A Regeneration Placement, Routing and Spectrum Assignment Solution for Translucent Elastic Optical Networks: A Joint Optimization Approach

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Abstract: In this paper, we propose a novel joint approach to solve the regeneration placement, routing, modulation level, and spectrum assignment (RP-RMLSA) problem using a binary integer program (BIP) model. Using a mock and real-world network topology, we conduct extensive numerical experiments testing the proposed optimization model's performance and analyzing the characteristics of the solutions found. Our results show that considering only an optimal solution occurs when signals in need of regeneration are concentrated in one regeneration node when considering the regeneration devices' capital and operational expenditure.

1 INTRODUCTION

Worldwide internet traffic continues to grow due to the ever-increasing popularity of established and emerging network services and applications. For instance, the main content and service providers (Google, Facebook, Amazon, and Microsoft) have become the primary source of bandwidth demands (TeleGeography, 2020). Nowadays, such bandwidth demands can only be supported by the current installed optical network infrastructure. However, the capacity of these networks is expected to be insufficient. This situation, called "Capacity Crunch" (CC), manifests an impending inability of current optical architectures to support future bandwidth demands (Ellis et al., 2016; Waldman, 2018).

Two different courses of action can be foreseen to solve this CC problem. The first option consists of installing more network resources. This investment cannot be avoided but should be postponed as long as possible due to the significant expenses involved. The second strategy is to manage the already installed network infrastructure efficiently. This second alternative has been an important focus of research. Current optical WDM (wavelength division multiplexing) networks are inefficient due to the spectrum grid's coarse granularity, typically of 50 GHz by channel, according to the International Telecommunications Union (ITU) standard (ITU-T, 2012). This situation implies that regardless of the user's bandwidth needs, the entire channel will be reserved.

A new proposal, called Elastic Optical Networks (EON), has been researched to face previous problems (Velasco et al., 2017). EON aims to allocate resources according to the user's bandwidth requirements, dividing the frequency spectrum into narrow bands called Frequency Slot Unit (FSU), typically of 12.5 GHz. This way, different FSUs can be group flexibly to satisfy users' needs. As a consequence, efficient management of the spectrum is achieved (Velasco et al., 2017).

One of the main tasks that elastic optical network operators must resolve is to compute a path and a portion of the frequency spectrum to each network connection, known as the "routing and spectrum assignment" (RSA) problem. This problem becomes more intricated in continental, and more extensive networks since a maximum range (in kilometers) can be found for each connection request due to the accumulation of physical–layer impairments (PLI). Therefore, we must add the modulation format on the tasks, called the "routing, modulation level, and spectrum assignment" (RMLSA) problem. This problem is subject to

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the following constraints. First, each channel (FSU) can host by one user at the same time; second, the same FSU allocated to the said user must be available in all the links on the user path (continuity constraint); and in case that the user requires more than one FSU, the spectrum assigned must be consecutive (contiguity constraint).

The accumulation of PLI limits the generation of end-to-end all-optical connections (transparent connections) in wide-area optical networks. In fact, several users may not achieve transparent communication through long distances despite the modulation format chosen. Therefore, the use of 3R (Reamplification, Reshaping, and Retiming) regeneration in wide-area optical networks cannot be avoided. A node with regeneration allows increasing connections optical range, improving the network spectrum usage by choosing more efficient modulation formats, and allowing to break the continuity constraint due to the OEO process. However, these devices add additional delays for the demands due to the optical transponder (OEO) needed to regenerate and significant deployment and operational costs. Therefore, the use of these devices should be avoided as much as possible.

RMLSA standard approaches establish transparent communication between source-destination node pairs (Velasco et al., 2017; Calderón et al., 2020). However, due to the need of regenerating on wide–area networks, some approaches consider the use of regeneration devices, resulting on translucent (regenerators found on some nodes) or opaque networks (all network nodes have regeneration capabilities) (Chaves et al., 2012; Chaves et al., 2015; Brasileiro et al., 2019).

The use of regenerator devices must be as efficient as possible, locating them strategically in order to avoid additional costs related to these devices. This problem is known as "regeneration placement" (RP) problem. In literature, we can find several optimization approaches (Wang et al., 2015; Yıldız and Karaşan, 2017). However, optimization approaches lack a joint solution for the RP and RMLSA problems or cannot be implemented in real-sized network topologies. To take advantage of the opportunities offered by the EON requires the jointly solution of RP and RMLSA problems.

In this work, we propose an integrated optimization model for solving the regeneration placement, routing, modulation format, and spectrum assignment (RP–RMLSA) problems for translucent elastic optical networks. We rely on a physical impairment model to compute the maximum reach of a given modulation format and bit-rate of a connection request. This strategy focuses on minimizing the use of regenerators due to the capital and operational expenditure needed, as well as analyzing the characteristics of good solutions found through optimality.

The remainder of this article is organized as follows: Section 2 reviews the main strategies found in the literature considering regeneration devices. Section 3 presents the network assumptions and the optimization model proposal. Section 4 shows some numerical experiments for two network topologies. Finally, section 5 illustrates conclusions and final remarks of the work.

2 STATE OF THE ART

In this section, we conduct a review of the leading strategies and contributions considering regeneration found in the literature.

The joint solution for the regenerator placement, routing, modulation level, and spectrum assignment problems (RP–RMLSA) is known to be NP–hard (Brasileiro et al., 2019; Calderón et al., 2020). Even some of these problems by themselves are also known to be NP–hard (Velasco et al., 2017).

Therefore, several ways to solve the regeneration problem can be found in the literature but with some sort of simplification. In (Klinkowski, 2012), the authors propose a heuristic algorithm to solve the regeneration placement and spectrum assignment problem jointly, but considering a static demand structure and a pre–computed fixed path for each network demand. Relaxing the fix route constraint, in (Kahya, 2013) the authors present a sequential solution approach, solving the regeneration placement, routing, spectrum assignment problem in EON, but for only one modulation format.

In (Wang et al., 2015) the authors present a Mixed–Integer Linear Programming (MILP) formulation to solve the regeneration placement problem in an elastic optical network. Since their proposal can not solve real-size problems, they proposed a sequential heuristic approach randomly partitioning the set of demands.

In (Yıldız and Karaşan, 2017) the authors present a branch–and–price algorithm to jointly solve the RP–RMLSA problem for real–size network topologies. They introduce a path segment formulation of the route to simplify the problem, imposing the maximum optical reach for the network demands. In our study, we use the same strategy but differing on the spectrum assignment treatment. Yildiz et al. compute only the usage of FSUs on each link by not calculating the portion of the spectrum used by all the network users; this way simplifying the model. However, network operators demand the position of the FSUs assigned to each network user in order to configure the network and assess the quality of the solution.

On the other hand, the regeneration problem in EON has been solved considering two different problems in a hierarchical modeling approach: the Regenerator Placement (RP) and Regenerator Assignment (RA) problems (Fontinele et al., 2016). The RP problem defines which nodes will allow regeneration capacity, and the RA problem defines, in each node, which connections are regenerated. Hence, the RP problem must be solved during the network planning phase while the RA problem during the network operation phase. The algorithms used to solve the RP problem are: Maximum Simultaneously Used Regenerator Placement (MSU), Most Used Regenerator Placement (MU), Distance Adaptive Regenerator Localization Algorithm (DA), and Node Degree First (NDF) (Chaves et al., 2012). The algorithms used to solve the RA problem are: First Longest Reach Regenerator Assignment (FLR), First Narrowest Spectrum Regenerator Assignment (FNS) (Chaves et al., 2015) and Circuit Invigorating Regenerator Assignment (CIRA) (Brasileiro et al., 2019).

To the best of our knowledge, our study is the first to consider every aspect of EON for the regeneration placement problem. To solve the regeneration placement, routing, modulation format, and spectrum assignation problem, we use the same path–segment formulation found in (Yıldız and Karaşan, 2017) but including the spectrum utilization decision and constraints.

3 NETWORK ASSUMPTIONS AND MODEL

This section comprises the main contribution of the article. First, we describe the physical–layer impairment model used to determine the number of FSU's assigned to each demand. Then, we present the optimization model used to jointly solve the regeneration placement problem (RP) and the RMLSA problem.

3.1 Physical-layer Impairments Model

The quality of transmission (QoT) of optical signals is degraded by different phenomena occurring during the modulation, propagation, and detection processes. In particular, to solve the RMLSA problem, we consider the impact that the amplified spontaneous emission (ASE) noise and non–linear interference noise has on the QoT. The accumulation of noise during propagation determines the maximum optical reach that a signal can have for a given modulation level and bit error rate (BER) combination. With a high number of bits per symbol, complex modulation formats increase the transmission sensitivity to degradation. Thus, the transmission reach is shorter for higher modulation levels compared to simpler formats (Yaghubi-Namaad et al., 2018). To consider this *route length - modulation level* trade–off, the most common approach is to associate any modulation format available at the transponder to its maximum transmission reach for a given BER value (Talebi et al., 2014). This approach is also used in this work.

The modulation formats used in this work are binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), and Λ–quadrature amplitude modulation (Λ-QAM), where Λ takes values 8 and 16. Table 1 shows the transmission reach, using single-polarization, as a function of the modulation format and bit–rates available at the transponders. The first two columns in Table 1 show the maximum achievable reach (MAR) that an optical signal can travel without exceeding a BER of 10^{-6}. – assuming single-polarization – as a function of the modulation format available at the transponders. The optical reach values were obtained using the GN model (Poggiolini et al., 2014) to estimate the received signal–to–noise ratio (SNR) degraded by ASE noise and non–linear interference noise. For more details about the optical reach calculation, the reader is referred to (Calderón et al., 2020), Section III.

Table 1: Maximum achievable reach (MAR) per modulation format and FSU requirements per bit–rate and modulation format pair, for a BER value equal to 10^{-6}.

Modulation	MAR [km]	Bit-rates		
		10	40	100
BPSK	5525	1	4	8
QPSK	2720	1	2	4
8-QAM	1360	1	2	3
16-QAM	560	1	1	2

3.2 Optimization Model

This subsection presents a binary integer program (BIP) to solve the regenerator placement, routing, modulation format, and spectrum assignment problem (RP–RMLSA), as well as its notation.

Let $G(N,A)$ be a directed graph representing an elastic optical network with node set N, and optical arc set A. The arc length are denoted by $l_{i,j}$ for each arc $(i,j) \in A$. We denote the set M as the available modulation formats, where l_m represents the maximum achievable reach of modulation $m \in M$. We define D as the set of transmission demands. For each demand $d \in D$ we denote o_d as the source node, t_d as the destination node, and b_d as the requested bit–rate in Gbps.

For the route assignment part of the problem we use the path segments formulation (Yıldız and Karaşan, 2017). A path segment p is a directed simple path with an associated modulation level $m(p)$. A directed path is simple if it does not repeat any node. We denote the source and destination nodes of a path segment p as o_p and t_p, respectively. Let $in_{i,j,p}$ be a parameter equal to 1 if the arc $(i, j) \in A$ is part of the path segment p. This way, we can calculate the length of the path–segment $l_p = \sum_{(i,j)\in A} l_{i,j} \cdot in_{i,j,p}$ as the sum of the arcs contained within p. Considering that each path–segment p is associated with a modulation format $m(p)$, a path–segment is feasible if it respects the MAR limitation of its own modulation format(Table 1). Namely, a path–segment p is feasible if $l_p \leq l_{m(p)}$. We define P as the set of all feasible path–segments. Then, a route is an ordered union of feasible path–segments $p^i \in P, i \in 1, \cdots, k$ where $t_{p^i} = o_{p^{i+1}}$ for all $i = 1, \cdots, k-1$. For that route to be assigned to demand d it must satisfy that $o_{p^i} = o_d$ and $t_{p^k} = t_d$. With this path–segment formulation, the MAR restriction is implicitly taken into consideration by using only the feasible path–segments.

We denote S as the set of FSU available for all optical fibers. The amount of FSU required for a demand d depends on the modulation level used and the amount of bit–rate requested. So, we denote the set of connections $C(m,b_r) = \{1,2,\cdots,c\}$ as all the different positions inside the spectrum where it can be assigned the signal depending on the bit–rate and modulation format. It does not depends on the fiber used. As an example, for modulation format BPSK and a bit–rate of 40 Gbps, the amount of FSU required is 4 and $C(m = BPSK, b_r = 40)$ represent the c different ways to assigned those 4 consecutive FSU in the spectrum represented by S. Let $p_{c,s}$ be a parameter equal to 1 if the connection $c \in C$ uses the FSU $s \in S$ within the spectrum. Then, forall $c \in C(m,b_r)$ the contiguity constraint is implicitly imposed by the proper definition of $p_{c,s}$ such that $\forall i, j \in S : p_{c,i} = p_{c,j} = 1,\ i < j \Rightarrow p_{c,k} = 1,\ \forall k \in \{i, \cdots, j\}$. And $\sum_{s\in S} p_{c,s}$ is equal to the amount of FSU needed given in Table 1. We denote C as the set of all possible positions for any amount of FSU required. So, $C(m,b_r)$ is a subset of C.

For the regeneration aspect, we denote c_o as the capital cost of installing a regenerator in node $i \in N$, and η as the cost of operating that regenerator for each signal regenerated. Using the path–segment formulation, where the route is the ordered union of $p^i, i \in 1, \cdots, k$, we can identify t_{p^i} as a regeneration node for all $i = 1, \cdots, k-1$. In other words, to use more than one path–segment the signal must be regenerated. Another aspect to consider is that there must be only one connection used for each path–segment used by demand d.

Table 2: Outline of notation.

N	Set of nodes, index n.
A	Set of arcs.
M	Set of modulation formats, index m.
D	Set of demands, index d.
P	Set of feasible path–segments, index p.
S	Set of FSU, index s.
C	Set of all connections available.
$C(m,b_r)$	Subset of connections available for modulation m and bitrate b_r.
o_d	Source node of demand d.
t_d	Destination node of demand d.
b_d	Bitrate requested by demand d.
o_p	Source node of path–segment p.
t_p	Destination node of path–segment p.
$m(p)$	Modulation format associated with the path–segment p.
$in_{i,j,p}$	Equal to 1 if arc $(i, j) \in A$ is part of the path–segment p.
$p_{c,s}$	Equal to 1 if connection c uses slice $s \in S$.
c_o	Cost for regenerator placement.
η	Regenerator usage cost.

Since it is of interest to use the least amount of regenerators, the main objective is to minimize the total capital and operational cost of regeneration. So the RP–RMLSA problem can be formally stated as follow: given a graph $G(N,A)$, the total spectrum S, the modulation formats M and the traffic demand D, we obtain as output the route composed by path–segments and the connection for each demand and the nodes where the demands regenerated, resulting from the minimization of the total cost of regeneration. The notation we use throughout this paper is outlined in Table 2.

The decision variables of the model are:

x_{dpc}	a binary decision that takes a value equal to 1 if demand d use path–segment p with connection c and 0 otherwise.
r_n	a binary decision that takes a value equal to 1 if node n is a regeneration point and 0 otherwise.

We name x_{dpc} as the flow variable that represents the routing and spectrum assignment decision. As we mentioned, the route is a concatenation of path–

segments, and in every path–segment where the demand passes through, we need to assign only one position inside the spectrum. So if $\sum_{p\in P} x_{dpc} \geq 1$ it means that it regenerated because it use more than one path–segment. We name $r_n, n \in N$ as the regeneration variable and indicates if node n is a regeneration site or not.

Then, the RP-RMLSA formulation is as follows:

$$\min \sum_{n\in N} c_o r_n + \sum_{\substack{d\in D\\ p\in P\\ c\in C\\ t_p\neq t_d}} \eta x_{d,p,c} \tag{1}$$

subject to:

$$\sum_{\substack{p\in P\\ o_p=i}} \sum_{c\in C(d)} x_{dpc} - \sum_{\substack{p\in P\\ t_p=i}} \sum_{c\in C(d)} x_{dpc} = \begin{cases} 1 & \text{if } i = o_d \\ -1 & \text{if } i = t_d \\ 0 & \text{e.o.c} \end{cases} \quad \forall i \in N,\ d \in D \tag{2}$$

$$\sum_{c\in C} x_{dpc} \leq 1 \quad \forall d \in D,\ p \in P \tag{3}$$

$$\sum_{\substack{p\in P\\ t_p=n}} x_{dpc} \leq r_n \quad \forall d \in D,\ c \in C,\ n \in N \setminus t_d \tag{4}$$

$$\sum_{p\in P} \sum_{d\in D} \sum_{c\in C(m(p),b_d)} in_{i,j,p} \cdot p_{c,s} \cdot x_{dpc} \leq 1 \quad \forall (i,j) \in A,\ s \in S \tag{5}$$

$$x_{dpc} \in \{0,1\}, \quad \forall d \in D,\ p \in P,\ c \in C \tag{6}$$

$$r_n \in \{0,1\}, \quad \forall n \in N \tag{7}$$

The objective function (1) minimize both the total cost of installing a regeneration site on the nodes and the cost of regenerating a signal. The first term represents the fixed cost of setting a regenerator site in node n. The second term represents the cost of adding a regenerator device to the regenerator site.

Constraints (2) are the flow balance equations that force each demand to be carried from its source to its destination. Constraints (3) are the continuity constraint which ensures that only one connection is used for every path–segment and demand. Constraints (4) enforce regeneration requirements by ensuring regeneration at the end of each possible path–segment that does not end in the destination node of the associated demand. Constraints (5) guarantees that every FSU at every arc is assigned at most to one demand. Finally, constraints (6) and (7) define the binary nature of the variables. This formulation is quite compact but contains every aspect of the regeneration and the RMLSA problems.

With this model's output, we can compute the number of signals regenerated in the regeneration site and see the spectrum utilization. The first one states as follows:

$$nr_n = \sum_{\substack{d\in D\\ p\in P\\ c\in C\\ t_p=n\\ t_p\neq t_d}} x_{d,p,c} \quad \forall n \in N \tag{8}$$

where nr_n is the number of signals regenerated in node n. The second one can be compute as follows:

$$u_{i,j,s} = \sum_{p\in P} \sum_{d\in D} \sum_{c\in C(m(p),b_d)} in_{i,j,p} \cdot p_{c,s} \cdot x_{dpc} \quad \forall (i,j) \in A, s \in S. \tag{9}$$

where $u_{i,j,s}$ is equal to 1 if FSU s is used by a demand in arc (i,j). With these extra results we expand the amount of info the RP-RMLSA gives without making more complex the formulation.

4 NUMERICAL EXPERIMENTS

In this section, several numerical experiments are conducted to test the proposed solution and derive insights from the instances. We implemented the optimization model using AMPL under MacOS and GUROBI 9.0.2. All experiments were done on a 3.1 GHz Dual–Core Intel Core i5 with 8 GB of RAM.

Table 3: Network characteristics summary.

Parameter	Value
Topology	Basic Net, NSFNet
Links Capacity	40 slots
Bitrates	10, 40, 100 Gbps
Modulation formats	BPSK, QPSK, 8-QAM, 16-QAM
FSUs and MAR	Table 1

Table 3 summarizes the network characteristics in which we execute our proposal. First, we studied a mock network called Basic Net (Figure 1) in order to preliminary test the model. Then, we use the well-known real network topology NSFNet (Figure 2). Extra network information can be found in Table 4.

Table 4: Network topologies parameters.

Network	Nodes	Links	Demands
Basic Net	7	11	42
NSFNet	14	21	182

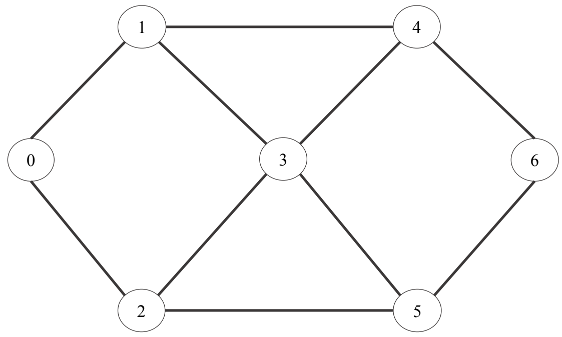

Figure 1: Basic Net network.

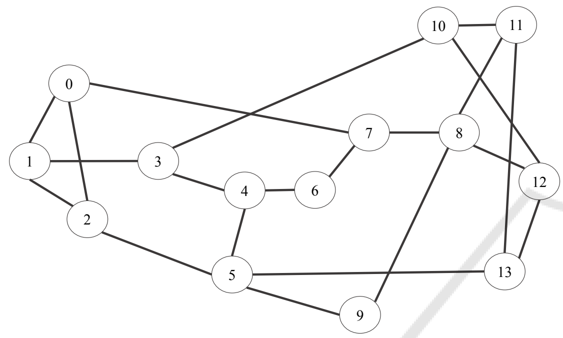

Figure 2: NSFNet network.

We compute the feasible set S composed of path–segments based on each network arc length and the available modulation formats available for each exercise. The network capacity was set to 1/8 of the total C-band spectrum frequency (40 FSUs per network link) (Calderón et al., 2020).

We assume that every source–destination node pair demand communication ($|D| = |N| \cdot (|N| - 1)$. The bit–rate requests were defined for each connection request using two criteria: the first one assigns randomly the bit–rate to each user uniformly distributed between the values 10, 40, and 100 Gbps; and the second one assigns the worst–case scenario with only the highest bit–rate available, this is 100 Gbps for all connection requests. The second scenario is considered the worst one since demands would need the highest amount of FSU possible, increasing link usage, and even increasing demand regeneration to reach destination nodes.

For this study, we run five instances of the proposed model considering different scenarios. Table 5 shows the solutions of the RP-RMLSA model for these instances. The first four columns represent the different characteristics of the instances. The Basic Net was only executed for the two criteria of bit–rate assignment, both using BPSK to 8QAM as an option for their connection modulation formats. On the other hand, the NSFNet was solved for both bit–rate assignment criteria and two different ranges of modulation formats (MF). These are BPSK to 8QAM and QPSK to 16QAM. The differences in modulation formats availability are based on increasing the chances of regeneration on the execution since complex modulation formats have a higher spectrum efficiency but with a lesser optical reach, incurring a higher use of regeneration.

The PS column represents the number of path–segments pre–computed. Lastly, the remaining columns represent the solution obtained by executing our model. For instance, the Basic Net with random bit–rate (Instance 1), the solution takes 17.8 seconds (RunTime column), it only used the node 3 (RN column) to regenerate two connection requests (NR), and with a spectrum frequency usage of 31.4% (%FSU column).

As shown in Table 5, almost on all the instances, the RP-RMLSA model chooses one at most one regeneration node as a regeneration site, then concentrating the regeneration of several connections in only one network node despite the number of connections being regenerated along their paths. This situation makes sense because the objective function is to minimize the costs related to regenerate optical signals. As expected, the running time of the instances with Basic Net was shorter than the ones with NSFNet because of the number of nodes, links, and demands. In fact, the computational complexity of the RP-RMLSA problem makes more difficult to solve large instances of the problem, as we can see at Instance 5.

In the Basic Net it regenerated on node 3 for both instances. In this case, the regeneration site is on the network core, also the node serving a larger number of users. We can see that the result of both random and worst–case instances is the same; the difference is in the running time and the spectrum's utilization. In the regeneration model, the primary constraint is the MAR, so increasing traffic in this network did not affect the regeneration decision.

On the NSFNet network, Instance 3 did not need to regenerate. This situation is due to the short distances of the arcs, where the minimum, average and maximum lengths are 212, 509, and 1140 km, respectively. By removing BPSK and adding 16QAM as a modulation format option, we are forcing the network to regenerate. So as expected, Instance 4 regenerate six demands in node 0. This node is on the network fringe, in contrast to the Basic Net solution. Table 6 exemplifies the six connection demands regenerated on the fifth instance separated by their path–segments. Notice that the users with regeneration are three nodes pairs communicating in a round–trip, For

Table 5: Results of the RP-RMLSA model.

Instances	Network	Bitrate	MF	PS	RunTime	RN	NºR	%FSU
1	Basic Net	Random	BPSK to 8QAM	122	17.885	3	2	31.4
2	Basic Net	Worst Case	BPSK to 8QAM	122	50.845	3	2	50.3
3	NSFNet	Random	BPSK to 8QAM	682	4472.390	None	0	60.5
4	NSFNet	Random	QPSK to 16QAM	404	46375.800	0	6	55.0
5	NSFNet	Worst Case	QPSK to 16QAM	404	298426.400	0	6	68.3

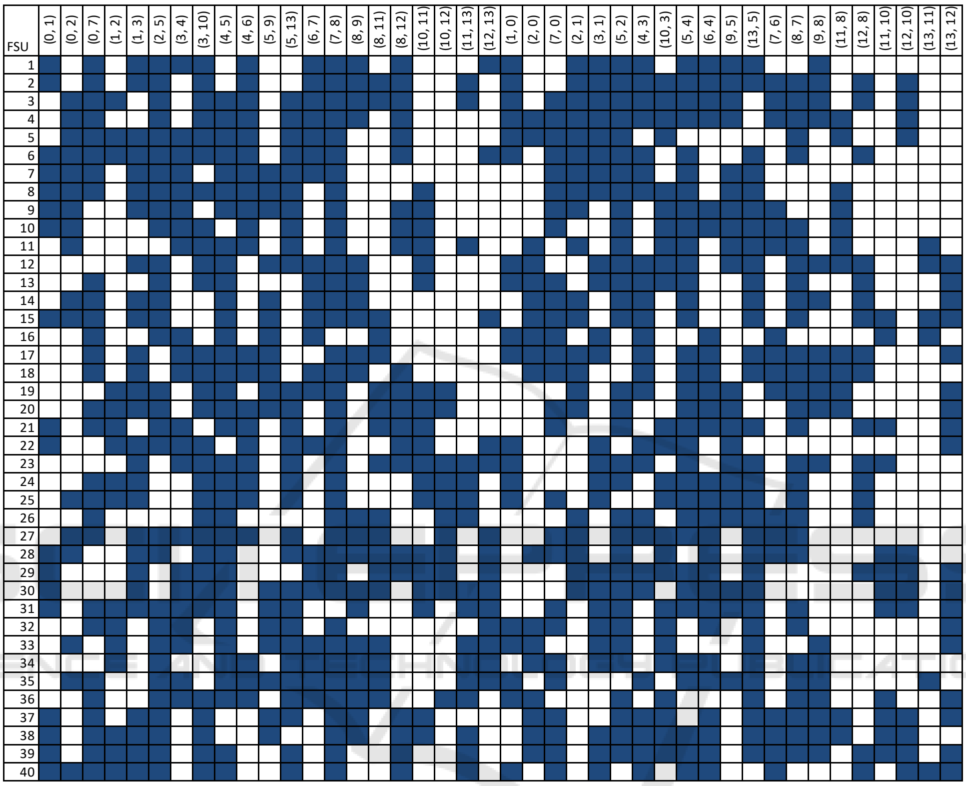

Figure 3: Spectrum utilization for instance 4.

instance, demands transmitting from node 1 to 12 and vice–versa (see demand 25 and 158 in Table 6). The same occurred in the Basic Net, with only one origin–destination pair.

Additionally, we can see that some demands changed the modulation format used on the different segments. This situation can be explained since users search for a room on each link's used capacity, therefore choosing a modulation format with higher spectrum efficiency if needed. However, It does not always select the most efficient modulation because it only minimizes the cost of using regeneration, not the spectrum usage.

Another interesting analysis is related to the utilization of the spectrum. By including regenerator nodes, we decrease the percentage of spectrum used. This reduction is coherent with previous references (Klinkowski, 2012). However, since we do

Table 6: Demands with regeneration for instance 4.

Demand	Path-Segment	Modulation	FSU used
25	(1,0)	QPSK	32,33
25	(0,7,8,12)	QPSK	20,21
37	(2,0)	QPSK	28
37	(0,7,8,11)	QPSK	26
47	(3,1,0)	8QAM	16,17
47	(0,7,8)	QPSK	1,2
108	(8,7,0)	QPSK	31,32
108	(0,1,3)	8QAM	1,2
146	(11,8,7,0)	QPSK	20
146	(0,2)	QPSK	33
158	(12,8,7,0)	QPSK	21
158	(0,1)	16QAM	14

not minimize the spectrum usage on the model, the utilization is not optimal. As we can see in Figure 3, the spectrum assignment does not seem to follow any observable rule. So the amount of fragmentation in the spectrum is very high. This performance opens the possibility of applying a de-fragmentation method like the ones found in (Velasco et al., 2017) or modifying the RP-RMLSA formulation to minimize the network fragmentation.

5 CONCLUSIONS

In this work, we propose a BLP formulation to jointly solve the regeneration placement, routing, modulation format, and spectrum assignment problems (known as RP–RMLSA). The RP–RMLSA model formulated is both complete and straightforward, considering every characteristic of the elastic optical network architectures, and regeneration devices. We show through different instances that the optimal number of regeneration sites is one or none, located on different network nodes depending on the topology. Finally, when regeneration occurs on a given source–destination node, it will also regenerate the same node pair but transmitting on the opposite side, solving the problems symmetrically.

Future work intends to include a cost of fragmentation to the RP–RMLSA formulation, seeking to minimize both the regeneration cost and the spectrum usage on the network links. Also, we intend to test the model with larger networks trying to reduce the execution time with OR techniques aiming to face the computational complexity of the problem. Finally, formulate an RP algorithm to reach a similar solution found in the RP–RMLSA model but with considerably lower running time, assessing the trade–off between complexity and optimality, and compare it with the hierarchical modeling approach.

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REFERENCES

Brasileiro, Í., Valdemir, J., and Soares, A. (2019). Regenerator assignment with circuit invigorating. *Optical Switching and Networking*, 34:58–66.

Calderón, F. I., Lozada, A., Bórquez-Paredes, D., Olivares, R., Davalos, E. J., Saavedra, G., Jara, N., and Leiva, A. (2020). Ber-adaptive rmlsa algorithm for wide-area flexible optical networks. *IEEE Access*, 8:128018–128031.

Chaves, D. A., Carvalho, R. V., Pereira, H. A., Bastos-Filho, C. J., and Martins-Filho, J. F. (2012). Novel strategies for sparse regenerator placement in translucent optical networks. *Photonic Network Communications*, 24(3):237–251.

Chaves, D. A., da Silva, E. F., Bastos-Filho, C. J., Pereira, H. A., and Almeida, R. C. (2015). Heuristic algorithms for regenerator assignment in dynamic translucent elastic optical networks. In *2015 17th International Conference on Transparent Optical Networks (ICTON)*, pages 1–4. IEEE.

Ellis, A. D., Mac Suibhne, N., Saad, D., and Payne, D. N. (2016). Communication networks beyond the capacity crunch. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 374(2062).

Fontinele, A., Santos, I., Durães, G., and Soares, A. (2016). Achievement of fair and efficient regenerator allocations in translucent optical networks using the novel regenerator assignment algorithm. *Optical Switching and Networking*, 19:22–39.

ITU-T (2012). Spectral grids for wdm applications: Dwdm frequency grid. ITU-T G.694.1, Telecommunication Standardization Sector of ITU, Ginebra, Switzerland.

Kahya, A. (2013). *Routing, spectrum allocation and regenerator placement in flexible-grid optical networks*. PhD thesis, bilkent university.

Klinkowski, M. (2012). On the effect of regenerator placement on spectrum usage in translucent elastic optical networks. In *2012 14th International Conference on Transparent Optical Networks (ICTON)*, pages 1–6. IEEE.

Poggiolini, P., Bosco, G., Carena, A., Curri, V., Jiang, Y., and Forghieri, F. (2014). The gn-model of fiber nonlinear propagation and its applications. *Journal of Lightwave Technology*, 32:694–721.

Talebi, S., Alam, F., Katib, I., Khamis, M., Salama, R., and Rouskas, G. N. (2014). Spectrum management techniques for elastic optical networks: A survey. *Optical Switching and Networking*, 13:34–48.

TeleGeography (2020). The state of the network 2020 edition.

Velasco, L., Vela, A. P., Morales, F., and Ruiz, M. (2017). Designing, operating, and reoptimizing elastic optical networks. *Journal of Lightwave Technology*, 35(3):513–526.

Waldman, H. (2018). The Impending Optical Network Capacity Crunch. *Sbfoton Conference*, pages 1–3.

Wang, X., Brandt-Pearce, M., and Subramaniam, S. (2015). Impact of wavelength and modulation conversion on translucent elastic optical networks using milp. *Journal of Optical Communications and Networking*, 7(7):644–655.

Yaghubi-Namaad, M., Rahbar, A. G., and Alizadeh, B. (2018). Adaptive modulation and flexible resource allocation in space-division-multiplexed elastic optical networks. *Journal of Optical Communications and Networking*, 10(3):240–251.

Yıldız, B. and Karaşan, O. E. (2017). Regenerator location problem in flexible optical networks. *Operations Research*, 65(3):595–620.