Minimum-Cost Optical Amplifier Placement in Metro Networks

Memedhe Ibrahimi, Omran Ayoub, Francesco Musumeci, Oleg Karandin, Andrea Castoldi, Rosanna Pastorelli, Massimo Tornatore

Abstract— **Emerging 5G services are revolutionizing the way operators manage and optimize their optical metro networks, and the metro network design process must be rethought accordingly. In particular, minimizing network cost is crucial to curb operators' investment. Taking advantage of relatively-short distances in metro networks, operators have the opportunity to optimize the placement of optical amplifiers (OAs) with the goal of minimizing amplifiers' cost (and hence decrease network cost) without significantly affecting the quality of transmitted optical signals. Minimizing OA cost translates not only in minimizing the cost of equipment (i.e., boosters, pre-amplifiers and inline amplifiers), but also in minimizing deployment and maintenance costs of active amplifier sites. In this paper, we propose a heuristic algorithm for OA placement and for the Routing and Spectrum Assignment (RSA) in metro networks, with the objective of minimizing the total cost of OAs while guaranteeing sufficient optical signal-to-noise ratio (OSNR) of established lightpaths. In our approach, we consider different cost for the deployed OAs, according to their location and type, i.e., inline amplifiers (ILAs), boosters and pre-amplifiers, and compare our optimized placement against benchmark strategies where OAs are pre-deployed at network nodes and at a fixed distance one from the other along optical fiber links. We also evaluate the impact of different routing strategies on the total cost and utilized spectrum. Simulative results, performed over realistic metro network topologies, show that our strategy provides up to 47% OAs cost savings while satisfying minimum OSNR constraints.**

Index Terms— **Cross-layer network optimization, Metro Networks**

I. INTRODUCTION

Optical metro networks must be designed keeping in mind the extensive demand for capacity required to support incoming 5G communications. This capacity increase must be guaranteed while keeping capital expenditures (Capex) and operational expenditure (Opex) under control.

Several cost-effective solutions such as, e.g., filterless networking [1-2] and wavelength-interleaved networks [3], are being investigated to replace costly state-of-the-art wavelength-switched architectures in metro. These solutions, however, are still under investigation, and cannot be used to satisfy the current need to reduce costs in the medium-short term. An alternative and less-disruptive strategy to minimize costs in metro networks consists in reducing the amount of expensive optical devices as well as the number of active sites in the network. Considering the relatively short distances in metro networks, operators can achieve this goal by optimizing the number, location and type of optical amplifiers (OAs) in egress of network nodes, i.e., booster amplifiers (*boosters*), in ingress of network nodes, i.e., pre-amplifiers (*pre-amps*), and those located along fiber links, i.e., in-line amplifiers (*ILAs*), while guaranteeing sufficient optical signal-to-noise ratio (OSNR) for the established lightpaths. Note that, decreasing the amplifiers' costs in a metro network does not only mean less equipment cost (less amplifiers), but, even more importantly, also cutting costs by reducing the number of active-node locations in metro areas (e.g., amplifiers huts).

Overall, the optimization problem to be addressed to return a feasible design with minimal amplifier cost can be summarized as quality of transmission (QoT)-aware routing and spectrum allocation with amplifier placement (RSA-AP). To solve the RSA-AP problem, we develop a heuristic approach which performs two main tasks: 1) RSA of traffic demands and 2) Placement of OAs. Since amplifier placement has a strong impact on the performance of optical signal transmission, an accurate physical layer modelling to capture the impact of amplifier placement on the Quality-of-Transmission, i.e., on the OSNR of lightpaths is needed. For this aim, we make use of well-known analytical non-linear propagation models [4] (detailed description of physical model is presented in Sec. II.A) and incorporate it in the proposed heuristic approach.

A. Related Work

The problem of amplifier placement with the objective of minimizing cost of amplifiers has received little attention in literature, as minimizing amplifiers cost in long-distance regional/backbone networks is not expected to lead to significant cost savings. In fact, signal amplification and regeneration in long-distance backbone networks is most often required, hence the placement of ILAs, boosters and pre-amplifiers cannot be avoided, making the associated RSA-AP problem ineffective in cutting costs in long distance networks. Only some recent work on amplifier placement refers to long-

haul communications where the placement of amplifiers along with regenerators is considered. Ref. [5] proposes a heuristic method to optimize the placement of hybrid Raman/EDFA amplifiers in mesh optical networks. It determines the placement of Raman amplification such that the number of optical regenerators is minimized. Ref. [6-7] consider the selective upgrade of line optical amplifiers to hybrid Raman/Erbium amplification in order to reduce the number of optical regenerators. Ref. [8] studies the problem of the upgrade of optical line amplifiers with Raman amplification (RA) modules and proposes three strategies for equipment upgrade. Conversely, in metro, the relatively high number of nodes (in this paper assumed to be Reconfigurable Optical Add-Drop Multiplexers – ROADMs) and short fibers make the problem tempting for operators. Seminal works in [9-10] investigated amplifier placement in metro networks providing mixed integer linear formulation with the objective of minimizing the number of amplifiers, but neglecting the impact of amplified spontaneous emission (ASE) noise introduced by amplifiers, which has a major impact on the OSNR of signals in the network. In our work, we consider the impact of ASE noise in signal propagation as well as the non-linearities due to signal propagation by using fiber non-linear propagation models which in turn do not enable an ILP formulation for this problem. We extend the preliminary analysis reported in [11] and investigate the placement of boosters, pre-amps and ILAs in metro networks employing coherent detection and uncompensated transmission techniques which allow us to consider a well-established and computationally-efficient GN-Model [4] for non-linear propagation.

B. Paper Contribution and Organization

The main contributions of this paper are as follows: 1) we formally define the RSA-AP problem in metro networks; 2) we propose a novel heuristic (the *MinOA* algorithm) approach to solve the RSA-AP problem, which minimizes the overall cost of OAs in the network while guaranteeing QoT of established lightpaths; 3) we discuss a model to set the gain of amplifiers in the network with focus on the case when boosters and pre-amps are absent at network nodes; 4) through a simulative study, we evaluate the impact of routing and optimized placement of boosters, pre-amps and ILAs on both the OSNR of lightpaths and the overall spectrum occupied in realistic metro topologies.

The rest of the paper is organized as follows. Section II introduces the OA placement problem and describes the physical layer model considered in our analysis. Section III states the RSA-AP problem and describes the heuristic algorithm proposed to solve it. Section IV presents numerical results and Sec. V draws paper conclusion.

II. BACKGROUND

A. Physical layer description

We consider the Gaussian Noise propagation model (GN-model). The GN-model allows to predict the performance of an uncompensated optical link by accurately estimating the non-linear interference (NLI) introduced by the signal propagation in the optical fiber.

The value of the optical signal-to-noise ratio received at the receiver for an optical lightpath is defined as the total OSNR ($OSNR_{TOT}$). It accounts for the linear OSNR contribution, i.e., $OSNR_{ASE}$, and the non-linear contribution, i.e., $OSNR_{NL}$, and for an optical lightpath traversing k optical spans, it is calculated as follows:

$$\frac{1}{OSNR_{TOT}} = \sum_{k=1}^{N_{spans}} \frac{1}{OSNR_{k,ASE}} + \sum_{k=1}^{N_{spans}} \frac{1}{OSNR_{k,NL}} \quad (1)$$

Since the linear OSNR ($OSNR_{ASE}$) contribution is due to the amplifiers in the network, care must be taken when deploying amplifiers and setting their gain so that signal quality is ensured and so that the ASE noise introduced by the OAs does not cause the signal to deteriorate below a certain quality level. In addition, the non-linear OSNR ($OSNR_{NL}$) depends on the fiber characteristics (local chromatic dispersion, refractive index, attenuation coefficient, span length) and on the traffic matrix. The linear OSNR and the nonlinear OSNR of a lightpath in the kth span are defined in [12] as follows:

$$OSNR_{k,ASE} = \frac{P_k}{h v B_n G_k F_k} \quad (2) \quad \text{and} \quad OSNR_{k,NL} = \frac{1}{B_n \eta_k P_k^2} \quad (3)$$

where P_k is the channel power, B_n is the noise reference bandwidth, h is the Planck's constant, v is the center propagation frequency, G_k is the gain and F_k is the noise figure of the kth amplifier, η_k is the non-linear efficiency (calculated as given in [4]).

In our analysis we consider Standard Single-Mode Fiber (SSMF) links with an attenuation coefficient of 0.22 dB/km and 0.03dB/km extra attenuation due to splice losses which amounts to 0.25 dB/km propagation loss, dispersion coefficient of 21 ps²/km and fiber non-linearity coefficient 1.3 W⁻¹km⁻¹. We compute lightpaths OSNR through the GN-Model assuming full spectral load and links operating at their optimal power, as prescribed by the Locally-Optimized-Globally-Optimized (LOGO) strategy [12-13]. According to the LOGO approach, $OSNR_{TOT}$ can be maximized by finding the optimal value of the launched power in each span. For a span k, characterized by a span loss $A_{k,span}$, the non-linearity efficiency η_k and noise figure of the OA at the end of the kth span F_k, the optimal launched power is defined as follows:

$$P_{k,opt} = \left(\frac{h v A_{k,span} F_k}{2 \eta_k} \right)^{1/3} \quad (4)$$

To determine lightpaths feasibility, the total OSNR ($OSNR_{TOT}$) of a lightpath is required to be above the OSNR threshold, i.e., the minimum required OSNR for a lightpath. Note that the OSNR threshold is given as the required OSNR considered in the back-to-back configuration ($OSNR_{B2B}$) [14]. In order to account for the impact of effects such as aging, optical filtering and power ripple, we consider a conservative system margin (i.e., variable Margin) of 2 dB. Therefore, a lightpath is defined to be feasible if its total OSNR ($OSNR_{TOT}$) is greater than the threshold, as given in (5):

$$OSNR_{TOT} > OSNR_{B2B} + Margin \quad [\text{dB}] \quad (5)$$

In addition to OSNR, to determine lightpath feasibility, also

the received power (P_{REC}) needs to be taken into consideration. P_{REC} is computed as follows:

$$P_{REC} = P_{TX} - \sum Loss + \sum Gain \qquad [dBm] \qquad (6)$$

where P_{TX} is the channel power launched at the source of the lightpath, sum of *Loss* accounts for all losses along the path, i.e., due to propagation loss, node loss and variable optical attenuators (VOAs) and the sum of *Gain* accounts for the gain of all amplifiers deployed along the path. We assume the total amount of loss of an express node to sum up to 17 dB due to splitters, combiners, VOAs and wavelength selective switches (WSSs) in the node while total loss of source and destination nodes is assumed to be half the loss of an express node (i.e., their joint loss contribution is equal to an express node loss).

B. Optical Amplifier placement

We consider the placement of amplifiers in three different locations: 1) at the ingress of a node, referred to as pre-amp, 2) at the egress of a node, referred to as booster and 3) along the fiber, referred to as ILA. Moreover, we consider two different types of amplifiers to be deployed in these locations. These two types of amplifiers differ in their physical characteristics, i.e., in terms of their gain and noise figure range (see Table I).

Table I. Optical Amplifier types and their characteristics

OA type	Gain [dB]	Noise Figure [dB]
Booster	10-20	12-6
Pre-amp	18-32	10.5-6.2

The relation between noise figure and gain of an amplifier is the following: $F = a + \frac{b}{G-1}$, given in linear units. The values of a and b for booster OA type are: a = 2.793 and b = 117.513 and for pre-amp OA type are: a = 3.88 and b = 455.814. In the figure below, we show the relation between gain and noise figure in dB units for both types of amplifiers we consider, booster and pre-amp OA type.
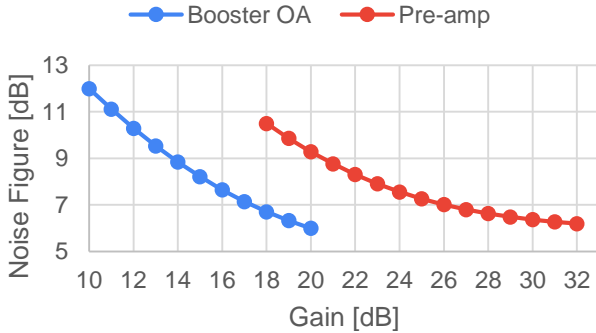

Figure 1. Noise Figure (dB) as a function of Gain (dB) for booster amplifiers (booster OA) and pre-amplifiers (pre-amps). Note that the gain range differs for each of amplifiers type. The curves show the relation between gain and noise figure for booster and pre-amp OA types

Considering that pre-amplifier type has higher gain values, we assume that it has a higher cost than the booster OA type. Common practice constrains the deployment of first amplifier
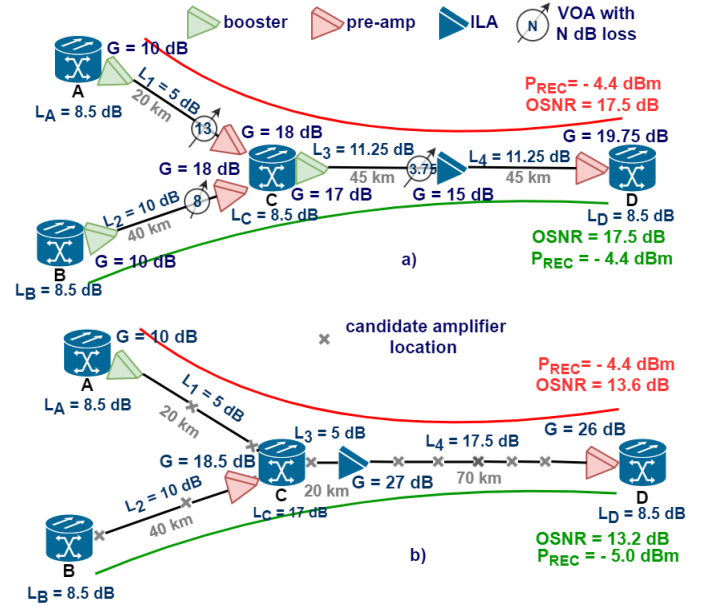

Figure 2. Example of OA placement a) baseline approach and b) optimized placement

type at egress of network nodes (therefore it is usually referred to as booster), and the deployment of second amplifier type at ingress of network nodes (therefore it is usually referred to as pre-amp). In our work, however, we do not restrict the deployment of any specific type of amplifiers at any location in the network. Instead, we allow the deployment of any amplifier type in any candidate amplifier locations, i.e., along the fiber or at ingress or egress of nodes, to evaluate possible cost savings with respect to a common practice case, where specific amplifier types are designed constrained to specific locations. As a consequence, the choice of the amplifier to be placed in a given location x depends on the desired gain for that location, i.e., on the optical span it terminates and its characteristics. In other words, if the desired gain is in the range (10-20) dB we assume the placement of booster amplifier type, while, if the desired gain ranges between (20-32) dB, we assume the placement of pre-amplifier type. In case there is a span whose loss is less than the minimal gain of the placed OA, e.g., span loss is 7 dB and minimal gain is 10 dB, we enforce the constraint of the minimal OA gain and consider additional attenuation (3 dB attenuation in this case) performed by a VOA, so that the span loss equals the OA gain and it is compensated.

Let us consider the simple example in Fig. 2, which illustrates the principle of OA placement and its effect in the lightpaths on the network. Fig. 2(a) shows a traditional OA placement, whereas Fig. 2(b) shows an optimized OA placement.

We consider two lightpaths originating at nodes A and B with the same destination node D. In case a), boosters and pre-amps are placed at each node and also an ILA placed in link C-D. Such deployment ensures that OSNR and P_{REC} requirements are ensured for both lightpaths, as shown in the figure. In case b) OAs can be placed in any of the candidate amplifier locations indicated by a "*x*". The optimized OA placement returns fewer OAs yet satisfying the QoT requirements for both lightpaths. Specifically, we save a pre-amp and two boosters in comparison

to the case in Fig. 2(a).

The example in Fig. 2(b) shows that there is no pre-amp at node ingress in link A-C and no booster at egress of nodes B and C, therefore the ILA placed just after node C will set its gain to compensate for both the node loss and propagation loss. Please note that in a case of a ROADM node without booster and pre-amp, the amplifier placed after the node may terminate different spans for different lightpaths. This determines also the power level of the lightpaths passing through the node. Since ROADM nodes are equipped with VOAs and perform power equalization, two lightpaths reaching the node with different power levels will exit the node with the same power according to the lightpath(s) with the lowest power level. In fact, since both lightpaths pass through node C, the VOA at the node will allow the lightpaths to have the same power after node C[1]. The ILA in link C-D terminates two different spans for both lightpaths and thus its gain is set so that it compensates for the span of highest loss (lightpath A-D). Its gain considers the loss in span L_1, L_3 and the loss of node C (L_C) amounting to 27 dB.

Regarding the P_{REC} constraint, since the gain of OAs along both paths is set to compensate for the losses in each span they terminate, also the P_{REC} constraint is met for both lightpaths[2]. Let us observe the calculation of the received power for lightpath B-D:
P_{REC} = P_{TX}-L_B-L_2+G-L_C-VOA_C-L_3+G-L_4-L_D+G = -5-8.5-10+18.5-17-5-5+27-17.5-8.5+26 = -5dBm. Node losses are noted according to node id (L_B is loss due to node B), propagation losses by the span id (L_2 is loss in link B-C), VOA_C is the VOA attenuation at node C and OA gains as G.

In conclusion, the same principle of OA placement shown in this example can be followed in more complex scenarios and may lead to significant cost savings in terms of placed OAs.

III. PROPOSED STRATEGY FOR OPTICAL AMPLIFIER PLACEMENT AND ROUTING AND SPECTRUM ASSIGNMENT

A. Problem Statement

The problem of RSA-AP placement can be formally stated as: **Given** a metro network topology, set of traffic demands (characterized by source and destination nodes, bit-rate request and modulation format) and set of candidate locations of optical amplifiers, **decide** the routing and spectrum allocation to all traffic demands and placement of OAs, **constrained by _i)_** quality-of-transmission constraint (sufficient OSNR and received power) of all traffic demands, **_ii)_** spectrum continuity and contiguity constraints, **_iii)_** network capacity constraints and **_iv)_** amplifiers gain range constraint with the **Objective** of minimizing the total cost of deployed OAs.

B. RSA-AP heuristic approach

The flow chart of MinOA heuristic algorithm is shown in Fig. 3. The algorithm is constituted by two main intertwined phases:
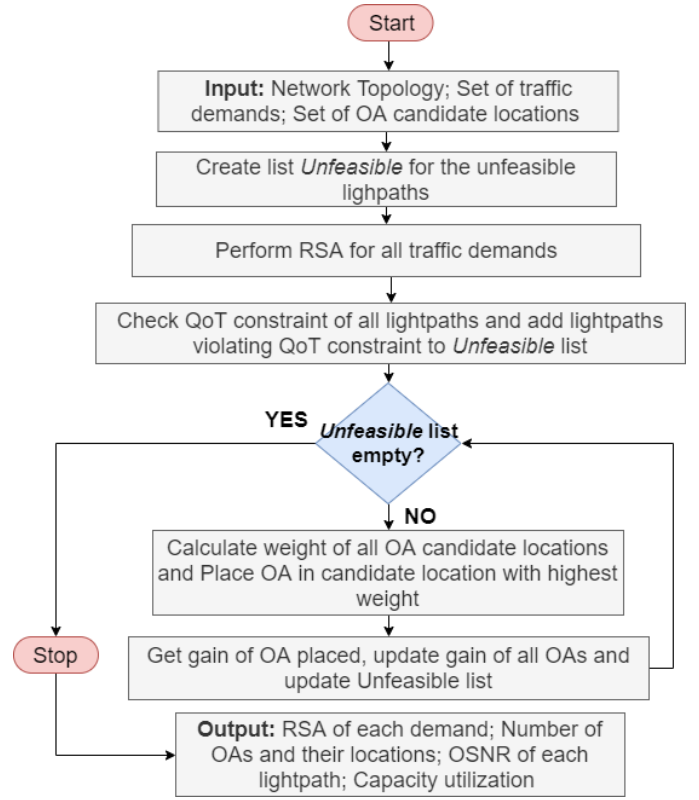

Figure 3. Heuristic flowchart

1) RSA for traffic demands and 2) Optical Amplifier Placement.

1) Routing and Spectrum Allocation

To perform the routing of lightpaths, we consider two routing algorithms, _i)_ Shortest-Path (_SP_) routing, which, for each demand, utilizes the path with minimum distance in kilometers, i.e., corresponding to minimizing the fiber propagation loss[3], and _ii)_ Minimal-Loss (_ML_) routing, which routes a lightpath on the path with the minimum loss on the end-to-end path, i.e., the sum of node losses and propagation losses minus the sum of the gain of OAs in the path. Fig. 4 shows a ring-link section of a metro network over which we can compare the routing of a
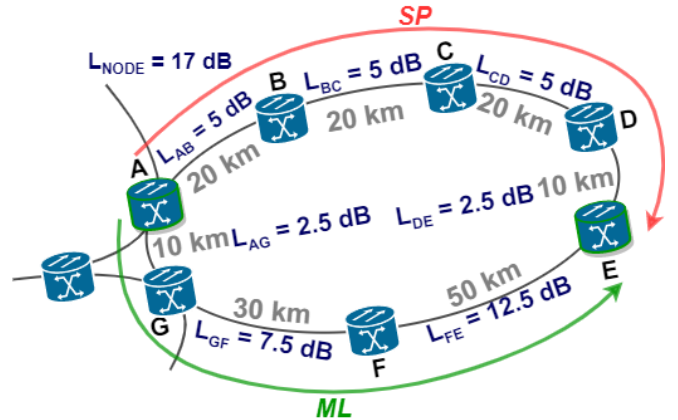

Figure 4. Sample topology used to compare _ML_ vs _SP_ routing

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[1] Note that we model a ROADM node as a fiber span of 68 km (equivalent to 17 dB loss). We assume that no non-linear interference (NLI) is generated along the fiber span which mimics the ROADM node. Note also that, in case of no pre-amplifier and booster being located at a node, only the fiber span located before the node is accounted when calculating NLIs (non-linear efficiency parameter η).

[2] Considering that the two lightpaths have different first spans, their launch power is slightly different and dependent on the span characteristics, as per LOGO principle.

[3] Note that this holds as we assume that all the fibers in the network have the same attenuation coefficient (0.25 dB/km).

lightpath from node *A* to node *E,* by using the two routing algorithms, *SP* and *ML*. With *SP* routing algorithm, the lightpath is assigned to path *A-B-C-D-E* with a total length of 70 km (total loss is 85.5 dB), while with *ML* algorithm, the lightpath is assigned the path A-G-F-E, having a total length of 90 km and total loss of 73.5 dB. As for the spectrum assignment, we consider flex grid spectrum allocation with first-fit allocation policy.

After the RSA of all traffic demands is performed, the OSNR and P_{REC} values are calculated for all the demands, which are then distinguished between feasible and unfeasible. A demand is considered unfeasible if its OSNR and/or P_{REC} are below the corresponding threshold values. Unfeasible lightpaths are then inserted in a list called *unfeasible lightpaths.*

2) Optical Amplifier Placement

MinOA evaluates placing an OA in each candidate OA location considering its impact on the OSNR and P_{REC} of the lightpaths traversing the location, as well as the cost of the OA to be deployed at that location, which is determined according to the required OA gain, and hence on the amplifier type.

We determine the weight of each candidate OA location using a ***"weight function"*** and, at each iteration, the candidate OA location with highest weight is selected and an OA is deployed there. Considering the importance of the weight function in our approach, we modelled several weight functions and compared their performance over different network instances and then considered the weight function which led to the best performance.

The weight of a candidate location *j*, w_j, is given by the sum of the OSNR improvements plus the sum of a feasibility parameter for all unfeasible lightpaths passing through that location, all divided by the cost of the OA considered for location *j*, as in (7).

$$w_j = \frac{\sum_{i \in I}(F_i + \Delta OSNR_i)}{c_j} \qquad (7)$$

where, *i)* $\Delta OSNR_i$ is the OSNR improvement for unfeasible lightpath *i* achieved thanks to the placement of OA at location *j* taking into account the current OSNR value ($OSNR_{i,now}$) and the OSNR in the previous iteration ($OSNR_{i,prev}$) and given as:

$$\Delta OSNR_i = OSNR_{i,now} - OSNR_{i,prev} \quad [dB] \quad (8)$$

ii) The feasibility parameter for lightpath *i*, F_i, depends on the OSNR of lightpath *i* ($OSNR_i$) and the received power of lightpath *i* ($P_{REC,i}$) in current iteration and is defined as:

$$F_i = \begin{cases} 2, if\ OSNR_i > threshold\ and\ P_{REC,i} > threshold \\ 1, \qquad\qquad otherwise \end{cases} \quad (9)$$

If an unfeasible lightpath *i* which passes through location *j* will become feasible ($OSNR_i$ > threshold and P_{RECi} > threshold) by

placing an OA in *j*, its feasibility parameter is considered to be twice compared to the case when it remains unfeasible.
iii) C_j is the cost of the OA type which depends on the gain, noise figure and location placed, as detailed later in Sec. IV.

After the placement of a new amplifier at each iteration, the optical spans in the network and the gain and noise figure of all the existing amplifiers are updated accordingly, i.e., considering the optimal input power at each span as provided by the LOGO approach, and the OSNR and P_{REC} of all lightpaths are calculated and the lightpaths which now meet the QoT constraint are removed from the list of *unfeasible lightpaths*. Finally, *minOA* stops when no more unfeasible lighpaths exist in the network, i.e., when all the lightpaths in the network meet their QoT requirements. If unfeasible lightpaths are still present in the network, *minOA* starts a new iteration to place a new amplifier until no more unfeasible lightpaths are present in the network or when no other OA candidate location is available.

IV. NUMERICAL RESULTS

We numerically evaluate the *MinOA* algorithm, by considering three scenarios which differ in the initial deployment of OAs, i.e.: *1) MinOA*, representing the proposed approach where we assume a green-field scenario where no amplifiers are deployed at the beginning in the network, *2) MinOA-bst*, where we assume an initial deployment with boosters in all network nodes, and *3) MinOA-pre*, assuming an initial deployment with pre-amplifiers in all network nodes. For each case we consider the two routing algorithms described previously, *ML* and *SP* resulting in 6 cases (*SP-MinOA, SP-MinOA-pre, SP-MinOA-bst, ML-MinOA, ML-MinOA-pre, ML-MinOA-bst*). Furthermore, we compare the 6 MinOA versions against two baseline amplifier placement approaches, where we assume boosters and pre-amps deployed at all network nodes and assuming ML routing (ML-Baseline) and SP routing (SP-Baseline). Baseline OA deployment assumes that the booster amplifier is set to compensate for the node loss whereas the pre-amp for the span it terminates. ILA amplifiers are placed approximately every 60 km (corresponding to a gain of 15 dB). Note that this assumption might be slightly adjusted, depending on the length of the fiber. If the length of the link is longer than 60 km, an ILA is placed in the middle of the link. For example, if the length of the link is 80 km, an ILA is placed in the middle of the link, e.g., at 40 km. However, if the length of the link is 120 km or longer, ILAs are placed approximately every 60 km. Overall, 6 different scenarios of *MinOA* and 2 versions of baseline approach are considered in our study, as summarized in Table II[4].

Finally, in our results we consider two cases regarding the deployment of amplifiers in candidate locations: 1) *location-unconstrained*, where any type of amplifier can be deployed in any location, and 2) *location-constrained*, where the type of amplifier deployed in a specific location has to correspond to location characteristics. The cost of each amplifier type is

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[4] Note that, as in our heuristic the routing is performed in the first step and does not change with the execution of the OA placement, for all the strategies adopting *SP*, routing of lightpaths does not depend on the initial OA deployment. Conversely, the initial OA deployment affects the routing in case

ML is adopted as, besides the loss contributions between source and destination nodes, when calculating loss along a path *ML* routing considers also the gain of pre-deployed amplifiers.

according to field observations and reflects the characteristics (gain and noise figure) of OAs. We assume the cost of a *booster* is 1 cost unit (*cu*) while the cost of a *pre-amp* is assumed equal to 1.2 *cu*. If deployed as an ILA, the cost of an amplifier assumes 0.8 additional *cu* accounting for the additional site cost, and so it is 1.8 *cu* if a *booster* type is deployed and 2.0 *cu* if a *pre-amp* type is deployed.

Table II. Different OA placement scenarios

Approach	Routing	Placement	Pre-deployed
SP-MinOA	*SP*	MinOA	None
SP-MinOA-bst	*SP*	MinOA	Boosters
SP-MinOA-pre	*SP*	MinOA	Pre-amps
ML-MinOA	*ML*	MinOA	None
ML-MinOA-bst	*ML*	MinOA	Boosters
ML-MinOA-pre	*ML*	MinOA	Pre-amps
SP-Baseline	*SP*	Baseline	Boosters, pre-amps and ILAs
ML-Baseline	*ML*	Baseline	Boosters, pre-amps and ILAs

A. Validation of the heuristic

In order to validate the effectiveness of *MinOA*, we compare its performance with that of brute force (*Brute*) approach. Note that a comparison with an optimal ILP-based placement is not possible due to the non-linear nature of the problem. We considered several case studies varying network topology, length of links and number of candidate locations. In Table III we report the results for *MinOA* and *Brute* for one topology composed by 8 nodes and 16 links. We increase the length of the links and consequently increase the number of candidate locations. Fig. 5 shows the topology considered for the validation of the heuristic.
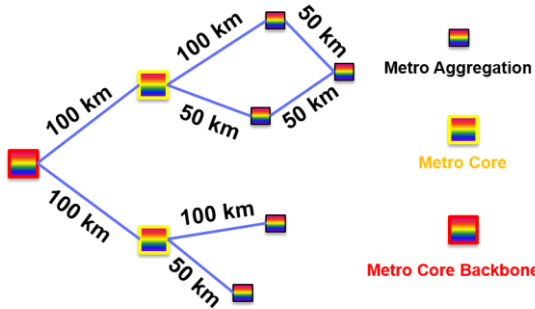

Figure 5. A sample section of a metro network topology (the case study with 40 amplifier candidate locations)

We consider a full-mesh traffic matrix with 100 Gbps and DP-QPSK demands. Results show that the overall cost of amplifiers considering *MinOA* is comparable to that of *Brute*, as the cost difference is always below 7%. Even if for such a small network instance, *Brute* has a computational time in the order of days, whereas *MinOA* provides a solution in order of minutes.

Table III. Total cost of amplifiers (*cu*) for *MinOA* and *Brute*

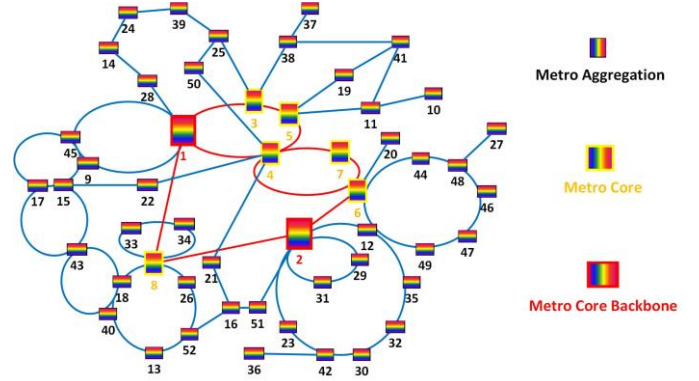| Nr. of candidate loc.	32	34	36	38	40
MinOA	34.2	37.8	42.4	45	48.6
Brute-force	32.2	35.8	40.4	42	45.6
Difference [%]	5.8	5.2	4.7	6.7	6.2

Figure 6. Schematic representation of 52Node-Metro network topology

B. Numerical results and discussion

We now consider two realistic metro topologies, referred to as 52Node-Metro (Fig. 6) and 159Node-Metro (Fig. 8). Characteristics of the two network topologies are shown in Table IV. The topologies include three types of network nodes, core-backbone, metro-core and metro-aggregation nodes.

Table IV. Characteristics of metro topologies considered

Network	52Node-Metro	159Node-Metro
Nodes	52	159
Links	144	438
Diameter	140 km	230 km
Max/min length	200 / 1 km	240 / 1 km
# Cand. OA loc.	402	1144

We consider full-mesh bi-directional traffic demands between metro-core and metro-core backbone nodes, and bi-directional traffic demands between metro-aggregation nodes and nearest metro-core nodes, simulating traffic exchanged between regional data centres and end-users. We consider frequency slot units (FSUs) of a granularity of 12.5 GHz and a 5 THz spectrum capacity, i.e., equivalent to 400 FSUs per link. We consider 100 Gbps and 200 Gbps traffic with DP-QPSK modulation format. Specifically, the traffic demands generated between metro-core and metro-core backbone nodes are 200 Gbps bitrates whereas the traffic demands between metro-aggregation nodes and nearest metro-core nodes are 100 Gbps. Each 100-Gbps traffic demand occupies a channel of 37.5 GHz, i.e., 3 FSUs, while each 200-Gbps traffic demand occupies a channel of 75 GHz, i.e., 6 FSUs.

Note that the feasibility of each demand depends on guaranteeing an OSNR threshold of **13 dB** and minimum received power P_{REC} of **-18 dBm**. Fig. 7 shows the overall cost of OAs deployed for each OA deployment strategy including baseline approach. Moreover, we show in Table V the minimum and average OSNR values in each of the cases.

1) MinOA vs. Baseline

Comparing the various versions of *MinOA* to the baselines, we observe that *MinOA* achieves cost savings between 26% and 30% in the location-unconstrained case, and between 30% and 35% in the location-constrained case.
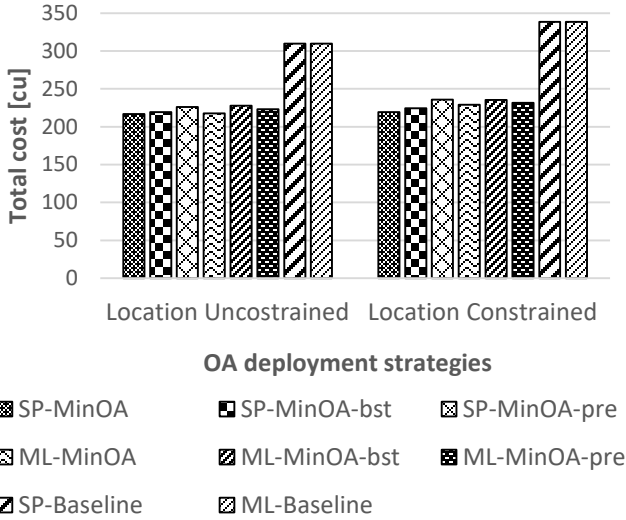
Figure 7. Total cost of OAs deployed for 52Node-Metro network

Table V. OSNR characteristics in dB for the different OA deployment strategies considered

Strategy	Location Unconstrained	Location Constrained
	minOSNR (avgOSNR)	minOSNR (avgOSNR)
SP-MinOA	13.67 (20.95)	13.38 (20.02)
SP-MinOA-pre	13.10 (18.75)	13.03 (17.37)
SP-MinOA-bst	14.48 (21.02)	13.99 (20.30)
ML-MinOA	14.70 (21.26)	14.77 (20.53)
ML-MinOA-pre	14.30 (18.91)	14.20 (17.57)
ML-MinOA-bst	14.16 (21.27)	14.00 (20.66)
SP-Baseline	13.82 (20.81)	13.01 (17.98)
ML-Baseline	13.19 (20.74)	13.00 (18.23)

This is because *MinOA*, at each iteration, places amplifiers in locations which mostly improve OSNR and P_{REC} of lightpaths, avoiding the deployment of unnecessary amplifiers. The baseline approach, however, places amplifiers at all network nodes, which penalizes the overall cost of amplifiers. Referring to Table V, which shows minimum and average OSNR values for each OA deployment strategy, we can also observe that cost savings by *MinOA* are achieved while maintaining a comparable performance in terms of OSNR. Specifically, we note a reduction in the case of *SP-MinOA-pre* of 0.72 dB in terms of minimum OSNR and 2.06 dB in terms of average OSNR in comparison to the baseline, i.e., *SP-Baseline*. Note that, in some cases, as for location-unconstrained *ML-MinOA-bst* the minimal OSNR and average OSNR values are higher with respect to baseline for 0.97 dB and 0.53 dB, respectively.

2) Location-Constrained vs. Location-Unconstrained
Now we focus location-unconstrained vs location-constrained amplifier placement. Fig. 7 shows that unconstrained amplifier deployment permits cost savings up to 8% for the baseline and between 2% and 5% for the various versions of *MinOA*. Moreover, as shown in Table V, the unconstrained deployment provides advantages also in terms of minimum and average

lightpaths OSNR. Specifically, in case of *SP-MinOA*, location-unconstrained deployment reaches 0.29 dB higher minimal OSNR compared to location-constrained and in case of *ML-MinOA-pre*, location-unconstrained reaches 1.34 dB higher average OSNR compared to location-constrained. The OSNR improvement is due to the fact that, with the location-unconstrained deployment, *MinOA* places amplifiers with lower gain ranges, hence, compared to the location-constrained case, less ASE noise is introduced.

3) Effect of the Routing Algorithm: SP vs. ML
Now we focus on the effect of the routing algorithm on the OA placement. Overall, *SP* and *ML* routing algorithms show comparable results in terms of OA cost, but, considering OSNR (see Table V), *ML* routing provides significantly better performance compared to *SP* routing. This is because *ML* routing assumes paths with minimum loss (in case no amplifiers are pre-deployed) or paths with highest compensation of loss (in case amplifiers are pre-deployed) thus achieving overall better minimum and average OSNR values.

Table VI. Spectral occupation (in #FSUS) for each routing algorithm

Routing algorithm	SP	ML	ML pre-deployed
Total number of FSUs	2817	2226	2289

Now, we observe the spectrum occupation for each routing algorithm. Note that the spectrum occupation per demand is calculated as the number of FSUs needed for that demand, times the number of links the demand traverses. For example, a demand carrying 100 Gbps, i.e. 3 FSU, and traversing 4 links, occupies 12 FSUs in total. The total spectrum occupation is given by the total number of FSUs for all the traffic demands in the network. We note that the two algorithms show different overall spectrum occupation (see Table VI). *ML* routing utilizes 19% to 22% less spectrum with respect to *SP* routing, because, given the relatively short links length, *ML* routing tends to accommodate lightpaths on routes with low number of nodes, since they introduce a significant loss, and consequently lower number of links, thus reducing occupied spectrum. Conversely, *SP* routing focuses on lightpaths length, i.e., it aims at reducing propagation losses only, so it routes lightpaths on paths with high number of links (note that the link lengths are relatively short in metro).

4) Further Analysis on larger topologies
We now consider only ML routing and location-unconstrained amplifier deployment (the strategy with best results) to extend our analysis on a larger reference network, as shown in Fig. 8 (characteristics shown in Table IV).
Table VII shows the total cost as well as average and minimum OSNR for different deployment strategies adopting *ML* routing and location-unconstrained OA placement.
Results show that *ML-MinOA* achieves 48% of cost savings with respect to baseline, and 35% (respectively, 36%) with respect to *ML-MinOA-pre* (respectively, *ML-MinOA-bst*).
In terms of OSNR, *MinOA* performs comparably to Baseline in terms of OSNR with an exception of a penalty of 1.98 dB in average OSNR for the case of *MinOA-pre*.
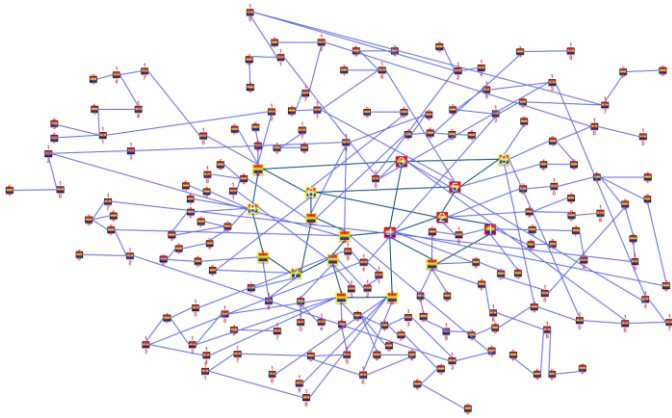
Figure 8. Schematic representation of 159Node-Metro network topology

This shows that in metro networks, where number of nodes is relatively high, a green-field deployment of amplifiers is largely preferred to significantly reduce the deployment of unnecessary amplifiers and therefore their cost.

Table VII. Cost in *cu* and OSNR in dB for 159Node-Metro topology

Strategy	Cost	minOSNR (avgOSNR)
ML-MinOA	466.8	13.17 (21.45)
ML-MinOA-pre	583.6	13.30 (19.41)
ML-MinOA-bst	582.6	13.01 (21.42)
ML-Baseline	909.6	13.04 (21.39)

V. CONCLUSION AND FUTURE WORK

The OA placement problem is a complex cross-layer non-linear optimization problem. We propose a novel optimization algorithm for the deployment of OAs in metro networks. We consider placement of amplifiers along fiber links and at network nodes. We evaluate the impact of considering different types of OAs, different routing algorithms and OA placement strategies. Numerical results obtained over realistic metro network topologies show that significant savings in total cost of OAs up to 48% are achieved in comparison to baseline OA placement strategies. Moreover, we also consider the case in which placement of different types of OAs is not constrained to specific locations, achieving further savings in total OA cost and higher ONSR (up to 1.34 dB) with respect to the location-constrained placement. We also observe that minimal-loss routing leads to higher overall OSNR, increasing average OSNR up to 0.31 dB compared to shortest-path routing.

As future work, we observe that one of the main drawbacks of *MinOA* is its greedy nature in placing OAs, i.e., once an OA is placed, its placement is not re-discussed. We are currently investigating evolutionary algorithms, i.e., genetic algorithms, that allow more effective exploration of search space. We are also investigating impact of OA gain ripple in this problem.

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