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Approaches to Maximize the Open Capacity of Elastic Optical Networks

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Abstract— This paper proposes a linear formulation and an iterative heuristic, both with traffic grooming capability, which can maximize the number of remaining available routes and minimize the number of transceivers in Elastic Optical Networks (EON). The aim of the proposal is to preserve the open capacity for the accommodation of future unknown demands. Case studies are carried out in order to analyze the basic properties of the formulation in a small network, and the heuristic is used for moderate larger networks. The results suggest that it is feasible to preserve enough open capacity to avoid blocking of future requests in EON with scarce resources.

Keywords—virtual topologies; optical networks optimization, RSA

I. INTRODUCTION

Recently, several authors [1]-[6] have pointed out that it is possible to increase the spectrum efficiency of WDM optical networks if a more elastic method of spectrum allocation is accomplished to make it “Gridless”. The “Gridless” network architecture is called Elastic Optical Network (EON) in the literature and was originally proposed in [2], [3]. In this new type of network, the bandwidth of a waveband on the spectrum is elastic to fit the amount of traffic demand from upper layer, instead of using an integer multiple of not efficiently utilized wavelength channels as in conventional WDM networks. Therefore, a considerable fraction of bandwidth can be saved without the rigid and individual “Grids”. To support the concept of this new network architecture, bandwidth-variable transponder (BV-transponder), spectrum selective switches (SSS), efficient modulation techniques and digital signal processing technologies have been proposed to allow the desired flexible granularity into the optical domain.

Analogue to the Routing and Wavelength Assignment (RWA) problem in WDM-based networks, Routing and Spectrum Assignment (RSA) is a fundamental problem in EONs [4]-[6]. The concerns of RSA are to find the most appropriate route for the given source and destination pair and assign a contiguous fraction of frequency spectrum to attend the traffic requirements. Similarly to the RWA problem, the RSA problem can be investigated under three traffic categories: static, dynamic and incremental. In the static traffic, the set of call requests is known in advance, and the main objective is to minimize the number of resources (usually slots) needed to establish a predefined set of call requests for a given network physical topology. In the incremental traffic, call requests arrive sequentially, a lightpath is established for each call

request, and the lightpath remains in the network indefinitely. For the case of dynamic traffic, a lightpath is set up for each call request as it arrives, and the lightpath is released after some finite amount of time. In this paper, we consider the case of static traffic profile for all analysis here presented, since it is still the most used profile to design operational optical networks.

On designing a network, it is common to define its physical topology and estimate a predefined traffic demand, which can be both based on the number of inhabitants of each region attended by the network nodes, and then estimate the necessary resources to attend that demand. Mixed/Integer Linear Programming has been traditionally used to the latter, as in [1]. However, network traffic has faced a fast and steady increase, mainly due to high demands Internet services, such as high-definition television, 3-D video on demand, cloud computing, and others. Therefore, if a network is not planned to receive possible future traffic increase, its design can quickly become obsolete and be not capable of attending the increasing traffic demand, which incurs in gathering efforts to define efficient upgrades, where extra costs are inevitable.

The necessity of upgrading efforts may be postponed if the network design is capable of including in its optimization process possible future resources to be used when the traffic increases. However, some telecommunication operators still prefer to invest just the necessary resource to attend current demand, without planning future traffic increase. In this work, we propose a MILP formulation that provides a network design with the lowest possible amount of resource to attend a predefined (i.e., current) traffic demand and, without using extra resources, determine optimal lightpath configurations that can attend the highest amount of future traffic increase without resource upgrades. These two types of traffic are treated jointly so that efficient designs can be obtained.

The key proposal is both a linear formulation and a heuristic, which are oriented towards optimizing the residual network capacity for the accommodation of future unknown demands, while guaranteeing the establishment of a predefined traffic demand. Both proposed approaches apply grooming to build the virtual topology along with the RSA to map the virtual topology into the physical optical resources. To the best of our knowledge, this is the first time that a solution to the virtual topology design and RSA problem with maximal residual capacity usage has been stated.

II. RELATED WORK AND VARYING TRAFFIC

To accommodate traffic in EONs, the total available spectrum is divided into constant spectrum units with a granularity finer than the typical 50 GHz grid used in WDM systems (e.g., 12.5 GHz), referred to as frequency slots (FSs). A set of contiguous FSs can carry some bit rate depending on the modulation format used. After traffic grooming, a connection is served by assigning a route and a set of contiguous FSs on all links along its path [1],[6]. The problem of static RSA has received the research community's attention, where the network traffic is known in advance and all connections are defined under the constraint that no spectrum overlapping is allowed among them. The solution defines the RSA constrained to minimizing a given performance metric, such as the total utilized spectrum, or maximizing the number of lightpaths for a given network resource. Some studies, such as those in [7]-[9], focus on virtual grooming and RSA (the grooming adds complexity to the RSA problem in elastic optical networks, mainly when it is required to constrain the use of transceivers at the nodes for multiple traffic aggregations), but they do not consider in their optimization process the maximization of residual network capacities so that the highest amount of traffic may be guaranteed to future traffic demands.

Figure 1a presents the spectrum utilization of an exemplary link in an EON and Figs 1b and 1c show two possible assignments of a new traffic demand [10]. Suppose that two specific sets of contiguous FSs (which are highlighted in the figures in red and blue) have been assigned to two distinct connections. It is worthwhile to note that the free FSs between these adjacent connections may be used to accommodate the mentioned new traffic demand, which requires a specific data rate. Notice that we can assign a single lightpath (Fig. 1b) with all required data rate or two or more lightpaths (Fig 1c) with an aggregated capacity equal to the required data rate. One can see that the approach in Fig 1b uses fewer transceivers and, by avoiding the need of additional guard bands, less FSs. In this paper we deal with the assignment as in Fig. 1b, i.e., all traffic between a source destination node will be aggregated in a single lightpath in order to reduce the number of slots in a lightpath and also of transceiver resources in the network.

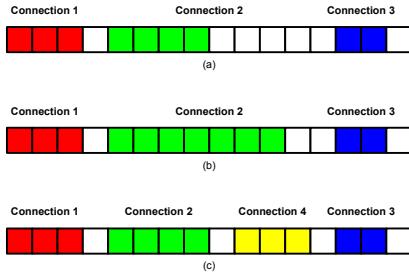


Fig. 1 Spectrum allocation of an exemplary link with two distinct assignments. In (b), a single lightpath is created, whereas in (c) multiple lightpaths are created.

III. MATHEMATICAL FORMULATIONS

In this section, we present a MILP formulation for the design of the routing problem with traffic grooming capability

to maximize the open capacity on EONs. The formulation is responsible for performing the virtual topology design and route the traffic on the physical topology by using the grooming facility for both current and future traffic demands. The solution of the MILP formulation must be able to fully attend the current demand and, at the same time, maximize the capacity for future demands, referred here to as remaining capacity. Notice that, in order to maximize the remaining capacity, the formulation deals jointly with the reservation of capacity for predefined and future traffic.

The used notations, given parameters and problem statement variables are described below:

A. Notation

- s and d denote the source and destination nodes of the traffic demands in the network, respectively.
- i and j denote originating and terminating nodes of a variable bandwidth lightpath, respectively.
- m and n denote endpoints of a physical link in the network.

B. Given

- N : Number of nodes in the network.
- Λ^{sd} : Traffic matrix element, used to denote the predefined traffic intensity from source node s to destination node d (in Gbps).
- Ω : slot width, which informs the slot spectrum width, in GHz.
- ε_z : spectral efficiency for the modulation format z , in (bits/s/Hz).
- d_{mn} : Link distance in the physical topology, which informs the distance of the fibers interconnecting node m to n .
- C_L : Minimum required capacity on each fiber, in terms of number of slots.
- L_H : The limit on the hardware processing capability at any node, in Gbps.
- L_Z : The maximum reach, in Km, for any predefined elastic lightpath.
- L_R : The maximum reach, in Km, for any remaining elastic lightpath.
- M : A large number to be used to make some integer variables.

C. Variables

- V_{ij} : Bandwidth, in Gbps, of the elastic lightpath from node i to node j .
- λ_{ij}^{sd} : Traffic flow, in Gbps, from source s to destination d , routed through the lightpath from node i to node j .
- b_{ij} : a binary variable to indicate the existence or not of a lightpath from node i to node j .
- S_{ij} : Number of slots of the elastic lightpath (b_{ij}) from node i to node j .
- P_{mn}^{ij} : Number of slots that the elastic lightpath from node i to node j uses in a fiber link $m - n$.

- A_{mn}^{ij} : A binary variable to indicate whether the lightpath from node i to node j passes through a link $m-n$. A_{mn}^{ij} equals to 1 if $P_{mn}^{ij} > 0$; equals to 0 if $P_{mn}^{ij} = 0$.
- L_k : The hardware processing used at any node $k \in N$.
- z_{ij} : a binary variable to indicate the existence or not of a remaining elastic lightpath from node i to node j .
- Q_{ij} : Number of available remaining slots of a remaining elastic lightpath (z_{ij}) from node i to node j .
- R_{mn}^{ij} : Number of slots that a possible remaining elastic lightpath from node i to node j can use in a fiber link $m-n$.
- B_{mn}^{ij} : A binary variable to indicate whether the possible remaining lightpath from node i to node j can pass through a link $m-n$. B_{mn}^{ij} equals to 1 if $R_{mn}^{ij} > 0$; equals to 0 if $R_{mn}^{ij} = 0$.

D. MILP

In the proposed problem optimization, since it is required that all traffic demand is attended in the network, the objective function has been chosen to maximize the saving of future resources (in terms of number of remaining slots in each remaining elastic lightpath) that can be used for future elastic lightpath assignments. Therefore, the problem will follow the approach as stated in Fig. 1b. The formulation below does not impose a constraint on the spectrum continuity and contiguity. Therefore, the output of the formulation is equivalent to as assuming spectrum conversion in any node of the network, which provides a lower bound on the number of required slots. However, such results will be used as input to the formulation provided at Section III.E, which will perform the spectrum assignment taking into account both the continuity and contiguity constraints to adjust the simplification previously assumed.

$$\text{Maximize: } \sum_{ij} (Q_{ij} + \alpha \cdot z_{ij}) \quad (1)$$

$$\sum_j \lambda_{ij}^{sd} - \sum_j \lambda_{ji}^{sd} = \begin{cases} \Lambda^{sd} & \text{if } i = s \\ -\Lambda^{sd} & \text{if } i = d \\ 0 & \text{if } i \neq s, d \end{cases} \quad \forall s, d, i \in N \quad (2)$$

$$\sum_{sd} \lambda_{ij}^{sd} = V_{ij} \quad \forall i, j \in N \quad (3)$$

$$\sum_{s,d,j} \lambda_{kj}^{sd} = L_k \quad \forall (k \neq j) \in N \quad (4)$$

$$L_k \leq L_H \quad \forall (k) \quad (5)$$

$$\lceil V_{ij} * \left(\frac{1}{\epsilon z}\right) * \left(\frac{1}{\Omega}\right) \rceil = S_{ij} \quad \forall i, j \in N \quad (6)$$

$$\sum_n P_{mn}^{ij} - \sum_n P_{nm}^{ij} = \begin{cases} (S_{ij}) & m = i \\ -(S_{ij}) & m = j \\ 0 & m \neq i, j \end{cases} \quad \forall i, j, m \in N \quad (7)$$

$$\sum_n R_{mn}^{ij} - \sum_n R_{nm}^{ij} = \begin{cases} (Q_{ij}) & m = i \\ -(Q_{ij}) & m = j \\ 0 & m \neq i, j \end{cases} \quad \forall i, j, m \in N \quad (8)$$

$$\sum_{ij} (P_{mn}^{ij} + R_{mn}^{ij}) \leq C_L \quad \forall m-n \in E \quad (9)$$

$$b_{ij} \geq \frac{S_{ij}}{M} \quad \forall i, j \in N \quad (10)$$

$$z_{ij} \geq \frac{Q_{ij}}{M} \quad \forall i, j \in N \quad (11)$$

$$A_{mn}^{ij} \geq P_{mn}^{ij}/M \quad \forall i, j \in N \text{ and } \forall m-n \in E \quad (12)$$

$$B_{mn}^{ij} \geq R_{mn}^{ij}/M \quad \forall i, j \in N \text{ and } \forall m-n \in E \quad (13)$$

$$\sum_{mn} A_{mn}^{ij} * d_{mn} \leq L_z \quad \forall i, j \in N \quad (14)$$

$$\sum_{mn} B_{mn}^{ij} * d_{mn} \leq L_R \quad \forall i, j \in N \quad (15)$$

Eqn. (1) denotes the objective function, i.e., the aimed maximization of the remaining number of slots that can be used to setup future lightpaths. Notice that we have weighted the number of remaining slots with αz_{ij} , where α is a small constant. This has been done to guarantee the maximum number of remaining slots and, in case of a draw, the maximum number of possible future elastic lightpaths. Eqn. (2) is the flow conservation constraints of flows on the virtual topology (grooming layer). Eqn. (3) denotes that low-speed traffic flows are groomed into bandwidth-variable lightpaths. Eqn. (4) calculates the amount of optical hardware processing at each node, whereas Eqn. (5) provides the bound to its processing capability. Eqn. (6) calculates the number of slots required by each elastic lightpath, which depends on the modulation format used and the given slot width. Eqns. (7) and (8) assure the flow conservation constraints of traffic routing at the optical layer for current and slot assignment, respectively. Eqn. (9) ensures that the number of slots per fiber, C_L , is not smaller than the total number of slots required by the elastic lightpaths routed on any fiber link $m-n$ in the network. Notice that, as stated before, the left-hand side of inequality (9) calculates the total required slots on any bi-directional fiber in a network with the capability of spectrum conversion, and thus performs as a lower bound for network without capability of spectrum conversion. This will be corrected below, at Section III.E. Eqns. (10) and (11) inform if there are active lightpaths. Eqns. (12) and (13) inform whether the active and future elastic lightpath, respectively, pass through a specific fiber link.

Eqn. (14) limits the reach of a lightpath. It may be used to restrict the enumerated (S_{ij}) variables to be only a path from i to j (non-bifurcation). Eqn. (15) works similarly to Eqn. (14). The values of L_z and L_R may be selected by the network designer and many times the equations are optional.

The number of actually used and reserved transceivers depends on the total number of elastic established and future lightpaths, which is given by the binary variables b_{ij} and z_{ij} . These take the value 1 if there is a lightpath (and, consequently, a transceiver) from node i to node j and 0 otherwise. Therefore, we also add the following constraints, from (16) to (18), which allow the MILP formulation consider the total number of transceivers, referred to as Δ .

$$\lambda_{ij}^{sd} \leq b_{ij} A^{sd} \quad \forall s, d, i, j \quad (16)$$

$$A_{mn}^{ij} \leq b_{ij} \quad \forall i, j, m, n \quad (17)$$

$$B_{mn}^{ij} \leq z_{ij} \quad \forall i, j, m, n \quad (18)$$

$$\sum_{ij} (b_{ij} + z_{ij}) \leq \Delta \quad \forall i, j \quad (19)$$

$$b_{ij} + z_{ij} \leq 1 \quad \forall i, j \quad (20)$$

The constraint (16) ensures that, if $b_{ij} = 0$, the link $i-j$ does not exist in the virtual topology, which implies that no traffic can be routed on that link and, therefore, $\lambda_{ij}^{sd} = 0$ for all values

of s and d . Otherwise, if the link i - j exists in the virtual topology, $b_{ij} = 1$, and (16) simply states that $\lambda_{ij}^{sd} \leq A^{sd}$, which is always true, i.e., do not imposing any constraint on the values of λ_{ij}^{sd} in this case. Similarly, the constraint (17) ensures that if $b_{ij} = 0$, $A_{mn}^{ij} = 0$ for all values of m and n , which can be understood by the fact that, if the lightpath i - j does not exist in the virtual topology, it cannot be routed on any physical link m - n . Otherwise, if the lightpath i - j exists in the virtual topology ($b_{ij} = 1$), it can be routed on an existing physical link m - n . The constraint (18) works similarly to constraint (16), but for future traffic. The constraint (19) ensures that the designed topology has no more than Δ transceivers in total. Then, equations (17) and (18) restrict the number of remaining assignable lightpaths to the total number of remaining transceivers. The constraint (20) ensures that multiple logical links between a node pair (i, j) are not allowed. Therefore, (z_{ij}, b_{ij}) is either (0,1) or (1,0).

E. Spectrum Allocation Phase.

The spectrum allocation is similar to the formulation presented in [11], but, instead of using the set P of pre-calculated paths, it is used the set P^* of paths calculated in the routing phase of the MILP formulation. The returned A_{mn}^{ij} and B_{mn}^{ij} denote the optical links included in the set P^* . Thus, for each set of assigned and reserved slots, S_{ij} and Q_{ij} , respectively, one path is included in P^* . The ILP spectrum allocation has as objective function the minimization of the total number of allocated slots. Then, the spectrum allocation phase minimizes the maximum slot index, F_{max} , among all links. Therefore $F_{max} \geq C_L$, since C_L is the lower bound on the number of slots as stated before. The proximity between C_L and F_{max} indicates the efficiency of the spectrum allocation phase for the paths found by the MILP. The ILP spectrum formulation is omitted for brevity purposes.

IV. DISCUSSIONS AND RESULTS

For evaluating the effectiveness of the proposed optimization, we analyzed a small topology. We use IBM ILOG CPLEX v.11.0 [12] on an Intel i3 2.27GHz 2GB computer to solve the MILP (routing phase) and ILP (spectrum allocation phase) problems. Below, we describe in detail the performance of the proposed approach and then summarize the results.

A. Small Network

We initially used a 4-node and 5-link topology (Fig. 2) to evaluate the performance of the proposed approach. We assume that there is a bidirectional fiber on each link and the available capacity (C_L) on each fiber is set to be 12 slots. The slot width, Ω , is set to be 12.5 GHz, the data rate-to-bandwidth ratio, ϵ_s , is set to be 1bit/s/Hz (just to easy the readability of the results). The traffic demand is 12.5 Gbps for each source-destination pair.

We have simulated three cases, where each of them assumes a different number of transceivers, Δ , and two different hardware processing capacities, L_H . We assume $L_Z=L_R=2000$ for non-allowed bifurcated lightpaths on physical routing.

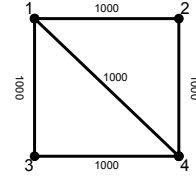


Fig. 2 Small network (4 nodes and 5 links)

In table I, one can observe that, with $\Delta=5$, $C_L=12$ and $L_H=75$, a remaining lightpath (z_{ij}) has been found. For this case, it is feasible to support a traffic growth of 6 slots on remaining virtual link 2-4. However, with $L_H=70$, the solution is infeasible, because the initial connections carry more traffic than the node processing capacity. In table II, we analyze a scenario with $\Delta = 8$, $C_L=12$ and $L_H=75$ or 70. Notice that 4 remaining lightpaths (z_{ij}) were found with a possible total traffic growth of 24 slots for $L_H=75$ and 12 slots for $L_H=70$. We can observe that less lightpaths were reserved for the traffic growth with $L_H=70$ due to the processing constraint. In Table III, with $\Delta = 12$, $C_L=12$ and $L_H=75$, 6 remaining lightpaths (z_{ij}) were found with a total traffic growth of 36 slots. Therefore, 2 ports (of total 12) could not be used due the routing constraints, because there is not enough capacity. For $L_H=70$, we observed that 5 remaining lightpaths are guaranteed to future traffic with a possible traffic growth of 29 slots. It is important to note that, in all cases, the spectrum allocation phase returned a maximum number of slots allocated (F_{max}) equal to minimum link capacity (C_L), which indicates the effectiveness of the combined use of the MILP and ILP formulations. Evidently, we can increase the number of slots of the remaining lightpaths by the increase in C_L or increase the number of remaining lightpaths by increasing L_H and C_L . The basic idea, however, is that the network design assumes a best configuration according to available resources.

Table I, $C_L=12$ and $\Delta=5$

L _H =75						
obj	P*		Route	# of slots	F _{max}	
6	1	b_{13}	1-3	S_{ij}	6	12
	2	b_{21}	2-1	S_{ij}	6	
	3	b_{34}	3-1-4	S_{ij}	6	
	4	b_{42}	4-2	S_{ij}	6	
	5	z_{24}	2-4	Q_{ij}	6	
L _H =70						
obj	P*		Route	# of slots	F _{max}	
0	-	-	-	-	-	-

Table II, $C_1=12$ $\Delta=8$

L _H =75					
obj	P*	Route	# of slots		F _{max}
24	1	b ₁₂	1-2	S _{ij}	6
	2	b ₂₄	2-4	S _{ij}	6
	3	b ₃₁	3-1	S _{ij}	6
	4	b ₄₃	4-1-3	S _{ij}	6
	5	z ₁₃	1-4-3	Q _{ij}	6
	6	z ₂₁	2-1	Q _{ij}	6
	7	z ₃₄	3-4	Q _{ij}	6
	8	z ₄₂	4-2	Q _{ij}	6
L _H =70					
obj	P*	Route	# of slots		F _{max}
12	1	b ₁₂	1-2	S _{ij}	1
	2	b ₁₃	1-3	S _{ij}	4
	3	b ₂₁	2-1	S _{ij}	5
	4	b ₃₄	3-4	S _{ij}	5
	5	z ₄₂	4-2	S _{ij}	4
	6	z ₄₃	4-3	S _{ij}	1
	7	z ₁₄	1-4	Q _{ij}	6
	8	z ₃₁	3-1	Q _{ij}	6

Table III, $C_1=12$ and $\Delta=12$

L _H =75					
obj	P*	Route	# of slots		F _{max}
36	1	b ₁₂	1-2	S _{ij}	6
	2	b ₂₄	2-4	S _{ij}	6
	3	b ₃₁	3-1	S _{ij}	6
	4	b ₄₃	4-3	S _{ij}	6
	5	z ₁₃	1-3	Q _{ij}	6
	6	z ₁₄	1-4	Q _{ij}	6
	7	z ₂₁	2-1	Q _{ij}	6
	8	z ₃₄	3-4	Q _{ij}	6
	9	z ₄₁	4-1	Q _{ij}	6
	10	z ₄₂	4-2	Q _{ij}	6
L _H =70					
obj	P*	Route	# of slots		F _{max}
29	1	b ₁₃	1-3	S _{ij}	1
	2	b ₁₄	1-4	S _{ij}	4
	3	b ₂₁	2-1	S _{ij}	3
	4	b ₂₃	2-1-3	S _{ij}	2
	5	b ₃₁	3-1	S _{ij}	2
	6	b ₃₂	3-1-2	S _{ij}	1
	7	b ₄₂	4-2	S _{ij}	4
	8	z ₁₂	1-2	Q _{ij}	5
	9	z ₂₄	2-4	Q _{ij}	6
	10	z ₃₄	3-4	Q _{ij}	6
	11	z ₄₁	4-1	Q _{ij}	6
	12	z ₄₃	4-3	Q _{ij}	6

V. HEURISTIC ALGORITHM

Due to the complexity of the problem for large networks, here we present a simple heuristic algorithm. Our main goal is to route traffic on the virtual layer by adopting the open capacity criteria studied in this paper to generate a solution with a viable simulation time.

The approach can be approximately decomposed into three sub-formulations. The decomposition results are usually not exact, since solving the sub-formulations in sequence and combining the solutions do not necessarily result in the optimal solution for the fully integrated problem. However, the strategy allows a much lower computational complexity.

The three sub-formulations are:

Sub-formulation 1 (Virtual Topology Design): to determine the S_{ij} and b_{ij} to be imposed on the physical

topology, i.e., determine all lightpaths terms of their source and destination nodes and jointly route Λ^{sd} demand between source and destination nodes over the virtual topology found.

Sub-formulation 2 (Routing Phase): to find the set P* with the lightpaths found in the Sub-formulation 1.

Sub-formulation 3 (Spectrum Allocation Phase): It is similar to section III.E.

The 3 sub-formulations are explained in 3 steps following.

Step 1: Given the traffic matrix demands $\{\Lambda^{sd}\}$ and Δ , find the virtual links (b_{ij}), S_{ij} and flow routes (F_{ij}^{sd}). The objective function now of minimizing the maximum number of setups lightpaths works like maximize the number of remaining lightpaths:

$$\text{Minimize } \sum_{ij} (b_{ij}) \quad (21)$$

In addition to the objective function (21), the constraints imposed by Eqs. from (2) to (6) and (16) are also used. That step the L_H is unlimited for that way we got a value (come of variable Lk) that to allow built the virtual topology.

Step 2: Solve the sub-formulation 2 using the equations (7) to (15) and (17) to (20) with the objective function (1), but using the values from S_{ij} , found in **Step 1** as inputs to **Step 2**. That step returns Q_{ij} , z_{ij} , and P*

Step 3: Solve the spectrum allocation with the paths (P*) found in **Step 2** and return F_{max} .

A. Simulations (Moderate Network)

We used a 9-node and 12-link topology (Fig. 4) to evaluate the performance of the proposed heuristic. The slot width (Ω) is set to be 12.5 GHz. The data rate-to-bandwidth ratio (ϵ_2) is set to be 1bit/s/Hz. The traffic demand is 12.5 Gbps for each source-destination pair and we limit the hardware processing capability at any node, in 450 Gbps. We specified an upper limit of 600 seconds as the maximum allowed computation time for solving each step. The step 3 is faster; all the solutions took less than 1 second. However, the steps 1 and 2 sometimes reached the limit time and we took the solution of that limit.

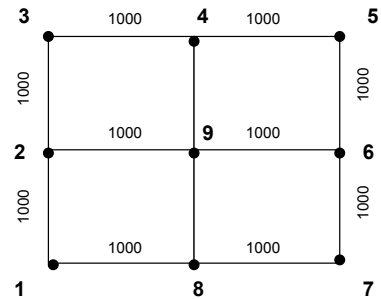


Fig. 3 Moderate network (9 nodes and 12 links), $L_Z = L_R = 3000$

Table IV. $C_L=100$

Δ	$\#z_{ij}$	$\sum_{ij} Q_{ij}$	F_{max}
12	3	300	100
14	5	428	100
16	7	520	100
18	9	612	100

Table V. $C_L=90$

Δ	$\#z_{ij}$	$\sum_{ij} Q_{ij}$	F_{max}
12	3	270	90
14	5	378	90
16	7	486	90
18	9	522	90

Table VI. $C_L=80$

Δ	$\#z_{ij}$	$\sum_{ij} Q_{ij}$	F_{max}
12	3	240	80
14	5	328	80
16	7	416	80
18	9	432	80

Table VII. $C_L=60$

Δ	$\#z_{ij}$	$\sum_{ij} Q_{ij}$	F_{max}
Step 1 is inviable			

We observed that 9 lightpaths were found in step 1. Evidently, that number of lightpaths is the minimum necessary for building the virtual topology and having all nodes connected for routing the Λ^{sd} of upper layer. The b_{ij} found were (1-2), (2-9), (9-3), (3-4), (4-6), (6-5), (5-8), (8-7) and (7-1). Each of these lightpaths has a size of 36 slots ($S_{ij}=36$). After step 1, the lightpaths were routed on the physical topology by step 2 (therefore we found the number of remaining lightpaths ($\#z_{ij}$) and their sizes Q_{ij}). Finally, the set of paths P^* found on step 2 were the input to step 3. In tables IV, V and VI, we can see that all remaining lightpaths (z_{ij}) with several network capacities (100, 90 and 80). However, with $C_L=60$ the solution already is inviable in step 1, because the initial connections carry more traffic than the capacity for building the virtual topology. Therefore, C_L 's less than 60 turns the problem inviable for that case study. We can see in the tables that we can increase the number of slots of the remaining lightpaths by the increase in C_L . Finally, it is important to note that similarly to the small network the spectrum allocation phase returned a maximum number of slots allocated (F_{max}) equal to minimum link capacity (C_L), which indicates the effectiveness of the paths found (P^*) and of spectrum allocation phase.

VI. CONCLUSIONS

This paper proposed novel approaches to maximize the open capacity of elastic optical networks. These approaches solve the virtual topology design and RSA problem with the aim to reserve optical resources and maximize possible future traffic. The computational experiments clearly show that our approaches with linear formulations give good solutions to maximizing the number of remaining routes, making efficient use of resources.

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