# Optical Metro Network Design with Low Cost of Equipment

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*Abstract*—New arising 5G services will pressure optical metro networks with unprecedented requirements. As operators' revenues are not scaling accordingly, several technical directions to design low-cost optical metro networks are being investigated. In this study we observe that operators can *jointly* i) enforce Filterless Optical Network (FON) architecture, hence removing costly Wavelength Selective Switches, ii) leverage relatively short links in metro networks to reduce the number of optical amplifiers (OAs), iii) place amplifiers intelligently to maximize signal quality (SNR), hence employing higher-order modulation formats (MF) and reducing the number of transponders. To quantify the achievable cost-reduction we develop a Quality-of-Transmission (QoT) aware planning tool, based on Genetic Algorithm, for joint optimization of fiber tree establishment (inherent to FON), OA placement and MF assignment. Results obtained over a realistic topology show that the proposed design achieves overall (4-8)% equipment cost savings compared to baseline optical network deployment, without affecting QoT.

*Index Terms*—Cross-layer network optimization, Filterless Optical Network, Optical Amplifiers, QoT-aware planning

## I. INTRODUCTION

To satisfy the ever-growing capacity demand and keep revenues stable, operators are always looking into new approaches to network design that lead to cost savings. A significant cost reduction can be achieved by cutting down equipment cost, typically by deploying less transponders, switching devices (e.g., Wavelength Selective Switches, WSSs) and optical amplifiers (OAs), while preserving network capacity.

*Transponders*. Coherent transmission has enabled the use of higher-order modulation formats (MFs) that allow to provision the same volume of traffic with fewer transponders. Two recent research directions suggest either to reduce system margins and operate closer to the maximum transmission capacity [1] or to expand this capacity by using advanced noise-resilient coding and constellation shaping [2]. Despite significant progress, saving transponders remains one of the highest research priorities, due to their high cost and energy consumption.

*Switching devices*. It has been observed that Filterless Optical Network (FON) [3] allows to remove complex and costly Wavelength Selective Switches from the traditional Wavelength Switched Optical Network (WSON), by substituting them with passive splitters and combiners that operate on the entire frequency band (see node architecture in Fig. 1). In FON optical signals at the input ports of a node are broadcasted to all its output ports. This might create undesirable loops, as

signals, if caught in a loop, infinitely accumulate noise from amplifiers. Hence, FONs must be divided into loop-free edge-disjoint fiber trees by physically limiting the default all-to-all interconnection of fibers in the nodes. This process of loop removal is called Tree Establishment (TE) [3]. Note that no wavelength in the fiber tree can be reused, as signals propagate into adjacent links even beyond the receiver. However, this is acceptable in metro-aggregation networks, where traffic is localized and can be provisioned in small fiber trees [4], [5]. For such networks, FON is a promising architecture due to its lower cost and energy consumption and reduced maintenance and repair expenses for passive devices. In Ref. [6] we estimated savings in the order of (3-4)%, although neglecting aspects related to physical layer performance.

*Optical Amplifiers*. Even though OAs are much cheaper than transponders and WSSs, in metro networks with relatively short links we can benefit from avoiding to place them at all input and output node ports (see Fig. 1) and at regular intervals along the fibers, as it is traditionally done. Ref. [7] shows that we can remove up to 55% of OAs in FON networks without deteriorating Signal-to-Noise Ratio (SNR).

In this paper, for the first time to the best of our knowledge, we investigate the savings that can arise from the joint consideration of the three factors discussed above: (i) removal of WSSs (that requires a TE in FON), (ii) optimized OA placement, (iii) optimized selection of transponders (note that we consider multiple MFs). Joint minimization of the numbers of the three devices (WSSs, amplifiers and transponders) is expected to be the low-cost design.
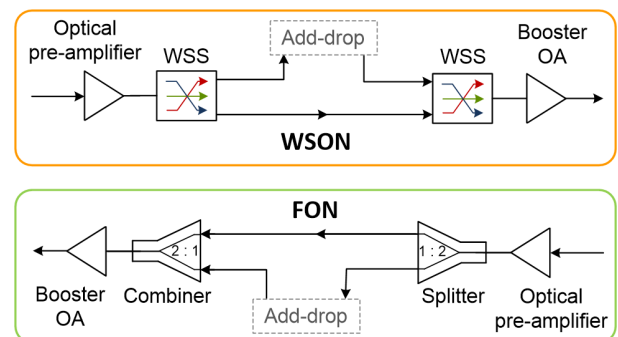


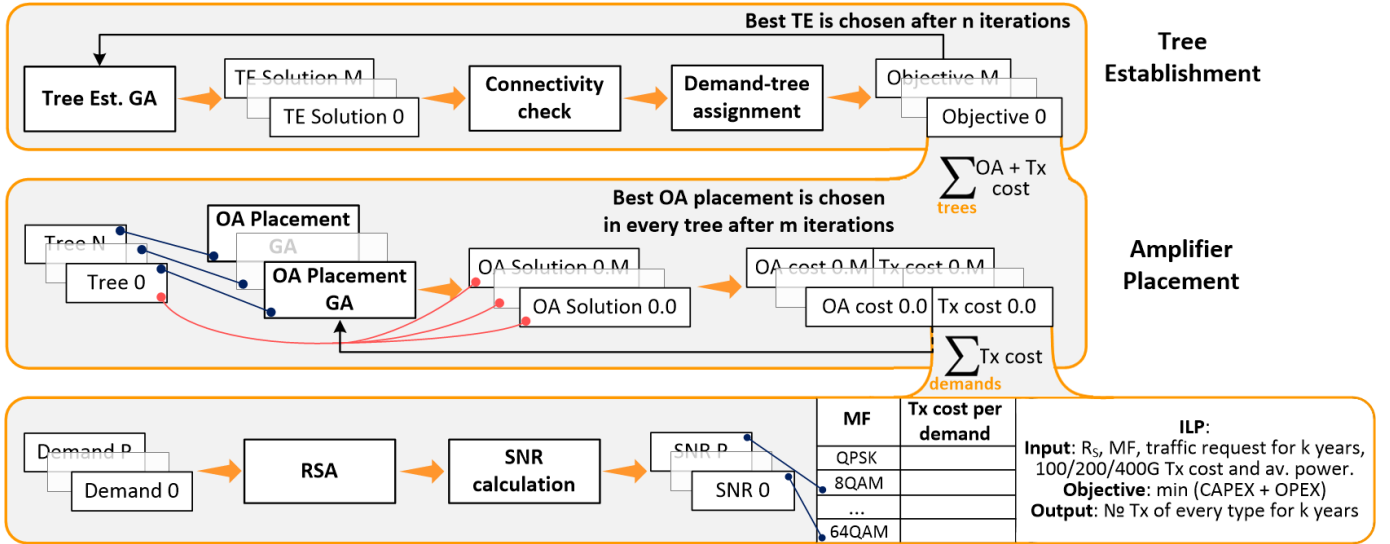Fig. 1. Architecture of degree-2 WSON and FON nodes

Fig. 2. Joint Tree Establishment and OA Placement algorithm

Note that the removal of OAs and WSSs must be carefully planned. The effect of amplified spontaneous emission (ASE) noise that is generated by OAs across the whole frequency band is exacerbated in FON, as the noise is not filtered by WSSs at intermediate nodes and hence affects connections further along the fiber tree. If OA placement is optimized to reduce the amount of noise accumulated along the lightpaths, while guaranteeing enough power at the receivers, modulation formats can be upgraded, and less transponders can be installed. As TE in FON is fixed during network's life, it can also be optimized to provide savings in transponders.

In the following, we quickly discuss the adopted planning methodology, our physical layer and cost models. Then we provide numerical results, showing an estimation of network cost savings during a 5 year period for different network scenarios (WSON vs. FON, with and without optimized OA placement, with and without optimized TE).

## II. METHODOLOGY

### A. Tree Establishment and Optical Amplifier Placement

Flowchart of the joint TE and OA placement algorithm for low-cost optical metro network design is shown in Fig. 2. It includes three subroutines: fiber tree establishment, OA placement and transponder selection. First two subroutines are based on the Genetic Algorithm (GA) introduced in [7]. In Tree Establishment every bidirectional link is either assigned to one of the fiber trees or not assigned to any tree at all. In OA placement every candidate location along the fiber and at the input and output ports of the nodes can host an amplifier or remain empty. Note that the subroutines can be carried out independently (e.g., TE can be performed to minimize the longest lightpath, without optimizing OA placement; OA placement can be performed not only in a fiber tree, but in the mesh WSON network) to separately estimate the effect of

the minimization of the number of each device (WSS, OA and transponder).

We now describe operation of the algorithm in the most general case, when TE and OA placement are jointly performed. Starting from the top of Fig. 2, for every fiber tree establishment generated by GA, tree connectivity constraints are checked, and traffic demands are assigned to fiber trees. If the demand can be assigned to more than one tree, we choose the one that guarantees the lowest propagation loss. To find the improved solutions in the next iteration of the GA, objective value of each TE solution is calculated. It is equal to the total cost of transponders and OAs in all the fiber trees (see next subsection for cost calculation). For every fiber tree a separate nested GA optimizes OA placement. The objective value for each generated OA placement is the total cost of OAs and transponders in that fiber tree.

Note that, to find the cost of transponders, routing and spectrum assignment must be performed for traffic demands in the fiber tree, and SNR of every demand has to be computed (for this computation, see next subsection). Routing in a tree is trivial, and spectrum is assigned using First Fit allocation scheme. Each traffic demand can be provisioned by a combination of three types of transponders (type 1 transponder only employs PM-QPSK, type 2 - also PM-8QAM and PM-16QAM, type 3 - also PM-32QAM and PM-64QAM). Available bitrate for a lightpath is defined according to the highest-order MF for the computed SNR. An Integer Linear

TABLE I
CONSIDERED TRANSMISSION RATES

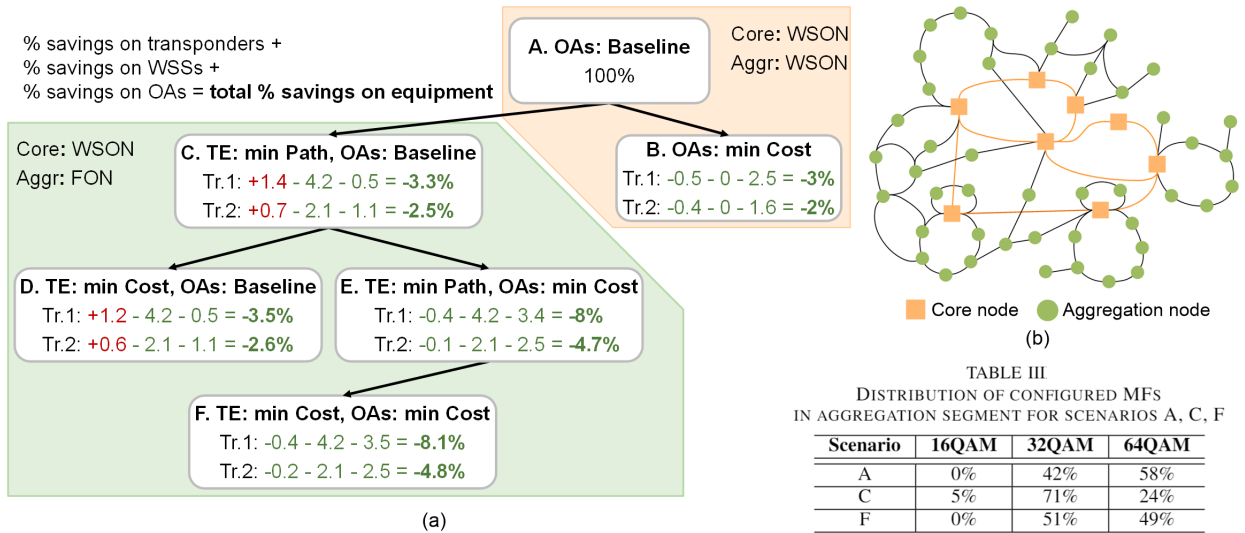| Transponder | MF | Data rate | SNR threshold |
|---|---|---|---|
| Type 1, 2, 3 | PM-QPSK | 100 Gb/s | 11 dB / 0.1 nm |
| Type 2, 3 | PM-8QAM | 150 Gb/s | 15 dB / 0.1 nm |
| Type 2, 3 | PM-16QAM | 200 Gb/s | 18 dB / 0.1 nm |
| Type 3 | PM-32QAM | 250 Gb/s | 20.8 dB / 0.1 nm |
| Type 3 | PM-64QAM | 300 Gb/s | 23.7 dB / 0.1 nm |

Fig. 3. (a) Savings by equipment type in different scenarios for "Traffic 1 and 2", relative to network cost in scenario A and (b) 52-node TIM topology

TABLE III
DISTRIBUTION OF CONFIGURED MFs
IN AGGREGATION SEGMENT FOR SCENARIOS A, C, F

| Scenario | 16QAM | 32QAM | 64QAM |
|---|---|---|---|
| A | 0% | 42% | 58% |
| C | 5% | 71% | 24% |
| F | 0% | 51% | 49% |

Program (not reported for the sake of conciseness) then outputs how many transponders of each type are needed to satisfy the requested bitrate, which grows every year, at minimal cost. Note that multi-hop traffic grooming is not considered.

After $m$ iterations of the OA placement GA, the best OA placement is chosen for every fiber tree, and the related cost of transponders and OAs is returned to the TE subroutine. TE subroutine then outputs the best solution after $n$ iterations.

### B. Physical model

To estimate SNR of the lightpaths, we use the LOGON-model [8], adapted to FON in [7]. It assumes full spectrum occupation, hence OA placement and TE result to be independent of traffic scenarios. Given the SNR and using SNR thresholds in Table I [9] (with an additional 2 dB margin), we determine the highest MF that can be configured for each lightpath. Note that we do not consider additional SNR impairments due to filtering in active switching nodes.

Characteristics of EDFAs are taken from [7], and their gains are set to compensate propagation losses as in [10]. Gain profiles are assumed to be flat and deterministic. Received optical power (computed as in [10]) must be above -18 dBm, putting a constraint on OA placement.

### C. Cost model

We adopt the cost model from [6], taking into account equipment cost as CAPEX and electricity cost as OPEX and extend it by estimating additional components of OPEX: installation cost as 30% of CAPEX and maintenance/repair costs as 75% of electricity cost, based on [11].

We consider only transponders, WSSs, splitters/combiners, multiplexers/demultiplexers and amplifiers. Their prices and energy consumption are listed in Table II. Price of electricity is estimated to be 0.001 CU/kWh. We also consider that price of any network component depreciates by 10% every year. Cost depreciation and OPEX make it advantageous to postpone the installation of new transponders.

## III. CASE STUDIES AND RESULTS

### A. Topology and Traffic

As a reference realistic metro network, we use the 52-node TIM topology shown in Fig. 3b. To guarantee efficient use of spectral resources (and to mimic realistic deployment), the core segment always uses a WSON architecture, while the aggregation segment can use a FON architecture. If FON is used, every tree must be connected to the core segment through at least one core node, and we assume to have 10 bidirectional fiber trees, which is the lowest number that allows us to find a feasible TE.

As for the traffic matrix, we consider initial traffic between every core node pair to be 300 Gb/s with 30% increase every year. In the aggregation segment we consider 200 Gb/s bidirectional traffic between each aggregation node and its closest core node, which grows by 20% per year. We call this traffic matrix "Traffic 1". In "Traffic 2" (that represents a more meshed traffic matrix), we additionally consider traffic requests between each node pair inside a fiber tree, which start from 100 Gb/s with 10% yearly increase.

### B. Numerical Results

In Fig. 3a, we report the cost savings by equipment type for six possible scenarios: two scenarios with WSON in the aggregation segment (i.e., with baseline or with optimized OA placement) and 4 scenarios with FON in the aggregation segment (i.e., with baseline or with optimized OA placement, and considering TE optimized for path length or for cost).

TABLE II
COST AND POWER CONSUMPTION OF COMPONENTS

| Network component | Cost, CU | Av. power, W |
|---|---|---|
| Splitter (combiner) 1x2; 1x4; 1x8 | 0.004; 0.01; 0.02 | - |
| WSS 1x4; 1x9 | 1.1; 2.2 | 30; 40 |
| Multiplexer/demultiplexer | 0.8 | - |
| Booster; preamplifier; inline OA | 0.3; 0.3; 0.5 | 27 |
| Transponder type 1; type 2; type 3 | 5; 8; 12 | 120 |

The reference scenario A (shown on top) refers to the WSON architecture with a baseline placement of OAs (i.e., OAs at input and output node ports and every 60 km along the fiber). We set its cost to 100%, so all savings are computed with respect to it.

In scenario B, optimization of OA placement in WSON allows (0.4-0.5)% savings thanks to transponders and (1.6-2.5)% thanks to OAs, amounting to a total (2-3)%, depending on the traffic scenario. Moving to FON, in scenario C we remove WSSs in the aggregation segment and find a TE that minimizes the longest lightpath in the segment, while OA placement remains baseline. Due to propagation of unfiltered ASE noise, average SNR decreases, hence cost of transponders increases by (0.7-1.4)%, but it is compensated by (2.1-4.2)% savings on WSSs and (0.5-1.1)% on OAs (note that savings on OAs occurs as some links are not included in any tree), giving (2.5-3.3)% savings in total. In scenario D, we keep OA placement baseline, but now we establish trees with the goal of minimizing network cost, obtaining only an additional (0.1-0.2)% increase in cost savings. In scenario E, we optimize OA placement jointly with TE, and we notice that cost of transponders, despite absence of ASE noise filtering in FON, slightly decreases by (0.1-0.4)%. In addition we observe (2.5-3.4)% savings on OAs and (2.1-4.2)% savings on WSSs, reaching a satisfactory (4.7-8)% of total. Finally, scenario F is the same as scenario E, but TE is performed to minimize network's cost, obtaining another small increase in savings (around 0.1%).

These results demonstrate that intelligent OA placement turns modest initial savings, obtained by FON architecture over the WSS architecture, to be more significant. Note also that savings tend to decrease with "Traffic 2", as the share of network cost due to transponders increases (as more traffic must be provisioned), but short paths between nodes in the same tree can support higher-order MFs even in the baseline network deployment, so cost of transponders cannot be effectively minimized.

To gain some further insights on previous results, in Table III we report the percentage distribution of MFs in the aggregation segment with "Traffic 1" for scenarios A, C and F (D and E are equivalent to C and F, hence removed). One can note that percentage of lightpaths with the highest available MF, 64QAM, falls down from 58% in scenario A to 24% in scenario C (from WSON to FON), but then grows back to 49% in scenario F (when OA placement gets optimized). This explains why cost of transponders increases with the transition from WSON to FON, and decreases if we perform intelligent OA placement.

## IV. CONCLUSION

Numerical evaluations show that when removing WSSs from the aggregation segment (2-4)% savings on WSSs are partially elided by increased costs of transponders. However, significant (4.8-8.1)% savings can be achieved with an intelligent placement of optical amplifiers. We leave for future work the extension of this analysis for core networks, where we also expect a substantial effect of OA placement on the cost of transponders, since core networks have more room for MF upgrades.

## V. ACKNOWLEDGMENT

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