Routing and Spectrum Allocation with Amplifier Placement in Elastic Metro-Aggregation Networks

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Abstract

We propose a quality-of-transmission (QoT) aware heuristic algorithm for the placement of amplifiers in elastic metro-aggregation networks with the objective of minimizing their number while guaranteeing lightpaths' QoT. Results show that optimized amplifier placement can lead to significant reduction of amplifiers with respect to baseline approaches.

1 Introduction

Today's Metro-Aggregation Networks (MANs) must be designed considering the unprecedented capacity that will be required in 5G communications as well as by the increasing amount of customers connected through Fiber-To-The-Home. Network operators are hence urged to devise new technical solutions to increase MANs' capacity while keeping network cost under control, both in terms of capital expenditures (Capex) and operational expenditure (Opex).

Several cost-effective MAN architectures are being investigated, as, e.g., those based on optical packet switching [1], time-domain wavelength interleaved networks [2], or "filterless" networks where active switching devices (e.g., wavelength selective switches) are replaced with passive devices, e.g., optical splitters and combiners [3]. However, deployment of these advanced MAN architectures presents several technical challenges for operators in the short-medium term. Hence, while the development of these architectures is posed for future considerations, operators are now considering solutions to minimize costs when deploying MANs based on state-of-the-art technologies.

A possible approach to minimize costs is to save on number of optical devices to be deployed and to minimize the number of active sites in the MAN infrastructure. In particular, taking advantage of the relatively short distances in metro networks, operators can aim to minimize the number of optical amplifiers needed to guarantee quality-of-transmission of lightpaths. The cost-effectiveness deriving from minimizing the amplifiers in the network is two-fold. Cost-savings are achieved by minimizing the overall number of optical inline-amplifiers located along the fiber and pre-amplifiers located at network nodes (leading mostly to a Capex reduction). Moreover, minimizing the number of inline-amplifiers yields further cost savings as it reduces the number of operational sites in the MAN (central office, cabinets, amplifier huts) to be equipped, managed and maintained (leading to both Capex and Opex savings).

In this work, we investigate how to optimally place optical inline- and pre-amplifiers in elastic MANs with the objective of minimizing the number of deployed amplifiers, while guaranteeing feasible (acceptable) quality-of-transmission (QoT) for all requested lightpaths. Overall, the optimization problem to be addressed can be summarized as *QoT-aware Routing and Spectrum Allocation with Amplifiers' Placement (RSA-AP).* In particular, we solved the RSA-AP problem in MANs employing coherent detection and uncompensated transmission techniques, which allowed us to make use of well-known analytical non-linear propagation models [4]. Note that, since amplifier placement has a strong impact on the performance of optical signal transmissions, solving the RSA-AP problem requires accurate physical layer modelling to capture the impact of amplifier placement on the Quality-of-Transmission, i.e., on the Optical Signal-to-Noise Ratio (OSNR) of lightpaths. This optimization problem has received very little attention in the optical networking literature, as most works assume optical-amplifier deployment as a given (hence avoiding to deal with the non-linear nature of this problem). Only Ref. [5] has recently investigated the amplifier placement problem, focusing on the placement of Raman amplifiers and regenerators in long-haul networks, and Ref. [6] considered the selective upgrade of inline amplifiers based to Hybrid Raman/Erbium Fiber Amplifiers with the objective of reducing the number of OEO regenerators.

2 QoT-Aware Routing and Spectrum Allocation with Amplifier Placement

The problem of QoT-Aware RSA-AP can be formally stated as follows: **Given** a MAN topology, a set of traffic demands (characterized by source and destination nodes and bit-rate request) and candidate locations of optical amplifiers, **Assign** route and spectrum to all traffic demands and **Place** OAs, **While** guaranteeing ***i)*** quality-of-transmission constraint (sufficient OSNR) of all traffic demands, ***ii)*** receiver received power constraint (in case of a pre-amplifier placement) ***iii)*** spectrum continuity and contiguity constraints and ***iv)*** network capacity constraints (number of Frequency Slot Units (FSUs)), with the **Objective** of minimizing number of OAs deployed. To solve this problem, we developed a novel heuristic approach, called *MinOA*, shown in Fig. 1, which performs two main tasks: **1)** RSA of traffic demands and **2)** Placement of Optical Amplifiers.

MinOA starts by **1)** performing RSA (using two possible **routing algorithms** that will be described later on) and then calculates the OSNR of each routed lightpath. For physical-layer modelling, we consider the Local Optimization - Global Optimization (LOGO) approach based on the Gaussian Noise model which allows us to ***i)*** estimate the total ASE and NL and thus the total Optical Signal to Noise Ratio (OSNR) and ***ii)*** maximize the OSNR of a lightpath by selecting the optimal launch power into each span. If received OSNR is below the OSNR threshold, the demand is inserted into a list of unfeasible lightpaths (i.e., not meeting QoT constraint). **2)** After all demands are checked, an iterative OA placement procedure takes place, in which we perform an estimation of the significance of each candidate OA location, taking into consideration the possible effect of an OA placement on all the traffic requests. This assessment is determined according to a ***'weight function'*** (to be described later on) which aims at capturing the importance of placing an OA in each candidate location. Once the weight of all candidate OA locations is calculated, an OA is deployed at the candidate location with highest weight and the gain of the amplifier is calculated according to span-loss. Specifically, we consider a gain range between 10-30 dB for both inline amplifiers and pre-amplifiers. Note that once an OA is placed, the optical between each two consecutive amplifiers in the network may get modified and thus the algorithm re-calculates and re-sets the gain of already deployed amplifiers accordingly. Then, the candidate location chosen is removed from the list of candidate locations, the new OSNR of each of lightpaths is re-calculated and the lightpaths which now meet the QoT constraint (thanks to the placement of a new OA) are removed from the list of unfeasible lightpaths. Then, next iteration starts. The stopping condition is met when the list of unfeasible demands is empty. **Routing Algorithms:** We consider two routing algorithms, ***i) shortest-path routing*** which chooses the shortest path in km, and ***ii) OSNR-aware routing*** which chooses the demand's route with the maximum OSNR. For both routing algorithms we consider a first fit spectrum allocation. **Weight Function:** The weight function estimates the significance of an OA candidate location in terms of improving the overall average OSNR and reducing the number of unfeasible lightpaths. Due to its decisive role in the heuristic, we modelled several weight functions and compared the performance of the heuristic approach for each weight function over different network instances. In the rest of the paper, we only describe the weight function which led to the best performance. The weight function for a candidate location *j*, w_j, is represented as the sum of the product of the relative improvement of an unfeasible lightpath *i*, $\frac{\Delta OSNR_i}{OSNR_{i,prev}}$, and its feasibility parameter, F_i, for all unfeasible lightpaths, as follows: $w_j = \sum_{i \in I} \frac{\Delta OSNR_i}{OSNR_{i,prev}} \, x \, F_i$ where $\Delta OSNR_i$ is the variation of the OSNR of lightpath *i* due to placement of an OA at location *j*, and $OSNR_{i,prev}$ is the OSNR of lightpath *i* at the previous iteration, and where:

$$F_i = \begin{cases} 1 + \Delta OSNR_{avg,} & if\ i\ becomes\ feasible \\ 1, & Otherwise \end{cases}$$

where $\Delta OSNR_{avg}$ is the difference between the OSNR at current iteration initial average OSNR found at the start of the evaluation. Note that the weight function is modelled to favour, at the start of the evaluation, the candidate locations allowing largest improvement in terms of OSNR, even if they do not allow lightpaths to meet QoT constraints. Then, as the overall average OSNR ($OSNR_{avg}$) improves, the weight function favours candidate OA locations permitting highest number of lightpaths to become feasible.

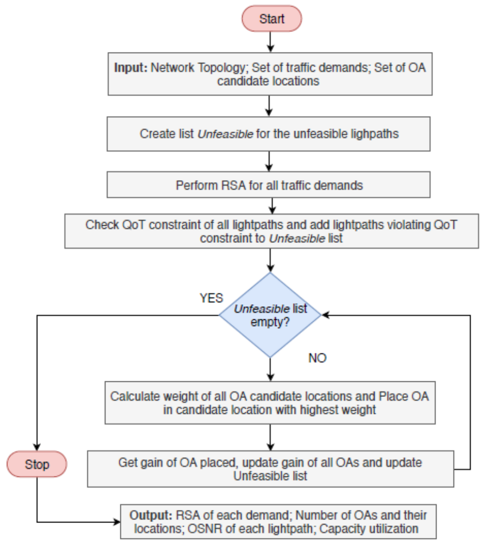

Figure 1 *MinOA* flow chart

3 Results

We consider two alternative versions of *MinOA*: 1) *OSNR-MinOA* (*OSNR-aware routing*) and 2) *SP-MinOA* (*shortest-path routing*). We first validate their performance and then compare it to a baseline approach (explained later on) assuming real MAN topologies.

4.1 Validation of Heuristic Approach

To validate the effectiveness of the *MinOA*, we first compare its performance with that of a brute force approach (note that a comparison with ILP was not recommended due to non linear nature of the problem). Specifically, we considered a brute force approach (i.e., we explored all possible solutions) to check if a solution exists assuming a number of OAs lower than that found by *MinOA* for several case studies.

Table 1: Validation of heuristic vs. brute force results

Approach	OAs deployed	$OSNR_{avg}$ (dB)
Brute force	12	24.0212
OSNR-MinOA	12	24.0212
SP-MinOA	12	23.9524

In Table 1 we report results of *OSNR-MinOA and SP-MinOA* and that of the brute force for a topology consisting of 6 nodes and 16 links (avg length of 120 km) assuming 48 candidate locations and full-mesh 200Gpbs demands. Results show that number of OAs deployed by both versions of *MinOA* equals that of the solution found by the brute force approach, i.e., 12 OAs, which validates their performance.

Moreover, *OSNR-MinOA* and brute force considered same OA deployment as they show the same $OSNR_{avg}$ value.

Table 2: Characteristics of MAN topologies considered.

Network:	Small	Large
# of nodes	52	159
# of links	144	438
Diameter	140 km	230 km
Max/min length	200/1 km	240/1 km
# candidate OA	120	250

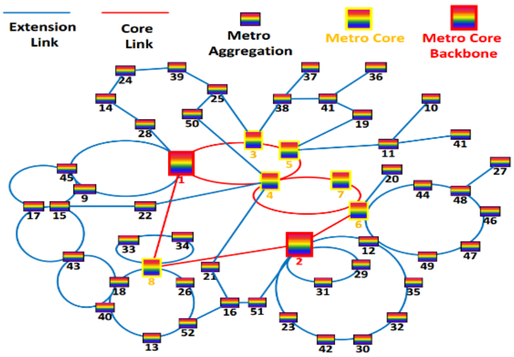

Figure 2 Schematic representation of Small network topology

4.2 Numerical Results and Discussion

We consider two real MAN topologies (referred to as *Small* and *Large*). Number and position of candidate OA locations per link are generated according to link's length. Both topologies contain three node types: core-backbone, metro-core and metro-aggregation nodes. Table **2** shows network settings and Figure **2** shows a schematic representation of small topology. We assume traffic demands between each node-pair of metro-core and metro-aggregation nodes (simulating traffic generated from regional data centers deployed at metro nodes towards end-users) with bit rates of either 200G or 400G, and a lower amount of 100G-traffic demands originated and terminated at metro-aggregation nodes. We assume 16-QAM modulation for all traffic demands. As a baseline comparison strategy, we assume a fixed amplifier gain of 15 dB, which translates to an amplifier placement every 68 km (0.22 dB/km attenuation), and that all nodes are equipped with pre-amplifiers. In the baseline strategy, demands are routed along the shortest path.

Table **3** and Table **4** show the number of inline and pre-amplifiers deployed considering *MinOA* versions and the baseline approach, for the *Small* and *Large* network topologies, respectively. Note that, we evaluate *OSNR-minOA* in two cases: ***1)*** when optical nodes are already equipped with pre-amplifiers (*OSNR-MinOA-pre*), and ***2)*** when pre-amplifiers are not deployed and are also considered as candidate locations, (*OSNR-MinOA-no-pre*). Results show that, when considering pre-amplifiers at all nodes, *OSNR-MinOA-pre* and *SP-MinOA-pre* achieve around 25% and 20% reduction in number of inline amplifiers with respect to baseline strategy (10 and 12 instead of 16 for *Small* and 22 and 24 for *Large*), respectively. For a network operator, this reduction reflects mostly in savings in terms of number of operational sites. In terms of $OSNR_{avg}$, *OSNR-MinOA-pre* and *SP-MinOA-pre* shows a value which is slightly lower, yet comparable, than that of the baseline. For the case when pre-amplifiers are not pre-deployed (and also become candidate locations), our proposed *OSNR-MinOA-pre* algorithm shows a very large reduction in the overall number of amplifiers with respect to baseline strategy (51 instead of 160 for *Small* and 83 instead of 466 for *Large*) while deploying significantly more inline amplifiers (24 instead of 16 for *Small* and 54 instead of 28 for *Large*).

Table 3: Results obtained for *Small* network topology.

	OAs deployed [pre + inline]	$OSNR_{avg}$ (dB)
Baseline strategy	160 [144 + 16]	27.387
SP-MinOA-pre	156 [144 + 12]	26.8015
OSNR-MinOA-pre	154 [144 + 10]	27.0635
OSNR-MinOA-no-pre	**51 [27 + 24]**	**27.8297**

Table 4: Results obtained for *Large* network topology.

	OAs deployed [pre + inline]	$OSNR_{avg}$ (dB)
Baseline approach	466 [438 + 28]	26.6117
SP-MinOA-pre	462 [438 + 24]	26.2051
OSNR-MinOA-pre	460 [438 + 22]	26.0893
OSNR-MinOA-no-pre	**83 [29 + 54]**	**27.5056**

The cost efficiency of our proposed solution is very promising in terms of CapEx savings, however it requires further investigation in terms of OpEx due to the higher number of inline amplifiers, i.e., higher number of operational sites outside the main network nodes. As for $OSNR_{avg}$, *OSNR-MinOA-no-pre*, even though it deploys less number of amplifiers, it shows a slightly higher value than that of other strategies. This is achieved thanks to QoT-aware routing and to gaining more freedom in deploying amplifiers at significant locations as pre-amplifiers are also considered candidate locations. Finally, we note that the *OSNR-aware* routing requires about 5% to 10% higher average link occupation than shortest path routing, which seems to be an acceptable price to pay for a significant amplifier reduction.

4 Conclusion

We defined a Routing and Spectrum Allocation with Amplifier Placement problem and provided a QoT-aware heuristic that minimizes the number of amplifiers while guaranteeing lightpaths' QoT in elastic MANs. Results show that significant reduction in number of amplifiers can be achieved by optimized amplifier placement with respect to baseline approaches.

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