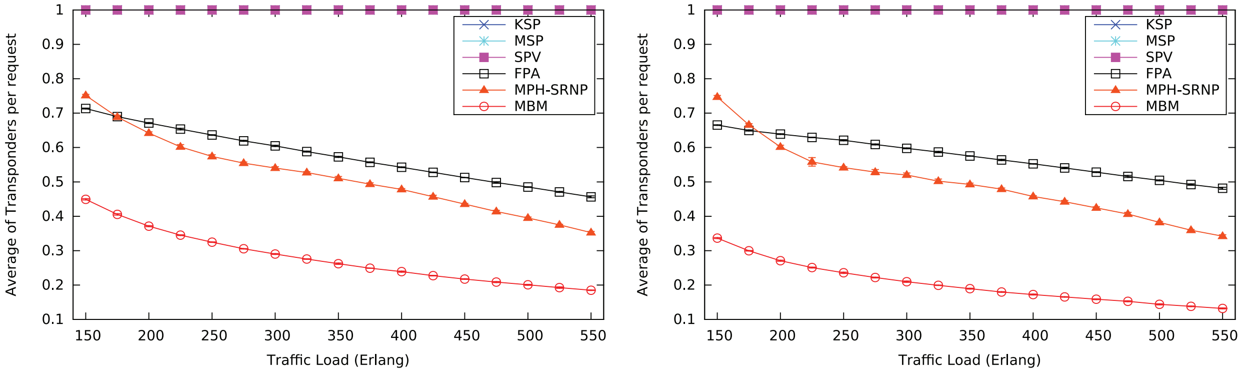


Fig. 13. Average ratio of transponders used per request for USANet (left) and PanEuro (right).

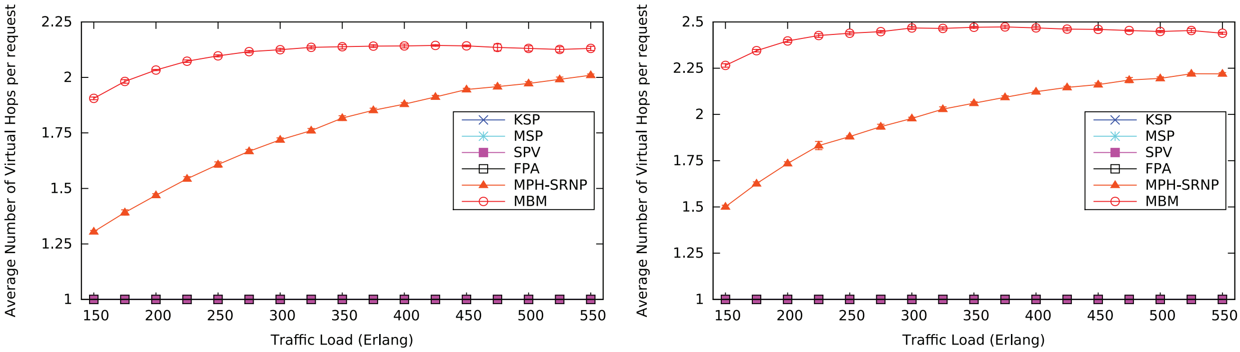


Fig. 14. Average number of hops in the virtual layer per request for USANet (left) and PanEuro (right).

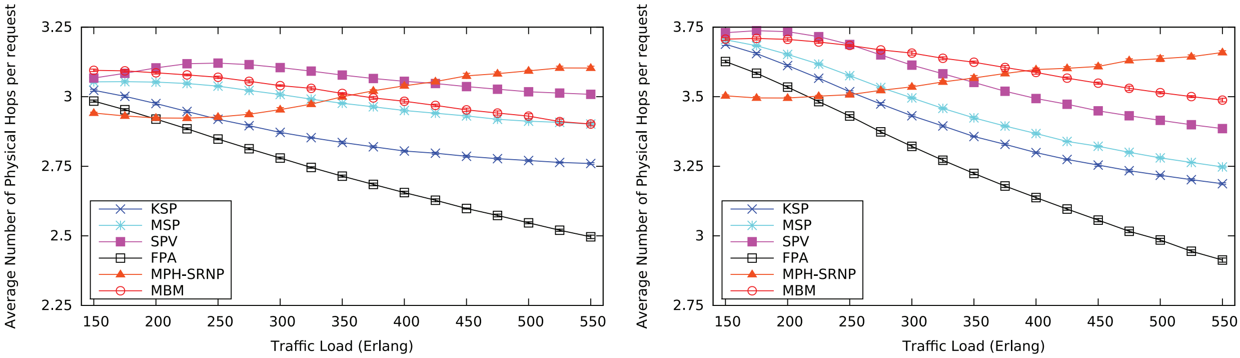


Fig. 15. Average number of hops in the physical layer per request for USANet (left) and PanEuro (right).

points for electrical and optical traffic grooming, resulting in a better use of the transponders and the network's spectrum. MBM can further exploit this by encouraging more physical hops, which are avoided in the MPH-SRNP. The result is a relative gain in transponder per request of up to 72%.

5.4. Average number of hops in the virtual topology per request

This indicates the number of OEO conversions and the electronic processing used in the network which relates to the operational costs, so lower values are desirable. Fig. 14 shows the average number of hops in the algorithms for different traffic loads in both topologies. The single-hop algorithms (KSP, MSP, SPV, and FPA) have only one conversion, obviously, while MBM has an average between 2 and 2, 5. The additional cost for this has little impact on BBR results, as can be seen by comparing MBM's to MPH-SRNP's results in Fig. 10.

5.5. Average number of hops in the physical topology per request

This reflects the use of spectral resources in the network and the use of modulation since using lower levels generally leads to more hopping, lower values mean fewer fiber links so they can save spectral resource and reduce latency. Fig. 15 shows the average number of hops in the algorithms for different traffic loads in both topologies. The results show that all algorithms, except MPH-SRNP, decrease in physical hops as the load increases. The MPH-SRNP behavior is due to the fact that the algorithm defines its routes through a hierarchical process that allows the composition of the final end-to-end path by attaching multiple paths. This characteristics allows MPH-SRNP find viable, but larger, paths in scenarios with resource scarcity.

The FPA algorithm has the lowest average, highlighting its efficiency using the spectral resources. The MBM algorithm has a higher average (approximately 3.5 hops considering both topologies) because its multi-hopping leads to longer paths; this, however, does not imply on greater use of the spectrum since it exploits the higher modulation levels.

5.6. Ratio of available spectrum

This ratio reflects the usage of spectral resources in the network, higher values mean more spectrum is available to handle increasing traffic (in the future). Fig. 16 presents the average ratio per request the algorithms for different traffic loads in both topologies. It is clear that MBM has from 7% to 23% less usage than others throughout the tested traffic loads.

5.7. Average rate of modulation used

This indicates the percentage of optical paths allocated per modulation level, and the average values of all loads are given in Table 2. There was little variation between loads, less than 2% standard deviation in average. MBM mostly uses the highest level provided by the transponders (16QAM), about 54% of the times in USANet and 79% in PanEuro. This means it makes better use of the spectral resources, which leads to lower BBR.

The MPH-SRNP algorithm showed a seemingly uniform distribution in USANet, but concentrated with 16QAM in PanEuro, since this topology has a smaller average distance between its nodes. However, due to the *mAdap* approach, this algorithm does not fully exploit the higher modulation levels as MBM does, which affects its BBR results.

The other algorithms use single-hop routing and, as expected, have similar distributions throughout the modulation levels in both topologies. They concentrate their uses on QPSK in UsaNet and 8QAM in PanEuro, since the higher modulations, in average, do not cover the distances for the longer optical paths of the latter.

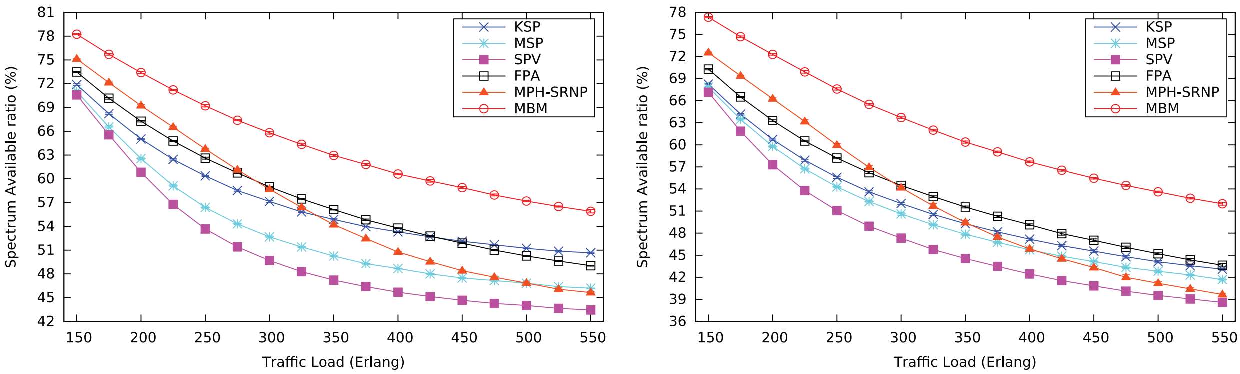


Fig. 16. Ratio of Available Spectrum for USANet (left) and PanEuro (right).

Table 2
Average rate of modulation used (%).

	Modulation	KSP	MSP	SPV	FPA	MPH-SRNP	MBM
UsaNet	*BPSK*	20.70	23.44	25.21	18.76	27.55	8.90
	QPSK	41.78	39.83	39.05	43.01	27.04	19.31
	8QAM	24.04	23.54	22.86	24.62	20.61	17.36
	16QAM	13.48	13.20	12.88	13.61	24.80	54.43
PanEuro	*BPSK*	1.74	3.04	3.97	1.62	18.15	1.08
	QPSK	39.22	38.16	39.43	38.92	19.90	10.00
	8QAM	38.82	38.39	36.89	39.22	23.19	9.03
	16QAM	20.21	21.41	19.71	20.24	38.76	79.88

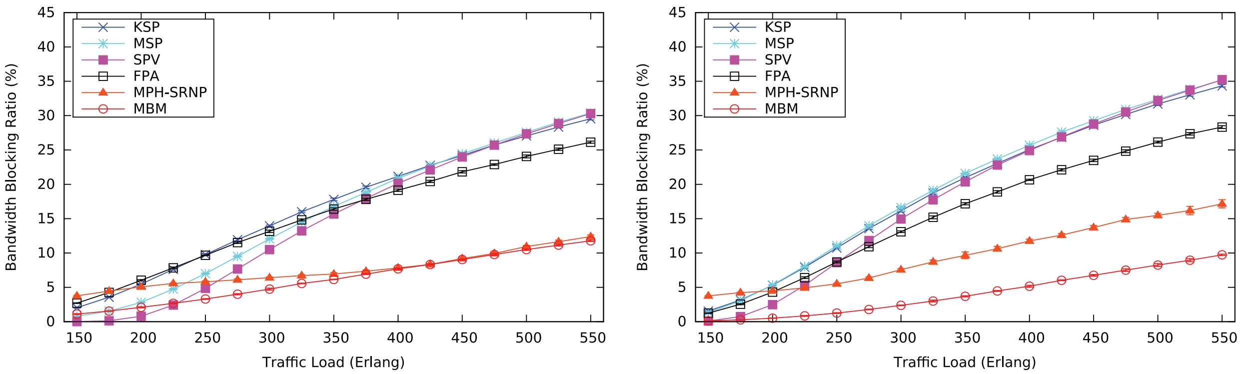


Fig. 17. BBR with unlimited transponders for USANet (left) and PanEuro (right).

Unrestricted scenarios

For further analysis of possible impacts of the proposed MBM algorithm, consider two scenarios with unrestricted resource provision. Fig. 17 presents BBR results for the algorithms considering an unlimited number of transponders in the networks. All algorithms have lower ratios compared to the experiments with 15 transponders, and MBM still presents the lowest values (up to 65% for USANet and 85% for PanEuro). Since MBM has no limits for hopping, it can better use the spectrum to achieve this results.

Fig. 18 presents BBR results for the algorithms considering an unlimited spectrum. In this scenario, all algorithms have a significant improvement of around 71%, showing that this resource has a strong impact in blocking, and the FPA algorithm stood out in performance. This is expected, the average ratio of available transponders for this algorithm is slightly better than the others (Fig. 12) and the limiting factor in this scenario is the number of transponders handling the demands. FPA satisfies the demands with lower modulation levels (using the unlimited spectral resources), and MBM's use of the higher levels to spare spectrum is not effective. MBM's average performance, however, is 59% worse than FPA's for the considered networks, which indicates that the use of spectral resources also has a strong impact in BBR.

6. Conclusions

The recent growth of Internet traffic and emerging applications demand high performance of the optical networks, but the current technology's rigid nature hinders the transmission of new demands, enforcing fixed data rates and reducing efficiency of the network's resources. In this context, elastic optical networks have become increasingly interesting due to their capacity to provide flexible transmission rates that adapt to the heterogeneous traffic demands, which brings a new perspective on future Internet demands.

This works focuses on solving the routing, modulation level, and spectrum allocation problem in a dynamic context through spectral modulation control, traffic and optical grooming. The proposed *Maximizing the Use of Best Modulation Format* approach associates these techniques to make better use of the networks' spectral resources and to satisfy larger data rate demands by using higher modulation levels through multiple hops in the virtual topology.

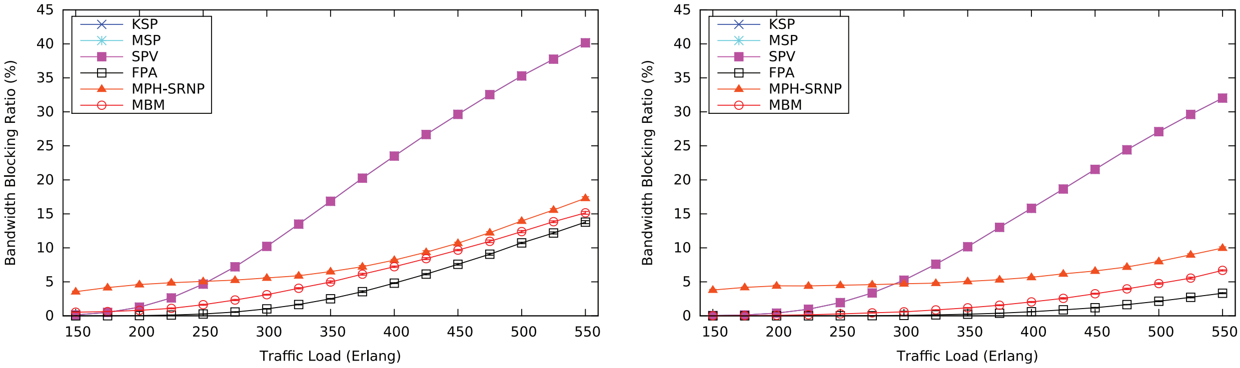


Fig. 18. BBR with unlimited spectrum for USANet (left) and PanEuro (right).

In order to evaluate the proposal, it was compared to five other well known algorithms on two network topologies, and results showed that MBM's bandwidth blocking ratio was lower than all others, and significantly so in most cases. Despite using more transponders than the others (around 2%), MBM makes better use of these and of spectral resources, which indicates it is better suited to absorb future demands.

Additional experiments considering different topologies (like NSFNet) and metrics (like spectrum fragmentation) should provide interesting insights, and are under consideration.

Acknowledgment

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