**Evolution Strategies for the Next Generation Passive Optical Networks**

Jorge Galveias, Nº 63134, IST

Abstract— The study carried out in this paper makes an extensive use of Integer Linear Program formulation to comprehend how several future passive optical networks may look like in terms of costs, focusing our attention in the upstream channels of those networks.

The study starts from the paper “Optimizing the Migration to Future-Generation Passive Optical Networks” by analyzing its hybrid TDM/WDM PON and Integer Linear Program (ILP). The number of ONUs in the PON was varied from 16, to 32 and 64.

Then two ILP models, ILP model number one and two, are presented, which major difference from “Optimizing the Migration to Future-Generation Passive Optical Networks” is the introduction of the tunable lasers at ONUs, and no line rate upgrades are allowed (the wavelength channels work only at 10 Gbps). Different tunable lasers are tried and so as different number of ONU in the PON for each model. Such models are tested under the same circumstances and compared.

The next step is to evolve ILP model number one to provide line rate upgrade and analyses the results.

Finally, the paradigm of network is changed and we study a PON which uses an arrayed wavelength granting at the central office to extend the capacity of the upstream direction in as needed fashion “. Once again, several setups for the simulation are tested, with an ILP formulation done on purpose for this paradigm, and compared.

Index Terms— Hybrid TDM/WDM PON, CWDM, DWDM, AWG, Mixed Integer Linear Programming

I. INTRODUCTION

The optical networks at the access level have gained a rising importance and the need to reduce the operational expenditures (OPEX) of these networks resulted in the appearance of the passive optical networks (PONs). The basic structure of such network is composed by one OLT, at the service provider’s premises, several client optical terminals, the so called Optical Network Units (ONUs) and one power splitter, in between those two elements.

In the downstream direction, the signal coming from the OLT is cloned at the power splitter, using couplers (passive elements), and send to each of the N clients. Now the uplink is a shared medium whose access is managed by one algorithm following the time division multiple access technique (TDMA).

From the group of PONs already mass deployed, the EPON and GPON take a big piece of the action. The former is working at 1 Gbps in both uplink and downlink, and the latter is providing up to 2.4 Gbps in the downlink and 1.24 Gbps in the uplink.

However, access packet based network’s traffic is growing in a sustained way, due to emerging or grow in utilization of applications such as HD IPTV, Peer-to-Peer, HD web video streaming. Thus the upgrade of the existing PONs must be done, sooner or later. The upgrade of an existing access network is never an easy question to deal with, since there are several interests that need to be guaranteed, or at least a good compromise between them must be found [1]. On this topic, [1] offers an extensive perspective on such step regarding the minimization of the CAPEX cost, maintenance of the fibers structure, coexistence with the previous system already deployed, reutilization of the existing resources.

![Figure 1.1 – a) legacy PON, b) partial upgrade for 10G-PON, c) extending capacity by adding downstream (and/or upstream) channel to a set of ONUs, d) extending capacity by adding more channels to sets of ONUs as needed][1]

[1] comprehends the two major steps towards the upgrade of a classic PON, so called legacy PON. The first step deals with the upgrade of the downstream signal and the upstream signal, first the downstream and then the upstream. At this stage the backward compatibility must be guaranteed and so an extra downstream signal is used to provide service for the upgraded ONUs/ONTs. The disadvantage of this approach is the need for wavelength blocking filters at each ONU in order to separate the bands. Regarding the upgrade of the upstream channels, it can be added another wavelength working at a higher data rate but the OLT must be added a WDM filter to separate the old and upgraded OLT (Figure 1.1/a). A cheaper approach, regarding the upstream channels, considers the utilization of the same upstream band for both the old and new data rates. In this case, the challenge is the need for a burst receiver at the OLT that need to adapt its sensibility so to receive both data rates in the same band.
The second stage of evolution comprehends the utilization of several wavelengths in PONs. In this stage the WDM-PONs and Hybrid TDM-WDM PONs come along. The former is a highly disruptive way of PONs’ upgrade, since the remote is no longer a power splitter, instead it is an arrayed waveguide grating (AWG). The AWG is a router of wavelengths, in the downstream direction, and a multiplexer of wavelengths, in the upstream direction, so that, unlike the legacy PON, the WDM-PON is a point-to-point network. The advantage of the WDM-PON is that each ONU/ONT has a dedicated wavelength in the downstream and upstream and so the bandwidth per client is huge. But there are several drop backs: the ONUs/ONTs are colored\(^1\); fixed assignment of wavelengths to ONUs is inflexible since a wavelength cannot be reused by more than one client.

On the other hand, Hybrid TDM-WDM PONs exploit the WDM technology but the remote node is a power splitter (P2MP network) and so only the end-devices of the network need to be changed. The wavelengths in the system are shared in time by the ONUs increasing the flexibility of the network and are added in “as needed” fashion.

In short, Figure I.1 summaries the idea supporting the evolution of PONs, which, starting from the classical PON (Figure I.1 (a)), introduces one wavelength at a higher data rate in the downstream and then in the upstream (Figure I.1 (b)). The next step is to increase the number of wavelengths so to reduce the number of ONUs sharing the same wavelength, creating several groups of ONUs (Figure I.1 (c)). Finally each groups of ONUs is given extra wavelengths in “as needed fashion” (Figure I.1 (d)). The evolution process seen in Figure I.1 comprehends two fundamental properties, which are the backward compatibility with the classical PON, and flexibility regarding the wavelength assignment.

In the context of the access networks, [2] used the ILP formulation to simulate several network paradigms with many restrictions. The purpose of its author was to study the PON planning strategies, for single-staged PONs or multi-staged PONs, taking into account the restrictions each PON system has. The study carried out for this paper is a bit different but have the same fundamentals, which is cost minimization for a certain network paradigm. The ILP formulations presented in [2] were fundamental to understand how the network planning and ILP formulation meet together.

[3] take the upgrade investigation to a next level, considering a Hybrid TDM/WDM PON that provides an “as needed” fashion of upgrading the clients, taking into account their needs and a cost policy. The main goal of such paper is create several paradigms of evolution for hybrid TDM/WDM PONs at the level of the ONUs by using different types of devices, namely single wavelengths transceivers or groups of transceivers, and compare the costs. Even so, WDM-PON architectures are being considered [4], but such networks need to change the remote node (from power splitter to AWG), which is a disruptive move, and it’s crucial to evolve the network in a smooth way [1], providing coexistence with the legacy PONs and minimizing the disruption of the service for the clients who are not migrating.

Following this philosophy of evolution, [3] does the study, using Mixed Integer Linear Program (MILP) formulation, of the TDM-WDM hybrid PON in which the remote node is not changed, remaining a power splitter, and extra wavelength channels are added on an “as needed” fashion to support ONUs that require upgrades. In [3] several setups, each with a specific pricing policy, for the TDM-WDM hybrid PON are studied, using sixteen clients to compare the cost of upgrading the network for each setup. These simulations consider a traffic increasing rate of 1.5 per period and simulate six periods of evolution where the wavelength channels, uplink channels, can work at 10 or 40 Gbps.

The article [5] shows an interesting upgrade of the upstream channels for GPONs taking advantage of temperature dependent transmission characteristic of the lasers of such PONs, the distributed feedback lasers. The variation of the transmitter wavelength with the temperature is exploited to divide the GPON receiver band in four sub-sections. So on the PON system, the clients would be divided in four types/groups, its ONUs would be thermally conditionated to match a specific sub-band within the four possible. Each group would then have at its disposal 2.5 Gbps to share among the ONUs of the same group, paradigm that promises an overall total upstream data rate of 10 Gbps, with minor changes at the ONUs.

II. MIGRATION SCENARIO TO THE NEXT GENERATION PON

A. Initial Considerations

[3] studies and formulates an evolution paradigm for PONs base on an Hybrid TDM-WDM PONs worth to be explained.

1) Paradigm of Hybrid TDM-WDM PON network

An hybrid TDM-WDM PON is a network that uses both TDM and WDM techniques. Either upstream and downstream have a grid of wavelengths whose channel’s spacing depends the WDM technology (CWDM\(^2\), DWDM or something else) in question. This way several wavelengths flow in the network (WDM principle). Still the number of wavelengths in each direction is most likely to be fewer than the number of ONUs, so there are groups of ONUs which share one or several wavelengths in time (TDM principle).

Adding the bonus of having no need for remote node substitution, the hybrid TDM-WDM PON keeps exploring the statistical multiplexing of the channels done in classical PONs, which is an important features for networks that carry bursty traffic. If a groups of ONUs, containing four ONUs, share a 1 Gbps wavelength, it is expected that each ONU can use 250 Mbps. Still, if in a given moment, one or more ONUs are using less than 250 Mbps and another ONU needs to use more than 250 Mbps, there is no problem, as long as the total capacity of the wavelength is not exceeded.

[3] starts from the paradigm of a single wavelength per direction wavelengths and moves towards an Hybrid TDM/WDM PON (as the demand by customers increase, from period to period), where only the end devices of the network need to be upgraded. However one of the golden rules for upgrading an existing network is never waste the previous

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\(^1\) Term used to say that each ONU must operate with its own wavelengths, which are different from the wavelengths the other ONUs use.

\(^2\) CWDM uses a channel spacing of 20 nm
resources, which in a hybrid TDM/WDM PON are the transceivers (end devices of the network).

As the new wavelength channels (that can work at 10 Gbps or 40 Gbps) are introduced in the PON, consequence of the increase of bandwidth per client, it is crucial to figure who are the clients that actually need an upgrade in its end device (that need to increase its number of transceivers), so to minimize the upgrading cost. To accomplish that, [3] uses a multistep cost-and-network-upgrade model based on Mixed Integer Linear Programming (MILP) formulations and pricing policies. Such pricing policy considers the cost of single wavelength transceivers during the upgrade of the network (for both OLT and ONU), and has no limit in the number of wavelengths channels that can be introduced in the network. So, the simulation of the MILP ends when the number of periods introduced by the user is over. Note that we only want to upgrade the upstream channels of the networks.

That is just the first MILP developed that comprises this paper. Two more have been developed, MILP formulation number one and two. Instead of using single wavelength transceivers, they use tunable lasers at the ONU and receivers at the OLT. Moreover, the number of wavelengths that can be introduced in the PON is just eight (it uses the CWDM grid - ITU-T G694.2- and the first channel is used for the initial upstream wavelength the PON has, so called legacy wavelength) and no line rates are allowed. All the wavelengths work at the same data rate, 10 Gbps.

For the first model, each laser has its own wavelengths and do not overlap with the wavelengths of the other lasers, as the Figure II.1 shows. The wavelength number one, in blue, is the legacy wavelength. Nevertheless, different ONUs can use lasers that transmit the same wavelengths at the same time. Figure II.2 shows several setups, one per row, with different wavelengths per laser. In the first row, four lasers are needed to fill the entire CWDM band and the ONUs will be given one of such laser needed. Note that one ONU with the Laser 1, can be given another Laser 1 so to transmitter both wavelengths such laser can transmit, wavelength #1 and #2, at the same time.

3) MILP Formulation from [3]

Variables:

- $l_{k,i,j}$ binary variable that is 1 if the $i$th ONU is operating on wavelength $j$ with rate $k$; note that an ONU, in order to support an additional wavelength $j$, needs to be equipped with an additional transceiver;
- $c_{k,j}$ binary variable that is 1 if the $j$th wavelength is operative on rate $k$;
- $\beta_{i,j}$ binary variable that is 1 if the $i$th ONU has any traffic over wavelength $j$;
- $U_{\text{max}}$ integer variable that represents the maximum bandwidth occupation over all wavelengths.

Constants:

- $K$ set of line rates supported by the PON;
- $N$ set of ONUs existing in the PON;
- $L$ set of wavelengths that can be used in the PON;
- $\alpha$ cost per unit of bandwidth to support load balancing over all wavelengths;
- $R_k$ value in Mbps of the $k$th line rate;
- $M$ value used to obtain a binary number out of an integer, and accomplishes : $M > \beta_{i,j}$;
- $F_i$ maximum number of wavelength channels that ONU $i$ can support.

Constants for Multiple Periods: The following constants will change with every period in which we apply the MILP, in order to calculate how a PON evolves. These constants will link one period to the other.

- $W_{k,j}$ cost to support wavelength $j$ with rate $k$ at the OLT;
- $Z_{k,i,j}$ cost to support wavelength $j$ with rate $k$ at the ONU $i$;
- $\Omega_j$ previous line-rate value of $j$th wavelengths before running the MILP;
- $B_i$ guaranteed bandwidth for ONU $I$;
- $E_i$ set of wavelengths that have not been allocated to ONU $i$ in any previous step;
- $F_{i,0}$ number of wavelengths channels that ONU $i$ previously supported.

Objective Function:

$$\min \left\{ \sum_{k=1}^{K} \sum_{i=1}^{N} \sum_{j=1}^{L} Z_{k,i,j} l_{k,i,j} + \sum_{k=1}^{K} \sum_{i=1}^{N} \sum_{j=1}^{L} W_{k,j} c_{k,j} + aU_{\text{max}} \right\}$$
Subject to:

\[
\begin{align*}
\sum_{j=1}^{K} R_{p,i,j} & \geq \sum_{j=1}^{N} b_{w_{ij}} : \forall j \in L \quad (I.2)
\sum_{j=1}^{K} R_{p,i,j} & \geq b_{w_{ij}} : \forall j \in L \quad (I.3)
\beta_{p,i,j} & \geq \frac{b_{w_{ij}}}{M} : \forall i \in N, j \in L \quad (I.4)
\beta_{p,i,j} & \leq b_{w_{ij}} : \forall i \in N, j \in L \quad (I.5)
\beta_{p,i,j} & \leq F_i - F_o : \forall i \in N \quad (I.6)
\sum_{j=1}^{K} c_{p,j} & \leq 1 : \forall j \in L \quad (I.7)
\sum_{j=1}^{K} I_{k,ij} & \leq 1 : \forall i \in N, j \in L \quad (I.8)
I_{k,ij} &= (c_{p,j}) AND (\beta_{p,i,j}) : \forall k, \forall i \in N, j \in L \quad (I.9)
U_{\text{max}} & \geq \sum_{j=1}^{N} b_{w_{ij}} : \forall j \in L \quad (I.11)
\end{align*}
\]

This model corresponds to the situation where the lasers used are allocated in the CWDM band the way Figure II.1 is showing.

Variables:

- \( U_{p,\text{max}} \) integer variable with the maximum value of bandwidth load among all the wavelengths belonging to the same group, where \( p \) is the index of that group.
- The wavelengths of the same group can be transmitted by the same tunable laser.
- \( b_{w_{p,ij}} \) integer variable that represents the bandwidth in the \( j \) wavelength of the \( p \) group demanded by the ONU \( i \).
- \( c_{p,j} \) binary variable that is 1 if the \( j \) wavelength of the \( p \) group is available in the PON system or not.
- \( \beta_{p,i,j} \) binary variable that is 1 if the ONU \( i \) wants to use the wavelength \( j \) of the \( p \) tunable lasers.
- \( I_{k,ij} \) binary variable that is one if the ONU \( i \) has traffic over the \( j \) wavelength of the \( p \) tunable laser.

Constants:

- \( L_p \) number of wavelengths the \( p \) tunable laser has.
- \( N \) number of ONUs in the PON.
- \( P \) set with the groups of wavelengths/different tunable lasers that can be used.
- \( Z_{p,ij} \) cost to support the wavelength \( j \) of the \( p \) tunable laser by the ONU number \( i \).
- \( W_{p,j} \) cost to support the \( j \) wavelength belonging to the \( p \) tunable laser at the OLT side (Introducing a CWDM receiver).
- \( \alpha \) cost per unit of bandwidth to support load balancing over all wavelengths.
- \( R \) is the only data rate available in the model.
- \( B_i \) is the total bandwidth required by the ONU number \( i \).

Objective Function:

\[
F = \min \left[ \sum_{p=1}^{P} \sum_{j=1}^{L_p} Z_{p,ij} + \sum_{p=1}^{P} W_{p,j} + \alpha \sum_{p=1}^{P} U_{p,\text{max}} \right] \quad (I.12)
\]

Subject to:

\[
\begin{align*}
R_{p,i,j} & \geq \sum_{j=1}^{N} b_{w_{ij}} : \forall p \in P, \forall j \in L_p \quad (I.13)
\end{align*}
\]

\[
\begin{align*}
\sum_{j=1}^{K} b_{w_{ij}} & = B_i : \forall i \in N \quad (I.14)
\end{align*}
\]

\[
\begin{align*}
\text{if} (b_{w_{p,ij}} > 0): \beta_{p,ij} &= 1, \text{else}: \beta_{p,ij} = 0 \quad \text{end} ; \forall p \in P, \forall i \in N, j \in L_p \quad (I.15)
\end{align*}
\]

\[
\begin{align*}
\text{if} (c_{p,j} = 1): c_p = 1, \text{else}: c_p = 0 \quad \forall p \in P, \forall i \in N, j \in L_p \quad (I.16)
\end{align*}
\]

\[
\begin{align*}
\sum_{j=1}^{K} c_{p,j} & = c_p : \forall p \in P \quad (I.17)
\end{align*}
\]

\[
\begin{align*}
\sum_{j=1}^{K} \beta_{p,ij} & \leq 1 : \forall p \in P, \forall i \in N \quad (I.18)
\end{align*}
\]

\[
\begin{align*}
I_{k,ij} &= \beta_{p,ij} AND c_{p,j} : \forall p \in P, \forall i \in N, j \in L_p \quad (I.19)
\end{align*}
\]

\[
\begin{align*}
U_{p,\text{max}} & \geq \sum_{j=1}^{N} b_{w_{ij}} : \forall p \in P, \forall j \in L_p \quad (I.20)
\end{align*}
\]
The objective function (I.12) has three parts. The first two parts stand for the cost of supporting wavelength $j$ of the $p$ wavelength group at the ONUs and OLT, respectively. The cost is related with the introduction of tunable lasers with $p$ number of wavelengths to tune at the ONUs and CWDM receivers at the OLT. The third term represents the sum of the maximum utilization among all wavelengths belonging to the same group $p$. Note that such sum has a small factor $\alpha$ behind so to give lower priority to the load balancing among the $p$ groups of wavelengths. So the idea is to minimize both the cost of the tunable lasers and receivers and minimize at the same time, with a small priority, the utilization of the channels belonging to the same wavelength group.

Equation (I.13) constrains the wavelength allocated to the PON must have enough capacity to support the bandwidth required by ONUs. Equation (I.14) clarifies that the traffic load spread across several wavelengths for a certain ONU must equal the total traffic demand of that ONU. Equation (I.15) constraints that if the ONU number $i$ wants to use the wavelength $j$ of the $p$ tunable laser, the corresponding beta variable must indicate it. Equation (I.16) indicates that downgraded are not allowed and so a wavelength channel once support in the PON will be supported until the end. Equation (I.17) constrains the wavelengths from the same $p$ group must to be added to the PON at the same time. Equation (I.18) stands to indicate each tunable laser can only transmit one wavelength at a time. Equation (I.19) constraints that a certain ONU can only use one laser if necessary ($\beta_{kij} \text{\ equals \ one}$) and is the OLT providing such wavelength ($c_{kj} \text{\ equals \ one}$). Finally (I.20) guarantees that each $U_{p,max}$ keeps the maximum value of bandwidth demand over the $p$ group of wavelengths.

5) MILP formulation number two

This second model was generically showed and explained using the Figure II.2. The MILP formulation one can serve, almost, the requirements of this model, namely the constraints required are the same present in the model one. The problem is that the model one was done using the notion of groups of wavelengths that represented the wavelengths channels each tunable laser could sintonize. And two different tunable lasers don’t use the same wavelengths in the CWDM grid. Now in the model two, two different tunable lasers can use the same wavelengths of the grid, as Figure II.2 shows. Because of this the model one needed to be adapted to build the model two’s MILP. So, the constants and variable at the level of the access lost its dependence with the tunable laser groups ($W_{pj}$ and $c_{pj}$) and were indexed directed to the wavelength channel ($W_g$ and $c_g$, where $g$ is the wavelength channel index). Another transformation happened at the level of the constraints, because the relative index of the wavelength channels (relative to the their wavelength group) needed to be converted to its absolute index. For that a variable transformation was applied, $(p + j - 1 = g)$. Using such transformation, the wavelength channel $g$ is obtained from the wavelength channel $j$ of the wavelength group $p$.

Finally to obtain the MILP model two from the model one the $W_{pj}$ constant is substituted by $W_g$ and the variable $c_{pj}$ is substituted by $c_g$, both in the objective function and constraints.

And every time some wavelength channel need to be verified using variables whose wavelength channel index is related with the wavelength group ($Z_{p,i,j}$, $l_{p,i,j}$, $bw_{p,i,j}$, $\beta_{p,i,j}$), the variable transformation explained is applied.

The $Z_{p,i,j}$, $l_{p,i,j}$, $bw_{p,i,j}$, $\beta_{p,i,j}$, $K$, $L_p$, $N$, $R$ and $B_i$ quantities were reused from the model one and have exactly the same meaning explained in the formulation of that model. As said previously the $W_g$ constant is the substitution for $W_{pj}$ and represent the cost of supporting the $g$ wavelength in the OLT. The same way, $c_{pj}$ is substituting $c_{pj}$ and is a binary variable that is one is the PON is supporting the wavelength channel $g$. The $U_{p,max}$ was substituted by the $U_{g,max}$ which is and integer variable that represents the maximum bandwidth occupation over all the wavelengths.

Objective Function:

$$F = \min \left( \sum_{p=1}^{P} \sum_{j=1}^{J} Z_{p,i,j} l_{p,i,j} + \sum_{g=1}^{G} W_g c_g + \alpha U_{g,max} \right) \tag{I.21}$$

Subject to :

$$\sum_{p=1}^{P} \sum_{j=1}^{J} Z_{p,i,j} c_{p,j} \leq 1, \forall i \in N, \forall G \in M : p + j - 1 = G. \tag{I.22}$$

$$\sum_{p=1}^{P} \sum_{j=1}^{J} Z_{p,i,j} c_{p,j} \leq 1, \forall i \in N, \forall G \in M : k + j - 1 = G. \tag{I.23}$$

The objective function (I.21) has again three parts. The first one is the same seen in the model one, second term stands to for the cost of supporting the wavelength $g$ in the OLT and the third term accounts for the minimization of the channels occupation, with lower priority.

Regarding the constraints of this model, apart from the transformations, already said, two extra constraints were added. If the same ONU has one or more lasers that share the same wavelengths, all the wavelengths used to transmit the information in a certain period must be different from each other. The constraint (I.22) and (I.23) are guaranteeing this statement in the model, at the level of the $1$ and beta variable respectively.

A collateral effect of this last constraint is that we cannot allocate a laser which all wavelengths are supported in a given ONU. For instance, taking the Figure II.2, if a certain ONU has already been allocated with the laser 1 and laser 3 we cannot allocate the laser 2 for that ONU, because by doing that we are not increasing the upload capacity the ONU in question.

B. Results

This section presents some results to illustrate the application of the methodologies described. In this way a C++ program has been developed, which relies on the CPLEX framework to solve the MILP problem and runs on an Intel Core2 Duo at 2.33 GHz processor with 2 GB of memory. Several number of ONUs will be tested in the simulations, namely, 16, 32 and 64.

1) Simulation conditions of [3]

The simulation has 16 ONUs, belonging to two different types, the first type, 6 ONUs, can only support one wavelength
channel during the whole simulation \((F_1 = 1)\) and the second type, 10 ONUs, can support up to four \((F_2 = 4)\). At the beginning of the simulation there is only one wavelengths working at 10 Gbps in the PON, serving the upstream, and the first type of ONUs start with 100 Mbps \((bw_{1,i} = 100)\) whereas the second type start with 600 Mbps \((bw_{1,i} = 600)\) each (Note: All the ONUs, regardless of the type, have already allocated one transceiver working at 10 Gbps, whose cost does not entry the MILP). The wavelength channels can work at 10 Gbps or 40 Gbps \((so R_1 = 10 \text{ Gbps and } R_2 = 40 \text{ Gbps})\). The total number of period of the simulation is six and from period to period the traffic demand increases by 50 percent. 

[3] presents the reader with three different pricing policies but only the single-wavelength transceivers policy, so called 1xTx, is going to be consider here. As its name suggests, such pricing policy guarantees that when an ONU needs extra transceivers it will be given a single transceiver at a time, which is able to transmit a single wavelength.

A pricing policy determines the value of \(W_{k,ij}\) and \(Z_{k,i,j}\) taking into account the presence (or not) of the wavelengths in the PON as follows. To calculate \(W_{k,ij}\) for a given period three cases must be analyzed: (i) if the previous line rate of wavelength \(j\) is zero (wavelength channel that have not been deployed yet), then \(W_{k,ij} = 1\) and \(W_{k,ij} = 2.5\) to activate wavelength \(j\) for the first time, (ii) if wavelength \(j\) was active at line rate \(R_1\), then \(W_{k,ij} = 0.1\) and \(W_{k,ij} = 3\) (higher value than in (ii) to reflect the line-rate change), (iii) if wavelength \(j\) was active at line rate \(R_2\), then \(W_{k,ij} = 10^6\) (extreme high value because downgrades are not allowed) and \(W_{k,ij} = 0.1\), Now to calculate \(Z_{k,i,j}\) information from the OLT and the ONU \(i\) is needed. If the ONU \(i\) was already supporting the wavelength \(j\), then \(Z_{k,i,j} = 0.1 \times W_{k,ij}\), otherwise \(Z_{k,i,j} = W_{k,ij}\).

For the simulations where the number of ONUS was changed from 16 to 32 and 64, everything was left the same from the already said, except for the number of ONUs each type and their respective initial bandwidth \((bw_{1,i})\). For 32 ONUs, 8 ONUs are type one with \(bw_{1,i} = 82.5\) Mbps and 24 ONUs are type two with \(bw_{1,i} = 247.5\) Mbps. Whereas for 64 ONUs, 12 ONUs are type one using an initial bandwidth of 55 Mbps each, and 52 ONUs are type two using an initial bandwidth of 114.2 Mbps. Note that for all the setups presented, the total initial bandwidth for the ONUs is the same and values 6.6 Gbps.

2) Simulation conditions for MILP formulation one and two

For the models one and two only one type of ONU is considered, whose initial bandwidth is 100 Mbps \((b_{W1} = 100)\). Because we are using the CWDM grid, eight wavelength channels are considered for allocation (Remember one is pre-allocated at the beginning of the simulation). The data rate of the channels is only 10 Gbps, so line rate upgrades are not considered. The data rate increasing pace is not static, instead, from period to period it can vary from 1.3 up to 1.7, according with a uniform distribution.

To calculate \(Z_{p,ij}\) it is necessary to know if the ONU \(i\) has the wavelength \(j\) of the wavelength group (tunable laser) \(p\). If so \(Z_{p,ij} = 0.05\) (representing the OPEX costs). Otherwise the cost of the tunable laser will depend the number of wavelengths \((\text{CWDM grid central wavelengths})\) the tunable laser can use. \(Z_{p,ij} = 1.5 + 0.05\) (CAPEX + OPEX cost) for tunable laser with two wavelengths, \(Z_{p,ij} = 2 + 0.05\), for tunable lasers with four wavelength and \(Z_{p,ij} = 2.5 + 0.05\), for tunable lasers with eight wavelengths. Regarding the \(W_p\) and \(W_{p,j}\) (remember they are the same quantity, \(W_{p,j}\) applied in the formulation of the model one and \(W_p\) for the formulation of the model two), the model two needs to know if the \(g\) wavelength of the grid is available, whereas for the model one it must be known is the wavelength \(j\) of the wavelength group \(p\) is available. If so, \(W_p = W_{p,j} = 0.15\) (Representing an OPEX cost). Otherwise, \(W_p = W_{p,j} = 0.50 + 0.15\).

3) Variation of the Number of ONUs for model from [3]

<table>
<thead>
<tr>
<th>Setup</th>
<th align="right">16@2</th>
<th align="right">16@4</th>
<th align="right">32@2</th>
<th align="right">32@4</th>
<th align="right">64@2</th>
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<tbody>
<tr>
<td>Difference</td>
<td align="right">-0.60</td>
<td align="right">0.950</td>
<td align="right">0.100</td>
<td align="right">1.250</td>
<td align="right">-2.800</td>
<td align="right">1.750</td>
</tr>
</tbody>
</table>

As the number of ONUs change, the period when the cost is higher in the simulations, apart from the period 1, change as well. For 16 ONUs, the higher value of cost happens at the fifth period, but for 32 ONUs and 64 ONUs it moves to the sixth period and second period, respectively. However the percentage of bandwidth allocated does not change because the total bandwidth needed per period does not change for the three different setups.

According to the simulation of 16 ONUs and 32 ONUs the simulation of 64 ONUs was expected to cost around 100 units of cost (when applying a linear rule). However its total cost is well below that, by around 10 units of cost, due to the lower cost of the fifth and sixth period.

4) Results for the Model one and two

The syntax presented in the following graphics of this section follows: number_of_onus_in_the_pon@number_of_wavelengths_per_tunable_laser. For example, 16@2 is refer to the simulation with 16 Onus using tunable laser that can sintonize up to two wavelengths.
The model two tends to have a bigger number of ONUs for the model two at the twelfth period, and so the Laser 2 won’t be further introduced in the model two.

There are two different line rates, $R_1$ and $R_2$ as seen in the Figure III.1. From such figure, note that the tunable laser 1 and tunable laser 6 use the same wavelength channels, namely $\lambda_2$ and $\lambda_3$, but the latter works at $R_2$ Gbps whereas the former works at $R_1$ Gbps. The same happens between the pairs Laser 2 and Laser 7, Laser 3 and laser 8, the Laser 4 and the Laser 9. For a given moment a certain wavelength channel can only operate with a certain data rate, $R_1$ or $R_2$, which means only one type of laser from each pair can be in PON at a given moment. Moreover, since $R_2 > R_1$, once the channel is working at $R_2$ it must not go back to work at $R_1$. This means that, for example, if the Laser 7 is being deliver to the ONUs, the wavelength channel $\#4$ and $\#5$ has been upgraded to work at $R_1$ in the OLT side (by using proper receivers for that data rate), and so the Laser 2 won’t be further introduced in the PON. It was decided to restrict the wavelength channel $\#1$ to work only at $R_1$, and so only eight wavelength channels are available to suffer the upgrade from $R_1$ to $R_2$.

At last, the goal in this section is given a certain PON, with a certain number of ONUs and chosen the number of wavelength per tunable laser, understand when the wavelength channels must be upgraded from $R_1$ to $R_2$ and what is the impact of such upgrade in the cost and in the bandwidth allocated per wavelength channel.

### III. MOVING TOWARDS THE 40 G TECHNOLOGY

#### 1) Initial Considerations

This section deals with the allocation problem of wavelength channels, which can have two different line rates in a single wavelength PON (counting only the upstream channel) as so as the upgrading of the ONUs it is serving. Note that we are still working with the CWDM grid, namely with its upstream channels and the lasers used are still tunable laser. The paradigm of the problem is shown in the Figure III.1 (Using tunable laser of two wavelengths per channel).

There are nine wavelength channels, from which one is pre-allocated, $\lambda_1$, working at $R_1$ Gbps and it is supported by the Laser 0 (it’s not a tunable laser, it’s a single wavelength laser coming from the old PON system.). The other eight channels, from $\lambda_2$ to $\lambda_9$, are going to be allocated using a simulation that is rules by a MILP formulation and a pricing policy.

### Table II.5 - Average bandwidth allocated per period

<table>
<thead>
<tr>
<th>Setup</th>
<th>Model</th>
<th>16@2</th>
<th>16@4</th>
<th>16@8</th>
<th>32@2</th>
<th>32@4</th>
<th>32@8</th>
<th>64@2</th>
<th>64@4</th>
<th>64@8</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>56.7</td>
<td>50.5</td>
<td>42.7</td>
<td>65.47</td>
<td>56.1</td>
<td>45.04</td>
<td>73.6</td>
<td>57.06</td>
<td>45.7</td>
<td></td>
</tr>
<tr>
<td>Two</td>
<td>58.5</td>
<td>53.4</td>
<td>42.7</td>
<td>64.4</td>
<td>52.7</td>
<td>45.04</td>
<td>76.1</td>
<td>62.7</td>
<td>45.7</td>
<td></td>
</tr>
</tbody>
</table>

#### 2) MILP formulation number three

The model is a simple extension of the Model one from, only a new index was introduced, the $r$ index, $r = 1$ for $R_1$ and $r = 2$ for $R_2$ (see Figure III.1) below the laser type alongside with the $p$ index. The model two is not considered in this section, because it would be more complex and time consuming to simulate the transition for the $R_1$, since it has a bigger number of tunable laser types.

Thus, the variables $l_{r,p,i,j}$, $bw_{r,p,i,j}$, $\beta_{r,p,i,j}$ have the same meaning of the model one, but the data rate discrimination is introduced by the $r$ index. The same happens with the $c_{r,k,j}$ and $U_{r,p,max}$ variables. Regarding the constants of this model, only three are different from the MILP formulation model one, which are $Z_{r,p,i,j}$, $W_{r,p,j}$ and $R_r$, all the other remain the same. The $Z_{r,p,i,j}$ represents a cost in the usage of the wavelengths $j$ of the $p$ tunable laser, working at $R_r$ data rate by the ONU number $i$, whereas the $W_{r,p,j}$ is a cost related with the availability of the $j$ wavelength of the tunable laser $p$, working at $R_r$ data rate.

#### Objective Function:

$$F = \min \left( \sum_{r=1}^{R} \sum_{p=1}^{N} \sum_{i=1}^{L_{1,r}} l_{r,p,i,j} Z_{r,p,i,j} + \sum_{r=1}^{R} \sum_{p=1}^{N} \sum_{i=1}^{L_{2,r}} l_{r,p,i,j} W_{r,p,j} + \alpha \sum_{r=1}^{R} \sum_{p=1}^{N} U_{r,p,max} \right)$$ (III.1)

#### Subject to:

$$R_r \times c_{r,p,j} \geq \sum_{i=1}^{N} bw_{r,p,i,j} ; \forall r \in R, \forall p \in P, \forall j \in L_p$$ (III.2)

Since this paradigm is an extension of the model one from the last section, then each tunable laser type can transmit only its own wavelengths and so two different tunable lasers types won’t use the same wavelength channels of the CWDM grid.

Only for the simulations with 32 Onus, the model one is always more expensive than the model two. In opposite, the simulations where tunable lasers of two wavelengths are use tend to oscillate its verdict regarding the more cost efficient model. The simulations where the total number of upgrades performed at the client side is the same for both models, the second model have a cheaper implementation. However the 16@2λ and the 64@2λ simulations do not behave the same way for the model one and two in terms of the total number of upgrades done at the client side. This has to do with the average load per channel. The model two tends to have a higher average load per channel in comparison with the model one, since the receivers are being added at the OLT in a smoother way. This tendency may lead to extra upgrade of ONUs, which is exactly what happens with the simulations mentioned previously. Regarding the 16@2λ simulation, for the model one at the eleventh period the average load per channel is around 61 percent, whereas for the model two such quantities is 75 percent. This difference will determine an extra upgrade of ONUs for the model two at the twelfth period. The same happens for the 64@2λ simulation but for the periods eight and nine, resulting in an extra two upgrades done by the second model that represent the major difference in cost showed in Table II.5.
The objective function (III.1) has three parts as the objective function of the previous chapters. The first and second terms stand to for the cost of supporting the wavelength \( j \) of the wavelength group \( p \) at data rate \( r \) data rate for both the OLT and ONUs. The third term represents the maximum utilization among the channels that can be transmitted by the same wavelength channel and work at a \( R_p \) data rate (this utilization has a lower priority in the objective function expressed by the factor \( \alpha \) which is a small one. So the goal is to minimize the cost of the equipment at the OLT and ONUs, with the awareness of the two possible data rates with which the wavelength channels can work, while minimizing the maximum utilization of the channels. From Equation (III.2) to Equation (III.9), the purpose of such constraints is the same explained for the model one of the last chapter. Equation (III.10) and Equation (III.11) stands to discard the possibility of two different line rates in the same wavelength channels.

3) Results

These section’s simulations were done using same computer of the laser section and were tested setups with 16, 32 and 64 ONUs, tunable lasers with different tuning ranges and two different line rates, \( R_1 = 10 \text{ Gbps} \) and \( R_2 = 40 \text{ Gbps} \). Still the legacy wavelength is the only wavelength that cannot be upgraded from 10 Gbps to 40 Gbps.

For the models described only one type of ONU is considered, whose initial bandwidth is 100 Mbps (\( B_1 = 1 \)).

To calculate the \( Z_{r,p,i,j} \) it is necessary to know if the ONU \( i \) has the wavelength \( j \) of the wavelength group (tunable laser) \( p \) working at \( R_p \) data rate. If so \( Z_{1,p,i,j} = 0,05 \) (representing the OPEX costs) or \( Z_{2,p,i,j} = 0,075 \) (representing the OPEX costs). Otherwise \( Z_{1,p,i,j} = 1,5 + 0,05 \) or \( Z_{2,p,i,j} = 2 + 0,05 \) or \( Z_{1,p,i,j} = 2,5 + 0,05 \) if the simulation uses tunable lasers of 2, 4 or 8 wavelengths per channel, respectively. Whereas \( Z_{2,p,i,j} = 4,5 + 0,075 \) or \( Z_{2,p,i,j} = 6 + 0,075 \) or \( Z_{2,p,i,j} = 7,5 + 0,075 \) if the simulation uses tunable lasers of 2, 4 or 8 wavelengths per channel, respectively. To calculate \( W_{r,p,j} \) it is necessary to know if the wavelength \( j \) of the wavelength \( p \) is working at \( R_p \) data rate. If so \( W_{1,p,j} = 0,15 \) and \( W_{2,p,j} = 0,20 \), representing OPEX costs at the OLT. Otherwise \( W_{1,p,j} = 0,50 + 0,15 \) and \( W_{2,p,j} = 1,50 + 0,20 \), representing CAPEX and OPEX costs.

### Table III.1 - Ratio Between the 40 Gbps side and the 10 Gbps side of the simulations

<table>
<thead>
<tr>
<th>Simulation</th>
<th>16@2</th>
<th>16@4</th>
<th>16@8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio</td>
<td>3,45</td>
<td>5,38</td>
<td>8,78</td>
</tr>
<tr>
<td>Simulation</td>
<td>32@2</td>
<td>32@4</td>
<td>32@8</td>
</tr>
<tr>
<td>Ratio</td>
<td>5,63</td>
<td>6,35</td>
<td>13,01</td>
</tr>
<tr>
<td>Simulation</td>
<td>64@2</td>
<td>64@4</td>
<td>64@8</td>
</tr>
<tr>
<td>Ratio</td>
<td>3,37</td>
<td>5,88</td>
<td>11,83</td>
</tr>
</tbody>
</table>

The direct transition from the 10 Gbps to the 40 Gbps, apart from the legacy wavelength, because of the lasers used, happens for the simulations using lasers with eight wavelengths. This setup for the upgrade is presenting serious disadvantages. Such value, after the technology transition takes place, is lower than for the other setups, with fewer number of wavelengths per laser, almost for the rest of the simulation, recovering one or two periods to the end of the simulation. This is then a quality sign saying the average of the data rate traffic grow factor is not demanding such an abrupt transition between the technologies in question. It is, so, more appropriate to use setup with tunable laser of two or four wavelengths when we start the network with the 10 Gbps technology and aim to face the transition to the 40 Gbps technology.

From Figure III.1, it can be seen that the hardest transitions occurs for the simulations with 32 ONUs, namely for the 32@8. Yet, the higher the number of wavelengths per tunable laser, the higher is the ratio, fact that is related with the increasing price of the tunable laser with the number of wavelengths they can transmit. The aforementioned facts are given more consistency to what it was concluded earlier, about the setups of upgrade using tunable lasers of eight wavelengths.

### IV. AWG AT THE ACCESS LEVEL

1) Initial Conditions

The arrayed waveguide grating (AWG) is the main disruptive component of the next generation passive optical networks, beyond implementations like the hybrid WDM/TDM PONs, the so-called long term future access networks. It can work as multiplexer/demultiplexer and as NxN router [6]. As a multiplexer, the AWG combines wavelengths from different incoming fibers to a single output fiber, increasing the capacity of the system. As a demultiplexer, it separates the wavelengths coming from a single fiber to several output fibers. As NxN router the AWG performs the multiplexing and demultiplexing function at the same time, realizing an Optical Cross-Connect.

The AWG has a cyclic behavior related with the output ports each wavelength is going to be sent. More precisely all wavelengths given by the formula : \( \lambda_j \pm n FSR, \forall n \in [0, \infty) \) are getting out of the same output port of the AWG. The free spectral range (FSR) is the distance in nanometers between two wavelengths using the same output port.
In Figure IV.1, it can be seen that the wavelength channel #1 uses the port one, and so as the wavelength channel #9, #17 and #25. Whereas the wavelength channels #8,#16,#24 and #32 use the port M.

The AWG in the WDM-PON networks acts as a remote node, meaning the remote nodes from other predecessor PONs (like 10GEPON, 10 GON or even Hybrid WDM/TDM PONs) need to be replaced. Two problems arise from this replacement, the price of the AWG is far higher than the cost of a specific transmitter corresponding to the specific wavelengths. Moreover, the AWG behavior depends on the temperature, and so, the remote node location might need to be thermally conditioned, which is certainly a wrong way to follow due to OPEX costs.

To overcome these drawbacks, a situation in the middle can be found by minimizing the number of AWGs in the network and at the same time guarantee a good location for them by placing them in the Central Office where the OLTs are located.

So, the idea is to keep the optical distribution network (ODN) the way it always have been (the power splitter are still used as remote nodes), changing the edges of the networks in an “as needed” fashion taking advantage of the free spectral range of the AWG. The ONUs linked to the same power splitter share the same wavelengths, but the number of available wavelengths can be increased if the AWG has more than one FSR for the upstream channels and if needed. So the ONUs start with a specific transmitter corresponding to the wavelengths they can use, which depends the power splitter each ONU is physically linked and, when needed, they can be given other transmitters whose working wavelengths are separated, in nanometers, the last integer number possible of FSRs from the first wavelength assigned, inside a region of channels destined for the upstream communication.

2) MILP formulation four

Variables:
- $c_j$ binary variable that is one if $j$th wavelength is supported in the network;
- $I_{ij}$ binary variable that is one if ONU $i$ is using the $j$ wavelength;
- $\beta_{m,i}$ binary variable that is one if the ONU $i$ is using the output port $m$ of the AWG;
- $U_{max,m}$ integer that represents the maximum traffic load value for the $m$ port of the AWG;

Constants:
- $M$ set of output ports of the AWG;
- $FSR_{upstream}$ number of free spectral ranges for the upstream;
- $W_j$ is cost at the OLT related with the utilization of wavelength $j$;
- $N$ set of ONUs inside the passive optical network;
- $Z_{ij}$ cost of the wavelength $j$ at the ONU $i$;
- $L_m$ set of wavelengths that can flow through the $m$ AWG port;
- $L$ set of wavelengths that can be used by the network;

Objective Function:

\[
F = \min \left( \sum_{j=1}^{N} W_j c_j + \sum_{i=1}^{N} \sum_{j=1}^{L_j} Z_{ij} I_{ij} + a \sum_{m=1}^{M} U_{max,m} \right) \quad (IV.1)
\]

Subject to:

\[
C_j \geq C_j \beta_{m,i} \quad \forall j \in M, \forall \beta \in [0, FSR_{upstream} - 1] \quad (IV.2)
\]

\[
if \left( l \geq 1 + \left( m - 1 \right) \frac{N}{M} \right) AND l \leq m \frac{N}{M} \beta_{m,i} = 1, else: \beta_{m,i} = 0; \forall m \in M, \forall i \in N \quad (IV.3)
\]

\[
\sum_{m=1}^{M} \sum_{i=1}^{N} bw_{ij} \beta_{m,i} = B; \forall i \in N, L_m
\]

\[
= \left[ m, m + M, \ldots, m + FSR_{upstream} \cdot M \right] \quad (IV.4)
\]

\[
if \left( bw_{ij} > 0 \right): l_{ij} = 1; \forall i \in N, \forall j \in L \quad (IV.5)
\]

\[
if \left( \sum_{j=1}^{N} l_{ij} > 0 \right): c_j = 1; \forall j \in L \quad (IV.6)
\]

\[
U_{max,m} > \sum_{j=1}^{N} bw_{ij} \beta_{m,i}; \forall m \in M, \forall j
\]

\[
\in \left[ m, m + M, \ldots, m + FSR_{upstream} \cdot M \right] \quad (IV.7)
\]

\[
R_i c_j \geq \sum_{i=1}^{N} bw_{ij}; \forall j \in L \quad (IV.8)
\]

Equation (IV.1) has three parts. The first one is minimizing the receiver at the OLT, the second stands to minimize the cost at the ONUs, and the last part is balancing the traffic that comes from each port of the AWG, but with less priority expressed by the $\alpha$ factor.

Equation (IV.2) constrains the order of wavelength introduction in the PON (So each wavelength may only be added if its equivalent wavelength in the previous FSR region has already been allocated) Equation (IV.3) stands to find what ONUs belong to each AWG port (the result is stored in $\beta_{m,i}$, since the physical topology of the access network is never changed, as we do not add or remove ONUs, the results of the second constraint concerning the $\beta_{m,i}$ do not change as well from period to period). Equation (IV.4) stands to tell that the traffic spread across the several wavelengths by some customer must be equal the total demand traffic of that same customer. Equation (IV.5) and (IV.6) constraint that the existence of traffic in the wavelength $j$ by the $i$ ONU must be influenced the value of the $l_{ij}$ variable (So that the objective function can account for this cost).

Equation (IV.7) guarantees that the variable $U_{max,m}$ end with the maximum value of the load over the wavelength that flows through the port $m$ of the AWG. And finally the Equation (IV.8) imposes that the resources must be available in the PON system to guarantee the OLT cope with all the traffic demands by the customers.

3) Results

For the simulations of this section, several configurations will be tested, using different number of ONUs (16, 32, 64) and tunable lasers with different tuning ranges.
For the model described only one type of ONU is considered, whose initial bandwidth is 100 Mbps \((B_i^{1}= 100)\). The data rate increasing pace from 1.3 to 1.7, according with a uniform distribution.

The most common commercial AWGs[7] use 32 channels of 100 Ghz (0.8 nm) of bandwidth each, reason more than enough to use this equipment as reference for the simulations.

The costs considered in the ILP of this section have a relative nature and the reference equipment is the 10 Gbps DWDM transmitter.

The CAPEX cost of the receivers and transmitter is the same as in the previous section. The OPEX costs has suffered a ten percent aggravation for both the receivers and transmitters because the DWDM channels demand mechanisms to avoid wavelength drifts.

To calculate the \(Z_{i,j}\) it is necessary to know if the ONU \(i\) has the wavelength \(j\). If so \(Z_{i,j} = 0.055\) (representing the OPEX costs). Otherwise, \(Z_{i,j} = 1 + 0.055\) (CAPEX + OPEX cost). Now, to calculate the \(W_j\), it is necessary to know if the wavelength \(j\) is allocated in the system. If so, \(W_j = 0.165\) (representing the OPEX costs), otherwise \(W_j = 0.50 + 0.165\) (CAPEX+OPEX cost).

The total number of ports for the commercial available AWG can take a wide range of values starting from 4 up to 40. However, the higher value considered is sixteen because the number of FSRs must be equal or greater than two (Remember that at least there is one FSR for the upstream and another for the downstream).

For the simulation with 16 ONUs (Table IV.1) the cost is getting higher as the number of AWG ports (M) increase. For the simulations with the 32 ONUs (Table IV.2), such quantity, first goes down and then goes up. Finally, when 64 ONUs (Table IV.3) are brought to the picture, the cost goes monotonically down. Let’s understand why. A larger number of ports (M) means a higher number of wavelengths available at the beginning of the simulation (so, groups of ONUs with fewer ONUs), and so a higher initial CAPEX cost and a consequent higher OPEX cost to maintain those wavelengths. On the other hand, as the number of ports of the AWG is reduced, there are more moments when the simulation needs to add other wavelengths, which are responsible for extra CAPEX investment beyond the initial investment.

For the simulations with 16 ONUs, as the number of output ports rise, the initial CAPEX investment and subsequent OPEX cost compensates all the initial CAPEX, OPEX and extra CAPEX investments for the simulations using AWGs with fewer ports.

Now, for the simulations with 32 ONUs, the decrease of the extra number of CAPEX investments, when we pass from \(M=4\) to \(M=8\), is the main element that drives the reduction of the overall cost seen in that transition. However the increase of the OPEX cost when we move to the simulation with \(M=16\), which is of about 1.32 units per period in relation with the simulation with \(M=8\), alongside with the significant increase of the total initial cost (cost for the first period), contributes to rise the overall cost of this specific simulation setup.

Regarding the simulations with 64 ONUs, the mean value of the extra CAPEX investments per period, for those periods where it is needed, has increased in relation to the other simulations with fewer ONUs. The aforementioned alongside with the fact that the difference in OPEX costs between two simulations with the same number of ONUs are constant, given by \(\Delta x \times 0.165\), where \(\Delta x\) is the difference in ports between the AWGs of the simulations) result in a decreasing cost with the number of ports of the AWG.

Regarding the bandwidth allocated to the clients, independently of the number of ONUs, the higher the number of ports of the AWG used, the lower is the average occupation of the channels, as expected.

Back to the costs, it was not considered the cost of the AWG element, and so the total costs presented here (Table IV.1, Table IV.2, Table IV.3 ) for the nine simulations and the relations between them, just analyzed, may be influenced, namely the simulation with the 32 and 64 ONUs. If the cost of the AWG is most likely to increase with the number of its output ports, then the simulations with 32 and 64 ONUs may suffer a turnaround regarding the AWG type that guarantee the cheaper implementation, since for these simulations the total costs, seen in the Table IV.2, Table IV.3, does not rise in a monotonic way with the number of ports.

V. CONCLUSIONS

In this paper, four paradigms of passive optical network were studied in different levels, focus on the upstream channels. The main goal was always generate several setups for each paradigm seeking the understanding of the behavior of the paradigms along several setups.

Each of those paradigms, related with the uplink channels of PONs, were built using ILP formulations, since these formulations can be constructed seeking the cheapest cost using one pricing policy.

The first paradigm, came from the reference [3], and its scope was extended by varying the number of clients in the PON. Part of the results from such paper were confirmed, namely the traffic occupation per channel but the wavelength allocation pattern did not match exactly. It was found that for 64 ONUs, the total cost of the implementation was lower than expected by 10 units of cost.

The second paradigm included the CWDM grid at the access network, which proved to be a good possibility to follow due to the maturity of the CWDM components. The
paradigm was sub-divided in two model whose common characteristic is the utilization of tunable lasers. What set those models apart is the way the tunable laser are distributed along the CWDM grid. In the first model, the tunable laser type used have a single piece of the grid, now, in the second model each tunable laser type may share wavelengths of the grid with other tunable lasers types. Inside each mode, several setups were tested, contemplating different number of ONUs in the PON and different number of wavelengths per tunable laser. It was found the simulations with fewer number of wavelength per tunable laser cost less to implement for both model. And, in general the model two is cheaper to implement (not by much) but it’s more complex to manage because of a larger number of wavelength types.

With these two paradigms, it was shown three models with a good capability of being the middle term evolution for the actual passive optical networks, since in all of them it is provided backward compatibility with the legacy system (which is a PON with one wavelength per direction working at 10 Gbps)

Next step done in the thesis was to understand how the model one of the second paradigm would perform while facing the transition for the 40 Gbps, resulting in another ILP model. It was used a cost factor of three between the technologies’ equipments (10 Gbps and 40 Gbps). The conclusion about this model was that for the factor of increasing used (between 1.3 and 1.7) the tunable laser with two wavelengths per channel provide the softer and more adequate (for the values used in this model) transition between the 10 Gbps and 40 Gbps.

Finally the Chapter 5 introduced the DWDM grid in the access network and so as the AWG. The cyclic property of the AWGs was exploited and it was seen how the cost can change (using ILP model IV) when the number of ONUs and output ports of the AWGs change. For this model the ONUs used single wavelength transmitter at 10 Gbps, rather then tunable lasers. It was found that the cost relation between the several setups (corresponding to several values of M), for a certain number of ONUs in the PON, varies with the number of ONUs in the PON.

These two last network paradigm, the hybrid TDM/WDM PON with the possibility to accommodate in an “as needed“ fashion 40 Gbps channels and the PON with the introduction of the AWG at the OLT, may be two possible solution for the long term future PONs. The first implementation’s success depends on the price of the tunable lasers and the feasibility of the a 40 Gbps CWDM channel. And both paradigms face the problem of the colored ONUs. This means the ONUs cannot transmit with every wavelength available in the system, and so this cases a problem of management to the service provider because it needs to have several types of ONUs. The Hybrid TDM/WDM PON may suffer from this problem if the tunable laser chosen does not tune the all CWDM grid (may be an expensive equipment for the access network).

VI. REFERENCES


