Optimization of long-reach TDM/WDM passive optical networks

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ABSTRACT

Long-Reach Passive Optical Network (LR-PON) using hybrid TDM/WDM techniques is one of the candidates for the future optical access that can solve the expected increase in terms of traffic demand and area coverage. One of its advantages is the possibility to share the capacity of any wavelength among more than one user, through TDM/WDM hybrid multiplexing. However, it is still an open issue which transmission technology (DWDM transmitters, colorless transmitters, coherent detection, direct detection) can more effectively satisfy the requirements and characteristics of the future long-reach access network. In this article we propose a new optimization model based on Mixed Integer Linear Programming (MILP) that formalizes the problem of selecting the most cost-effective transmission technology in LR TDM/WDM PONs while also assigning the wavelength-channels line rate and the splitting ratio of the remote nodes at different levels, under bandwidth and power budget constraints. Using this proposed MILP formulation we can identify the optimal transmission technology for a wide set of possible LR-PON scenarios of interest. In this work we provide an evaluation of the optimal transmission technologies under several PON scenarios with varying traffic loads and area coverage. We also analyze the cost sensitivity of the optimization process for coherent-detection technology since it is still under research and development.

1. Introduction

Passive Optical Network (PON) is considered to be a suitable and promising candidate to convey the ever-growing traffic demands at the access level. Targeting an increase in PON's capacity, new standards have been released in the past few years to support the migration from line rates of 2.5 Gbit/s (in Gigabit-capable PON, GPON) or 1 Gbit/s (in Ethernet-based PON, EPON) to a line rate of 10 Gbit/s. Also, next generation PONs are being studied using a diverse set of multiplexing techniques to significantly scale their capacity, such as Wavelength Division Multiplexing (WDM), Ultra Dense WDM (though the use of coherent detection and diverse modulation techniques), Frequency Division Multiplexing, Code Division Multiplexing, and possibly, hybrids of the previous options combined with Time Division Multiplexing (TDM) [1]. The main motivation for this intense investigation on PONs is the savings due to shared costs involved in the point-to-multipoint architecture deployed only with fibers and passive devices (such as optical splitters and Array Wave-length Grating, AWG) at the outside plant. Moreover, nowa-days it is universally recognized the need for new high-speed access network architectures capable of transporting the new bandwidth-consuming services and applications

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such as HD TV, online gaming, VoD, video conferencing, and mobile traffic. In particular, high-capacity PON is becoming more important nowadays to support backhauling of increasing mobile traffic and achieve the benefits of fixed-mobile network convergence.

New PON-based architectures are being explored to expand the access network geographically and reach even larger distances, beyond 100 km [2]. These would allow consolidation of metropolitan Central Offices, that is, reducing their number and operational expenses by extending the access network toward the metro segment, and serving a larger base of users in farther locations. Long-Reach PON (LR PON) can be the answer to these new requirements. Moreover, the next-generation optical access network is expected to provide mobile and wireless backhauling over a wide coverage area, which will require supporting a high capacity [3].

A number of LR PON architectures and technologies have been proposed so far [4]. An important problem faced by operators and vendors is to identify the most appropriate transmission technologies, multiplexing techniques, and architectures that address all the new access requirements in a cost-effective manner. Before selecting and deploying a specific transmission technology, it is essential to evaluate and compare its pros and cons from different points of view, such as cost, reach, capacity, and user scalability.

In this article, we focus on the study of the most promising transmission technologies for LR TDM/WDM PON. We aim at devising the optimal combination of devices that will suffice the connectivity and bandwidth requirements of such networks. The advantage of TDM/WDM PON is the possibility to use multiple wavelengths and share them in time among multiple users. Sharing wavelengths in time allows to minimize the number of wavelengths in the network, and therefore to reduce the number of transceivers at the Central Office. The study of transmission technologies for LR-PON architectures should not be carried out separately from networking aspects such as traffic load and network scalability. Therefore, we propose a Mixed Integer Linear Programming model that optimizes the access network design, by choosing the most cost-effective transmission technology at a certain line rate (in bit/s) using certain mod-ulation format, and the best combination of passive remote nodes to be installed in order to satisfy traffic, distance, optical power, and topology constraints. This article is an extension of our work in [5]. Here we present a compre-hensive set of optimization results for the assumed scenarios and parameters. We also provide a cost sensitivity study for the technologies based on coherent detection given that they are still under research and development and it is dif-ficult to estimate their cost. In [6], we have also addressed this problem through the use of a heuristic/algorithmic sub-optimal solution.

Several works in literature investigate TDM-based PONs in order to find the best geographical location of cascaded optical splitters, and the most suitable splitting ratio [7, 8]. A recent work [9] optimizes the splitter topology in a LR TDM-based PON, but it does not include any traffic or optical power constraints. The authors of [10] propose a network design based on ILP, which takes into consideration mobile traffic backhauling requirements and the already existing fiber plant. However, in their work, WDM technologies were not studied. In [11], authors also aim at finding the best geographical location of cascaded splitter and/or AWG, and they also include traffic constraints for WDM-PON. However, this study only includes an optical power constraint for a unique transmission technology, and it does not support long reach. None of the above research works has considered the implications of involving diverse technologies in the optimization problem of future LR PON operating over multiple wavelengths which are shared in time. In this work we show how the choice of the transmission technology is crucial to decide the most effective combination of passive remote nodes to be installed (if splitters, or AWGs or a combination of them). To the best of our knowledge, this is the first study that addresses such design problem.

The rest of the article is organized as follows. Section II introduces the architecture and technologies evaluated by the MILP. Section III describes the proposed MILP model. To show numerical results, various scenarios are proposed and evaluated in Section IV, along with results on our cost sensitivity study. Section V concludes this work.

2. Long-reach TDM/WDM passive optical networks

A PON is a point-to-multipoint network where the elements in the signal's path from the central office (where we locate the Optical Line Terminal, OLT) to the user (where we locate an Optical Network Unit, ONU) are fully passive, and consist of fibers and optical passive splitters/combiners [12]. Usually it operates on two wavelengths channels, one for each traffic flow direction (upstream and downstream). The capacity of both channels is shared in time (using TDM) among all ONUs, and the quality of service is guaranteed by means of a Dynamic Bandwidth Allocation algorithm [13, 14].

The reach of a PON is typically 20 km. However, in order to reduce the number of central offices, and expand the coverage of a single PON, it is required to extend its reach. In an already existing PON, the OLT is moved toward the metro network and, at its place, a new remote node (primary remote node) is installed, usually an AWG (due to its lower insertion loss compared to splitters). The existing remote node near the ONUs (secondary remote node) is usually an optical splitter.

Extending the coverage involves not only longer distances, but also larger number of users and large traffic aggregation capacity. In particular, along with residential and business traffic, the next-generation PON must provide mobile/wireless backhauling to transport large amounts of traffic from and to the cellular base stations or wireless network head-end. To approach this capacity upgrade requirement, other multiplexing techniques are added to the PON. In particular, the WDM technique is often a preferred candidate due to the maturity of its transmission technologies. In order to minimize the number of required wavelengths (i.e., transceivers) in the LR WDM-based PON, it is possible to make a hybrid with TDM. The hybrid TDM/WDM is a way to utilize the whole capacity of a wavelength by sharing it among several ONUs, according to their bandwidth requirements.

In the LR-TDM/WDM-PON architecture, depicted in Fig. 1, we have a primary remote node which is an AWG, and a secondary remote node which is an optical splitter. Therefore, the wavelengths on any output port of the AWG will feed an optical splitter and will be shared in time among the ONUs connected to this splitter. The OLT would arbitrate the transmissions coming from different ONU over the same wavelength, such that there is no collision. This process will be applied for every single active wavelength in the system that is shared with other ONUs.

Some of the technological options for transmission in this architecture are enumerated below:

1) Colored dense WDM (DWDM) technology with On-Off-Keying (OOK) modulation using p-i-n photodetector (PIN) and Direct Detection (DD): off-the-shelf solution based on colored transmitters and direct-detection. The PIN-based receiver is relatively simple and inexpensive.
2) Colored DWDM technology with OOK modulation using Avalanche PhotoDiode (APD) and DD: colored transmitters with enhanced sensitivity based on direct-detection.
3) Ultra DWDM (UDWDM) technology with either OOK or Quadrature-Phase-Shift-Keying (QPSK) modulation, and coherent detection [15, 16]: solution with highest sensitivity to enable longer reach, at the cost of a complex transceiver architecture based on tunable laser sources. QPSK modulation with coherent detection allows for a high spectral efficiency, while providing an extra 3-dB gain in the sensitivity compared to OOK modulation (at the same bitrate). In both cases, there are extra losses at the OLT related to the use of a coupler, and at the ONU due to two couplers.
4) DWDM technology with OOK modulation using Reflective-Semiconductor-Optical-Amplifier-based (RSOA-based) ONU and DD [17, 18]: cost-effective, color-less solution based on RSOA. RSOA-based ONUs detect the seed light sent by the OLT, re-modulates it with the data of the ONU, amplifies the signal, and transmits the optical signal in the upstream direction using the carrier provided by the seed light. It is the cheapest colorless WDM transceiver.
5) UDWDM technology with QPSK modulation using RSOA-based ONU and coherent detection [19]: cost-effective ONU transceiver with enhanced sensitivity achieved by coherent detection. There are extra losses at the OLT and ONU due to the use of a faraday rotator in each case.

In all the aforementioned technologies, there are added losses at the OLT due to the use of an internal AWG to separate the upstream wavelengths before feeding the receivers at the OLT, and to combine the wavelengths to be transmitted downstream over the fiber.

3. Mixed-linear integer programming formulation for transmission technology selection and bandwidth assignment in LR-PON

Our proposal is intended to identify the most cost-effective design for an optical access network, such that requirements of traffic demand and distance coverage are satisfied. This proposal is intended as a design tool that is able to retrieve the optimal network configuration at the lowest cost while assuring technical feasibility. This design includes adopted transmission technologies, remote node type and splitting ratio, and capacity resources required. In this section, we formally define the problem, we present the variables and input parameters, and we describe our proposed mixed-linear integer programing (MILP).

3.1. A. Problem definition

Aim: Select the transmission technology and appropriate type of remote nodes that guarantee certain power budget target and satisfy bandwidth requirements at minimum cost.

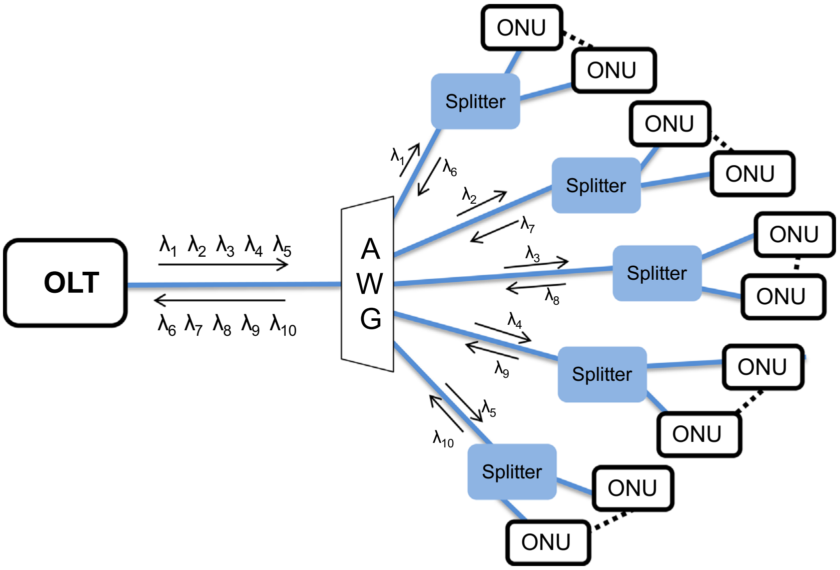

Fig. 1. A LR-TDM/WDM-PON architecture.

Given: (*i*) a set of optical devices (OLT, ONU, optical splitter, AWG) for which different transmission technologies are applicable, (*ii*) their cost and optical specifications, that is, power losses, transmission power, and optical sensitivity whenever applicable, (*iii*) the maximum distance at which the remote nodes can be placed, (*iv*) the distance between ONUs and OLT, and (*v*) the traffic demand for every OLT-ONU pair.

3.2. B. Parameters and component sets

In this section we define all sets of components and parameters used in the MILP formulation.

N	Set of ONUs; $N_{\text{tot}} = \lvert N \rvert$;
A	Set of AWG types that are defined by the splitting ratio 1:2^n, where the content of the set are integer numbers that indicate the value of n. Example: $n=3$ refers to an AWG with a splitting ratio 1:8;
S	Set of optical splitters types that are defined by the splitting ratio 1:2^m, where the content of the set are integer numbers that indicate the value of m. Example: $m=3$ refers to a splitter with a splitting ratio 1:8;
L	Set of wavelengths;
K	Set of line rates (Mbit/s);
T	Set of transmission technologies;
$Co_{t,k}$	Cost of the OLT for technology t, and rate k ($);
$Cu_{t,k}$	Cost of the ONU for technology t, and rate k ($);
Ca_n	Cost of the AWG which depends on n and is related to the number its output ports 2^n ($);
Cs_m	Cost of the optical splitter which depends on m and is related to the number of its output ports 2^m ($);
C_{f}	Cost of the fiber per km ($/km);
$d_{\max}$	maximum distance found between the OLT and any ONU (km);
D_{r}	average distance between remote nodes (km);
B_i	Guaranteed bandwidth for transmission between OLT and ONU i (Mbit/s);
R_k	Line rate k (Mbit/s);
$To_{t,k}$	OLT's transmission power (dBm) for technology t, and rate k;
$Tu_{t,k}$	ONU's transmission power (dBm) for technology t, and rate k;
$So_{t,k}$	OLT's sensitivity (dBm) for technology t, and rate k;
$Su_{t,k}$	ONU's sensitivity (dBm) for technology t, and rate k;
Po_t	OLT's power loss (dB) for technology t;
Pu_t	ONU's power loss (dB) for technology t;
Pa_n	AWG's power loss (dB) for 2^n output ports;
Ps_m	optical splitter's power loss (dB) for 2^m output ports;
P_{f}	power loss of the fiber per km (dB/km);
G	power budget margin (dB), usually set to -3dB;
Q_i	number of wavelengths over which ONU i is transmitting its traffic;
M	a large number (10^{6});

3.3. C. Variables

In this section we define all variables used in the MILP formulation. $x_{n,m}$: binary, 1 if both the AWG with 2^n output ports and optical splitter with 2^m output ports are installed as primary and secondary remote node, respectively;

$z_{t,k}$	binary, 1 if the technology t, at rate k is chosen;
u_n	binary, 1 if the AWG with 2^n output ports is selected;
v_m	binary, 1 if the optical splitter with 2^m output ports is selected;
p_t	binary, 1 if the technology t is selected;
q_k	binary, 1 if rate k is selected;
$\lambda_{k,j}$	binary, 1 if the wavelength j with rate k is used;
$\beta_{i,j}$	binary, 1 if the ONU i uses wavelength j;
$bw_{i,j}$	integer variable that represents the bandwidth allocated to the ONU i, over wavelength j;
PL	integer variable that represents the total power loss for the longest path OLT-ONU;

3.4. D. Objective function

The objective function of the proposed MILP is to minimize the total cost:

$$\min\Big(\sum_{t\in T}\sum_{k\in K} Co_{t,k} z_{t,k} + N_{\text{tot}} \sum_{t\in T}\sum_{k\in K} Cu_{t,k} z_{t,k} + \sum_{n\in A} Ca_n u_n + \sum_{n\in A}\sum_{m\in S} 2^n Cs_m x_{n,m} + C_f D_r \sum_{n\in A} 2^n u_n\Big) \tag{1}$$

The first four terms account for total cost of the OLT, the ONUs, the AWG (at the primary remote node), and the splitters (at the secondary remote node), respectively. The fifth term is the part of the total fiber cost that depends on the chosen primary remote node output ports. Indeed, depending on the splitting ratio of the AWG, the number of fiber segments (with average size D_{r}) that connect primary and secondary remote nodes may vary. Other terms of the total fiber cost are considered here as known and do not bring any change in the objective function. For this reason, the rest of the fiber cost is not included.

3.5. E. Constraints

To complete the MILP specification, we formulate all the constraints that need to be fulfilled.

$$\sum_{n\in A}\sum_{m\in S} 2^n 2^m x_{n,m} = N_{\text{tot}} \tag{2}$$

$$\sum_{k\in K}\sum_{j\in L} \lambda_{k,j} \le \sum_{n\in A} 2^n u_n \tag{3}$$

$$\sum_{i\in N} \beta_{i,j} \le \sum_{m\in S} 2^m v_m \quad \forall j \in L \tag{4}$$

$$\sum_{n\in A} u_n = 1 \tag{5}$$

$$\sum_{m\in S} v_m = 1 \tag{6}$$

$$\sum_{t\in T} p_t = 1 \tag{7}$$

$$\sum_{k\in K} q_k = 1 \tag{8}$$

$$x_{n,m} = u_n \wedge v_m \quad \forall n \in A, \forall m \in S \tag{9}$$

$$z_{t,k} = p_t \wedge q_k \quad \forall t \in T, \forall k \in K \tag{10}$$

$$\sum_{k \in K} \lambda_{k,j} \leq 1 \quad \forall j \in L \tag{11}$$

$$\sum_{j \in L} \beta_{i,j} = Q_i \quad \forall i \in N \tag{12}$$

$$\sum_{j \in L} bw_{i,j} = B_i \quad \forall i \in N \tag{13}$$

$$\beta_{i,j} \geq \frac{bw_{i,j}}{M} \quad \forall i \in N, \forall j \in L \tag{14}$$

$$\beta_{i,j} \leq bw_{i,j} \quad \forall i \in N, \forall j \in L \tag{15}$$

$$q_k \geq \frac{\sum_{j \in L} \lambda_{k,j}}{M} \quad \forall k \in K \tag{16}$$

$$q_k \leq \sum_{j \in L} \lambda_{k,j} \quad \forall k \in K \tag{17}$$

$$\sum_{k \in K} R_k \lambda_{k,j} \geq \sum_{i \in N} bw_{i,j} \quad \forall j \in L \tag{18}$$

$$PL \leq PB_{\mathrm{DS}} - G \tag{19}$$

$$PL \leq PB_{\mathrm{US}} - G \tag{20}$$

where PL, PB_{DS}, and PB_{US} are defined as follows:

$$PL = \sum_{t \in T} Po_t p_t + \sum_{t \in T} Pu_t p_t + \sum_{n \in A} Pa_n u_n + \sum_{m \in S} Ps_m v_m + P_f d_{\max}$$

$$PB_{\mathrm{DS}} = \sum_{t \in T} \sum_{k \in K} To_{t,k} z_{t,k} - \sum_{t \in T} \sum_{k \in K} Su_{t,k} z_{t,k}$$

$$PB_{\mathrm{US}} = \sum_{t \in T} \sum_{k \in K} Tu_{t,k} z_{t,k} - \sum_{t \in T} \sum_{k \in K} So_{t,k} z_{t,k}$$

Eq. (2) identifies the total number of output ports of all the secondary remote nodes (splitters), which should match the number of ONUs installed. In (3), we ensure that the total number of wavelengths equals the number of output ports of the primary remote node (AWG), that is, only one wavelength per AWG output port is allowed. Eq. (4) limits the total number of users sharing the same wavelength to the number of output ports of the secondary remote node (optical splitter). Eqs. (5) to (8) indicate that only one option is allowed: only one type of AWG in (5), only one type of splitter in (6), only one transmission technology in (7), and only one line rate in (8).

Eq. (9) defines the variable $x_{n,m}$ as a result of the logical AND between the AWG selected and the optical splitter selected. Note that the AND operator in (9) is not, rigorously speaking, a linear constraint, however logical operators among binary variables can be easily linearized [20]. In (10), $z_{t,k}$ is defined as the logical AND between the transmis-sion technology and the line rate that are chosen. The fact that every wavelength can only operate at one line rate is expressed in (11). The limitation on the number of wave-lengths that an ONU can support is set in (12). In this work, we assume that an ONU transmits all its traffic on only one wavelength ($Q_i = 1$) to avoid having multiple transceivers for one ONU, and also to avoid assigning simultaneous trans-missions over two different wavelengths when using tunable laser. In (13), we state that the total bandwidth allocated to a certain ONU i over different wavelengths should be equal to the total requested traffic by such ONU. Eqs. (14) and (15) determine the binary equivalent of the variable that repre-sents bandwidth allocated to ONU i and wavelength j. Similarly, (16) and (17) determine the binary variable that represents which line rate is used in the system.

Eq. (18) is a constraint on the capacity of each wavelength, which cannot be less than the traffic allocated over it. Eqs. (19) and (20) limit the total power loss to the power budget (considering a practical loss margin, G) for downstream and upstream directions, respectively.

We assume that precise location of remote nodes (splitters, AWGs) can be calculated using any available placement and allocation algorithm [10], and it can be introduced as input to our optimization model in order to find the best technological solution and remote devices. In our problem, we can associate the cost derived from the number and distance of fiber segments between cascaded remote nodes, since it directly depends on the splitting ratio chosen. That is, if the splitting ratio of the primary remote node is high, then more fiber segments should be deployed to connect the primary remote node with the secondary. If the splitting ratio is low, then lower number of fiber segments will be required, and therefore a lower cost. Note that when the chosen splitting ratio of the secondary remote node is 1:1, then there is no optical splitter installed. In such case, the network will be deployed as a pure WDM PON, where a dedicated wavelength is allocated to each ONU.

4. Numerical results and discussion

Our optimization model has been solved using CPLEX [21]. To illustrate the model, we study a PON where we vary the number of ONUs, the maximum distance range, and the network traffic load. We have set three PON scenarios composed by: 64, 128, and 256 ONUs. We also vary the total OLT-ONU distance for a range that covers: 20, 40, 60, 80, and 100 km. The distance between remote nodes D_{r}, is considered to be in average 9 km for all the cases, while the distance from remote node to ONU has been fixed to 1 km. In this numerical example, we only consider downstream traffic, but note that both upstream and downstream power budget constraints are evaluated through (19) and (20). We have distributed different user traffic types uniformly through the ONUs in the network. We have defined that approximately 50% of the ONUs handle residential traffic, 40% carries traffic from small cells, and 10% take business traffic. The peak traffic demand is assumed to be 100 Mbit/s for residential users, 300 Mbit/s for small cell backhauling, and 500 Mbit/s for business users. Then, these traffic values are modified by a multiplicative factor, which we refer to as traffic factor, in order to help observing how the optimal solution changes for different traffic loads of a network. The traffic factor can be considered as a multiple of the per-year forecast traffic growth, which we assume as 1.5. Although diverse types of traffic may grow differently, we assume the types of traffic considered in this article grow in a similar manner. This way, a traffic factor corresponds to the multiplicative factor used to obtain the traffic growth for a certain number of years. We have considered that the traffic factor takes the following values: 1, 3, 6, 9, 12, 15, and 18, where 1 represents the current traffic expectation, 3 represents 2 years later, 6 represents 4 years, and so forth. The traffic increase may correspond to a higher demand from a single user or service, or a cluster of users or small cells being aggregated at an ONU.

Every transmission technology has its own parameters regarding optical transmission power, sensitivity, and losses for OLT and ONUs. The sensitivity depends on the line rate, which has been chosen to be either 2.5 Gbit/s or 10 Gbit/s. In Table 1, we summarize the set of sensitivity values, power losses, and cost for the OLT and ONU according to the technology used. We assume $\mathrm{BER}=10^{-4}$. We have chosen a unique transmission power (3 dB) in order to evaluate the reach of the signal over multiple technologies under the same assumption. Most of the values have been obtained from the references described in Section II. Note that interfaces of technologies based on RSOA are not available for a line rate of 10Gbit/s, at the time of this study.

We have estimated the cost for ONU and OLT that directly depend on the performance of each technological option (based on sensitivity, line rate, and complexity). Since the cost assumptions may not be fully realistic, especially for the coherent technologies, we include in this work a cost sensitivity analysis to verify our estimations.

Other values have been estimated, assuming they would not vary much from the commercially available devices. For example, in the case of the AWGs, we have considered losses of −5 dB. The losses of the optical splitters follow the rule: $-3.5^{*}\log_2$(No. output ports) [dB]. As for the cost, the AWG may follow this equation: $500+70^{*}\log_2$(No. output ports) [\$], and the optical splitter this equation: $200+50^{*}\log_2$(No. output ports) [\$]. The loss of the fiber per km is P_f= 0.2 dB/km, whilst its cost per km is C_f= 160 \$/km.

4.1. A. Numerical results

We have run the MILP for all the combinations of N_{tot} (total number of ONUs), distance, and traffic load. The results in terms of selected remote node splitting ratios, number of wavelengths, and line rate have been summarized in Table 2, while the resulting optimal transmission technologies for every PON scenario have been included in Table 3.

In Table 2 we can notice that for some cases there is no secondary remote node, which leads to the note that that the network type is a pure WDM-PON, that is, without wavelength sharing. Indeed, having a single AWG in the network leads to a single wavelength per output port, and therefore a single dedicated wavelength per ONU. This selection only happens when the network traffic load is large (traffic factor 18) for all network scenarios and distances, making it necessary to have a single wavelength at 10 Gbit/s per ONU to respond to the traffic demand. Note that this network has no optical splitter at the secondary remote node and therefore the insertion losses due to those devices is absent, while the insertion loss of the AWG is relatively low and constant regardless of the splitting ratio. As a consequence, the reach is extended due to reduces losses in the optical path from OLT to an ONU. However, from the AWG we must extend a fiber till the user facility where the ONU is located, which without a secondary remote node implies an increased fiber segment lengths, and therefore higher costs. This is the reason why this solution does not appear to compete with TDM/WDM PON at lower traffic loads. However, it is worth mentioning that TDM/WDM PONs require the implementation of resource management mechanisms or a dynamic wavelength and bandwidth allocation algorithm which may imply added complexity, cost, and delay, when compared to WDM-PON. Such added cost was not considered in the current analysis, but it is important to keep in mind the possible effects.

Also we can see that in Table 2, most of the solutions make use of a 10-Gbit/s line rate for high traffic loads. On the other hand, the choice of 2.5 Gbit/s appears at low traffic factors such as 1 and 3. Although the use of WDM transmission technologies at 2.5 Gbit/s is limited to lower traffic volumes, they offer a better sensitivity compared to 10 Gbit/s.

Table 1
Input Parameters.

Parameter	**OOK DD PIN**	**OOK DD APD**	**OOK Coh. homodyne**	**QPSK Coh. homodyne**	**RSOA DD APD**	**RSOA QPSK Coh. homodyne**
DOWNSTREAM Sensitivity (dBm) @2.5 Gbit/s	−26[a]	−36[a]	−49[b]	−52[b]	−36[a]	−52[b]
DOWNSTREAM Sensitivity (dBm) @10Gbit/s	−20[a]	−30[a]	−43[b]	−46[b]	NA	NA
UPSTREAM Sensitivity (dBm) @2.5 Gbit/s	−26[a]	−36[a]	−49[b]	−52[b]	−32[c]	−45[d]
UPSTREAM Sensitivity (dBm) @10Gbit/s	−20[a]	−30[a]	−43[b]	−46[b]	NA	NA
Loss (dB) @OLT	−5	−5	−8	−8	−5	−6
Loss (dB) @ONU	0	0	−6	−6	0	−1
Cost($) OLT @2.5Gb/s	20000	28000	40000	40000	15000	25000
Cost($) OLT@10Gbit/s	30000	38000	50000	50000	NA	NA
Cost ONU($) @2.5Gb/s	300	400	500	550	250	350
Cost($) ONU@10Gbit/s	400	500	600	650	NA	NA
Loss (dB) in OLT	−5	−5	−8	−8	−5	−6
Loss (dB) in ONU	0	0	−6	−6	0	−1

NA: Not Available

[a] Experimental measurements.

[b] Extrapolated from [15].

[c] Extrapolated from [18], and assuming seedlight power > −22 dBm.

[d] Extrapolated from [19], and assuming seedlight power > −22 dBm.

Table 2
Optimization result for all scenarios.

PON Scenario	Traffic factor	Distance (km)	AWG	Splitter	No.λs	Line rate	Network Type
64-ONUs	18	20–100 km	1:64	-	64	10 Gbit/s	WDM-PON
	12-15	20–100 km	1:32	1:2	32	10 Gbit/s	TDM/WDM PON
	6-9	20–100 km	1:16	1:4	16	10 Gbit/s	TDM/WDM PON
	3	60–100 km	1:32	1:2	32	2.5 Gbit/s	TDM/WDM PON
		20–40 km	1:8	1:8	8	10 Gbit/s	TDM/WDM PON
	1	20-40 km & 80-100 km	1:8	1:8	8	2.5 Gbit/s	TDM/WDM PON
		60 km	1:16	1:4	16	2.5 Gbit/s	TDM/WDM PON
128-ONUs	18	20–100 km	1:128	-	128	10 Gbit/s	WDM-PON
	12-15	20–100 km	1:64	1:2	64	10 Gbit/s	TDM/WDM PON
	6-9	20–100 km	1:32	1:4	32	10 Gbit/s	TDM/WDM PON
	3	60–100 km	1:64	1:2	64	2.5 Gbit/s	TDM/WDM PON
		20–40 km	1:16	1:8	16	10 Gbit/s	TDM/WDM PON
	1	20–100 km	1:16	1:8	16	2.5 Gbit/s	TDM/WDM PON
256-ONUs	18	20–100 km	1:256	-	256	10 Gbit/s	WDM-PON
	12-15	20–100 km	1:128	1:2	128	10 Gbit/s	TDM/WDM PON
	6-9	20–100 km	1:64	1:4	64	10 Gbit/s	TDM/WDM PON
	3	100 km	1:64	1:4	64	10 Gbit/s	TDM/WDM PON
		20–80 km	1:32	1:8	32	10 Gbit/s	TDM/WDM PON
	1	20–100 km	1:32	1:8	32	2.5 Gbit/s	TDM/WDM PON

Table 3
Transmission technology solutions for all PON scenarios.

PON Scenario	Traffic factor	Distance				
		20 km	40 km	60 km	80 km	100 km
64-128-256 ONUs	18	DWDM DD PIN	DWDM DD PIN	DWDM DD APD	DWDM DD APD	OOK Coherent
64-128-256 ONUs	12-15	DWDM DD PIN	DWDM DD APD	DWDM DD APD	DWDM DD APD	OOK Coherent
64-128-256 ONUs	6-9	DWDM DD APD	DWDM DD APD	DWDM DD APD	OOK Coherent	QPSK Coherent
256 ONUs	3	DWDM DD APD	DWDM DD APD	OOK Coherent	QPSK Coherent	QPSK Coherent
64-128 ONUs	3	DWDM DD APD	DWDM DD APD	DWDM DD RSOA-based	DWDM DD RSOA-based	QPSK Coherent RSOA-based
128-256 ONUs	1	DWDM DD RSOA-based	DWDM DD RSOA-based	QPSK Coherent RSOA-based	QPSK Coherent RSOA-based	QPSK Coherent RSOA-based
64-ONUs	1	DWDM DD RSOA-based	DWDM DD RSOA-based	DWDM DD RSOA-based	QPSK Coherent RSOA-based	QPSK Coherent RSOA-based

In this way, using a 2.5 Gbit/s line rate can help achieving longer reach with a cheaper technology and/or the use of higher splitting ratios in the optical splitter, compared to 10 Gbit/s.

Looking at the results in Table 3, WDM transmission technologies based on coherent detection are the choice for all cases at an OLT-ONU distance of 100 km. This is mainly due to the high sensitivity required to counteract the losses of lengthy fiber segments. At distances 20–40 km, all solutions are based on DWDM with DD. Since at lower distances the sensitivity requirement is lower, this situation fit the low-cost DD as most cost-effective solution. We also note that for the lowest traffic load (traffic factor 1), the solutions are based on RSOA, with reasonable sensitivity and low cost compared to tunable solutions. However, RSOA solutions are limited to a line rate of 2.5 Gbit/s, that is, traffic factors 1 and 3.

In Table 3 we can see that for highest traffic volume (traffic factor 18), DWDM colored technology with OOK modulation and DD using PIN is chosen for low distances and all PON scenarios. It is possible to use this technology with lowest sensitivity because the network uses a single AWG and no splitters (see Table 2), leading to reduced insertion losses due to the remote nodes. PIN becomes unfeasible when the distance increases (60 and 80 km) because the fiber losses turn more significant, and the technology selected is then based on APD. When the traffic volume decreases (represented by traffic factors 12 and 15), DWDM colored technology with OOK modulation and DD using PIN is then limited to 20 km for all PON scenarios because now there is an optical splitter (1:2 splitting ratio, see Table 2) inserted as secondary remote node in order to minimize the cost of the total fiber segments in the network. Therefore, DWDM colored technology with OOK modulation and DD using APD is selected for distances from 40 to 80 km. At traffic factor from 6 to 9, the network has a lower traffic volume and wavelengths can be shared among more ONUs. The splitting ratio of the splitters at the secondary remote nodes increases (1:4, as shown in Table 2) in order to minimize the total fiber length, and hence the cost. However, already at 80 km there is the need to use UDWDM with coherent detection and OOK modulation to cope with the total optical losses from the fiber length and the secondary remote node. Also at 100 km, the solution is based on QPSK modulation to offer extra sensitivity and compensate the losses.

In Table 3 we can see that traffic factors 1 and 3 have some differences between PON scenarios. For the 256-ONUs PON scenario and traffic factor 3, the solution for high distances (60 to 100 km) is based on UDWDM coherent detection. The reason is that, in this scenario, the effect of the additional fiber segments on the cost is more important than in the other two scenarios, leading to the need of using higher splitting ratios at the secondary remote nodes and therefore increasing the insertion losses. Indeed, we can see in Table 2 that the 256-ONUs PON scenario uses splitters with splitting ratio 1:8, while 64- and 128-ONUs PON scenarios use splitting ratio 1:2. In the last cases, the selected technology is DWDM colorless with OOK modulation and DD based on RSOA, which offers lower sensitivity and is cheaper than the coherent solution. It provides enough savings to counterbalance the expenses in total fiber length. At 100 km, the 64- and 128-ONUs PON scenarios obtain as solution the use of DWDM colorless with QPSK modulation and coherent detection based on RSOA. In this case, as mentioned earlier, we there is the added benefit of using a line rate of 2.5 Gbit/s, which allows for a high sensitivity.

Finally, for the lowest considered traffic volume (traffic factor 1), in all PON scenarios the DWDM colorless technology with OOK modulation and DD based on RSOA is selected for low distances (10–40 km), while DWDM colorless technology with QPSK modulation and coherent detection based on RSOA is chosen for high distances (80–100 km). This is reasonable given the low cost of RSOA-based technologies, and the need for the coherent-detection option for high distances. For 60 km, both 128- and 256-ONUs PON scenarios take as solution the DWDM colorless technology with QPSK modulation and coherent detection based on RSOA, because the total cost is lower when using a splitting ratio of 1:8 at the secondary remote node (lower total fiber length), while accomplishing the required power budget thanks to the high sensitivity of this technology. On the other hand, the 64-ONUs PON scenario obtains the DWDM colorless technology with OOK modulation and DD based on RSOA at 60 km. The reason is that, even with low splitting ratio at the secondary remote nodes (1:4, as shown in Table 2), the cost related to total length of fiber in a PON with 64 ONUs has not such a large impact as it would in larger scenarios because the number of fiber segments is lower. Moreover, the low cost of this technology compensates for the fiber-related costs.

4.2. B. Cost sensitivity study

In this work, we have covered a number of transmission technologies that could be used for future PONs. Among them, the UDWDM technology based on coherent detection is currently attracting significant attention and investigation. Its projected cost in the market could be affected by diverse aspects such as the volume of market demand and technological evolution. Therefore, it is very difficult to estimate such cost and in this subsection, we aim at evaluating the impact on the optimization process when the cost varies. We increase and decrease the cost of coherent-based technologies for all the scenarios, by performing gradual variations in the cost from −20% to +20% in steps of 5%. From −5% till +20%, no variation was observed in all cases. For the −5% till −15% variations in the cost, we observe mild cost sensitivity in the optimization results. When the variation is −20%, the cost is closer to the non-coherent technologies; therefore, the sensitivity is high and most of the solutions change.

To illustrate these observations, in Table 4, we present the results with diverse cost variations (−5%, −10%, −15%, −20%) for one of the scenarios: 128-ONU PON. We can observe that for cost reductions of 5%, 10%, and 15% are observed only when the traffic factor of 3. This is a turning point where two solutions are very near in cost and therefore affected by some degree with every cost reduction. In order to better observe the effects of cost reduction, we present all results for a 20% cost reduction in Table 5, while all results specific to traffic factor 3 are presented in Table 6. Observing Table 3 and Table 5, we observe that DWDM colored technology with OOK modulation and DD using APD has been replaced by UDWDM with coherent detection and OOK modulation. However, the remote node splitting ratios remain the same for most of the cases (except for traffic factor 3). The reason is that, with 20% cost reduction, the cost of the ONUs for the coherent solution becomes lower than their cost with DD and APD. The rest of the cases remains without variation.

In Table 6 we observe all changes due to diverse cost reductions for a traffic factor of 3. With cost reductions of 5%, 10%, and 15%, the results changed only at 60 and 80 km. Indeed, DWDM colorless technology with OOK modulation

Table 4
Sensitivity of the optimization results to cost variations of coherent detection technologies for the scenario of 128-ONU PON.

PON Scenario	Traffic factor	Coherent technology cost reduction	Distance (km)	AWG	Splitter	No.λs	Line rate	Network Type
128-ONUs	18	20%	20–100 km	1:128	-	128	10 Gbit/s	WDM-PON
	12-15	20%	20–100 km	1:64	1:2	64	10 Gbit/s	TDM/WDM PON
	6-9	20%	20–100 km	1:32	1:4	32	10 Gbit/s	TDM/WDM PON
	3	20%	100 km	1:32	1:4	32	10 Gbit/s	TDM/WDM PON
			20–80 km	1:16	1:8	16	10 Gbit/s	TDM/WDM PON
		5–15%	100 km	1:64	1:2	64	2.5 Gbit/s	TDM/WDM PON
			20–80 km	1:16	1:8	16	10 Gbit/s	TDM/WDM PON
	1	20%	20–100 km	1:16	1:8	16	2.5 Gbit/s	TDM/WDM PON

Table 5
Transmission technology solutions for the sensitivity analysis when a 20% cost reduction of coherent detection technologies is applied, for the scenario of 128-ONU PON.

Traffic factor	Distance				
	20 km	40 km	60 km	80 km	100 km
18	DWDM DD PIN	DWDM DD PIN	OOK Coherent	OOK Coherent	OOK Coherent
12-15	DWDM DD PIN	OOK Coherent	OOK Coherent	OOK Coherent	OOK Coherent
6-9	OOK Coherent	OOK Coherent	OOK Coherent	OOK Coherent	QPSK Coherent
3	OOK Coherent	OOK Coherent	OOK Coherent	QPSK Coherent	QPSK Coherent
1	DWDM DD RSOA-based	DWDM DD RSOA-based	QPSK Coherent RSOA-based	QPSK Coherent RSOA-based	QPSK Coherent RSOA-based

Table 6
Transmission technology solutions for the sensitivity analysis when diverse cost variations of coherent detection technologies are applied, for the scenario of 128-ONU PON with a traffic factor of 3.

Cost reduction	Distance				
	20 km	40 km	60 km	80 km	100 km
20%	OOK Coherent	OOK Coherent	OOK Coherent	QPSK Coherent	QPSK Coherent
5–15%	DWDM DD APD	DWDM DD APD	OOK Coherent	QPSK Coherent	QPSK Coherent RSOA-based
No cost reduction	DWDM DD APD	DWDM DD APD	DWDM DD RSOA-based	DWDM DD RSOA-based	QPSK Coherent RSOA-based

and DD has been replaced by UDWDM technologies with coherent detection (with OOK modulation for 60 km, and with QPSK modulation for 80 km). The reason is that this cost reductions are enough to trigger the possibility to reduce also cost by increasing the splitting ratio of the splitter and therefore reduce the overall cost due to fiber length. The high sensitivity of the coherent solutions can compensate the extra insertion loss of the splitter. So we can see in Tables 2 and 4, that the splitting ratio of the secondary remote node changes from 1:2 to 1:8. The same happens at 20% cost reduction, at 60 and 80 km. Moreover the DWDM colored technology with OOK modulation and DD using APD, is replaced by UDWDM with coherent detection and OOK modulation, for the same reason explained for the cases in Table 5. We conclude that if the cost of coherent transmission technologies goes down to -20% or less, the influence of cost on the adoption of the coherent technology is high. Nevertheless, we can affirm that our results hold within an acceptable range.

5. Conclusion

In this work we investigate the optimal design of future LR TDM/WDM PONs by considering relative cost and physical properties (such as optical power and insertion loss) of the devices and fiber to be installed in the network. The devices can only support one of the available WDM transmission technologies, namely: DWDM with direct detection, UDWDM with coherent detection, colorless RSOA-based DWDM with direct detection, and colorless RSOA-based UDWDM with coherent detection. Our proposed MILP model evaluates the optical network configuration using different transmission technologies that may operate at different line rates. As a result, the model can select the optimal transmission technology and the most convenient splitting ratios of the remote nodes, taking into account bandwidth allocation, capacity, and power budget constraints. The optimal transmission technology is the one accomplishing all the requirements with minimal cost for a given network scenario.

For high distances up to and beyond 100 km, we find that the most appropriate solution is based on coherent detection. Colorless DWDM RSOA at the ONUs with coherent detection for low traffic and high distances and RSOA with direct detection for low traffic and low distances, are the technologies that suffice all the requirements with lowest cost. On the other hand, DWDM-based strategies with direct detection can serve the scenarios for low to medium distances. The splitters with high splitting ratio allow higher wavelength capacity sharing, however, they insert higher losses, which in some cases can only be solved with a transmission technology with high sensitivity. On the other hand, low splitting ratio at the splitters can lead to higher deployment of fiber segments, increasing the total fiber length cost.

Finally, we also analyze the cost sensitivity of the transmission technologies based on coherent detection given that they are still under research and development, and hence, their projected cost is difficult to estimate. We notice that the optimization process becomes strongly affected only when the cost of these technologies is reduced by 20% or more. For variations in the cost from $+5\%$ to $+20\%$, the results remain unaffected, while variations between -15% to -5% report some exceptional variations in the results. This suggests that our results and conclusions on the role of coherent detection in LR-PON hold for an acceptable range of cost projections for this technology.

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References

[1] Y. Luo, X. Zhou, F. Effenberger, X. Yan, G. Peng, Y. Qian, Y. Ma, Time-and wavelength-division multiplexed passive optical network (TWDM-PON) for next-generation PON stage 2 (NG-PON2) (Feb.), J. Lightwave Technol. 31 (2013) 587–593.

[2] G. Talli, P.D. Townsend, Feasibility demonstrator of 100 km reach DWDM super PON with upstream bit rates of 2.5Gb/s and 10Gb/s,(March), OFC, Anaheim (2005).

[3] Optical Seamless Access Evolution (OASE) European Project, Requirements for European Next-Generation Optical Access Network, D.2.1. ⟨http://www.ict-oase.eu/⟩, 2011 (accessed, 01.03.14).

[4] D.P. Shea, J.E. Mitchell, Long-reach optical access technologies, (September), IEEE Network 21 (5) (2007) 5–11.

[5] M. De Andrade, A. Buttaboni, M. Tornatore, P. Boffi, P. Martelli, A. Pattavina, G. Gavioli, Design of long-reach TDM/WDM passive optical access networks, (October), XVth Int. Telecomm. Network Strat. Plan. Symp. (NETWORKS) (2012) 1–6.

[6] M. De Andrade, M. Tornatore, A. Pattavina, Optimization scheme for WDM-based transmission technology selection in future passive optical networks (September), OSA/IEEE J. Opt. Commun. Networking (JOCN) 5 (9) (2013) 1010–1020.

[7] J. Li, G. Shen, Cost Minimization Planning for Passive Optical Networks, (February), NFOEC, San Diego, 2008 (NThD1).

[8] Y. Kim, Y Lee, K. Han, A splitter location/allocation problem in designing fiber optic access networks, (April), Eur. J. Oper. Res. 210 (2) (2011) 425–435.

[9] B. Lin, L. Lin, P-H. Ho, “Cascaded Splitter Topology Optimization in LRPONs,” (June), ICC, Otawa, 2012.

[10] C. Ranaweera, M.G.C. Resende, K. Reichmann, P. Iannone, P. Henry, K. Byoung-Jo, P. Magill, K.N. Oikonomou, R.K. Sinha, S. Woodward, Design and optimization of fiber optic small-cell backhaul based on an existing fiber-to-the-node residential access network, (September), IEEE Commun. Mag. 51 (9) (2013) 62–69.

[11] B. Jaumard, R. Chowdhury, “Location and Allocation of Switching Equipment (Splitters/AWG) in a WDM PON Network,” (August), ICCCN, Maui, 2011.

[12] G. Kramer, B. Mukherjee, G. Pesavento, Ethernet PON (ePON): design and analysis of an optical access network, (July), Photon. Network Commun. J. 3 (3) (2001).

[13] D. Nikolova, B. Van Houdt, C. Blondia, Dynamic bandwidth allocation algorithms for ethernet passive optical networks with threshold reporting in telecommunication systems, (January), Telecommun. Syst. J. 28 (1) (2005) 31–52.

[14] T. Ngo, A. Gravey, D. Bhadauria, Controlling QoS in EPON-based FTTX access networks, (October), Telecommun. Syst. J. 48 (1-2) (2011) 203–217.

[15] D. Kong, et al., Novel high-sensitivity coherent transceiver for optical DPSK/DQPSK signals based on heterodyne detection and electrical delay interferometer, (March), Chinese Opt. Lett. 10 (3) (2012) 030603.

[16] D. Lavery, et al., Demonstration of 10∼Gbit/s Colorless Coherent PON Incorporating Tunable DS-DBR Lasers and Low-Complexity Parallel DSP, (March), OFC/NFOEC, Los Angeles, 2012 (PDP5B.10).

[17] L. Marazzi, et al., Network-embedded self-tuning cavity for WDM-PON transmitter, Opt. Express 20 (2012) 3781–3786.

[18] P. Chanclou, et al., Demonstration of RSOA-Based Remote Modulation at 2.5 and 5 Gbit/s for WDM PON, (March), OFC/NFOEC, Anaheim, 2007 (OWD1).

[19] S.P. Jung, Y. Takushima, Y.C. Chung, Generation of 5-Gbps QPSK Signal using Directly Modulated RSOA for 100-km Coherent WDM PON, (March), OFC, Los Angeles, 2011 (OTuB3).

[20] R.G. Jeroslow, Logic-based decision support: mixed integer model formulation, Elsevier, North-Holland, 1989.

[21] CPLEX Optimizer, IBM, ⟨http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/⟩.