

On the Optimization of Survivable Mesh Long-Reach Hybrid WDM-TDM PONs

Dieu Linh Truong, Phan Thuan Do, and Anh T. Pham, *Senior Member, IEEE*

Abstract—Long-reach hybrid wavelength-division multiplexing (WDM) and time-division multiplexing (TDM) passive optical networks (PONs) allow deploying access networks for remote service areas with thousands of customers. Typically, several long fiber cables are run between the central office of the service provider and each service area in order to feed the service area with data flows. In the service area, array waveguide gratings (AWGs) multiplex and demultiplex wavelengths; then splitters split wavelengths in order to serve multiple optical network units. This paper proposes to use a mesh topology in service areas, i.e. AWGs can feed each other. This architecture has two main advantages. First, mesh linkages between AWGs make the network structure more robust with a high possibility to integrate survivable schemes. Second, fewer fibers are required between the central office (CO) and service areas leading to a reduction of total length of fiber deployment; and consequently a reduction of fiber installation and maintenance costs. We support this proposal by showing that i) the proposed architecture is feasible provided some modification/combination of conventional PON devices; and ii) while using our optimal and heuristic algorithms for designing survivable long-reach hybrid WDM-TDM PONs, most of these PONs should use the mesh topology in order to minimize the total length of fiber deployment.

Index Terms—Long-reach Passive optical network (PON); Wavelength-division multiplexing (WDM); Time-division multiplexing (TDM); Survivability; Mesh networks; Heuristic algorithms.

I. INTRODUCTION

Passive optical network (PON) technology is widely accepted as the solution for deploying access networks since it allows sharing single optical fiber among multiple customers at low cost. More recently, the integration of both wavelength-division multiplexing (WDM) and time-division multiplexing (TDM) to PON has been introduced under the name hybrid WDM-TDM PON [1]. In such PON, multiple wavelengths over the same fiber are exploited to carry traffic from an optical line terminal (OLT) in a central office (CO) to a point close to the customers area. Then, an arrayed waveguide grating (AWG) [2] demultiplexes the signal into different wavelengths, each of which goes to a different direction. Finally, each wavelength is split again by a passive splitter before ending at optical network units (ONU) in customer premises. It is shown in [3] that more than 4,000 customers can be served by a branch of a hybrid WDM-TDM PON.

The term *long-reach PON* [4] refers to the PON that covers a long distance. Customers are regrouped in service areas that are 20 to 100 km away from the CO. They share

Dieu Linh Truong is with School of Information and Communication Technology, Hanoi University of Science and Technology, Vietnam. Email: linhtd@soict.hut.edu.vn (corresponding author)

Phan Thuan Do is with School of Information and Communication Technology, Hanoi University of Science and Technology, Vietnam. Email: thuandp@soict.hut.edu.vn

Anh T. Pham is with the Computer Communications Lab., University of Aizu, Japan. Email: pham@u-aizu.ac.jp

extended fibers to connect to CO. Long-reach hybrid WDM-TDM PON [3] at the same time covers a long distance and serves numerous customers thanks to multiple wavelengths. OLTs remain in CO on the service provider side while AWGs, splitters and ONUs reside in service areas. The diameter of a service area could be a few kilometers.

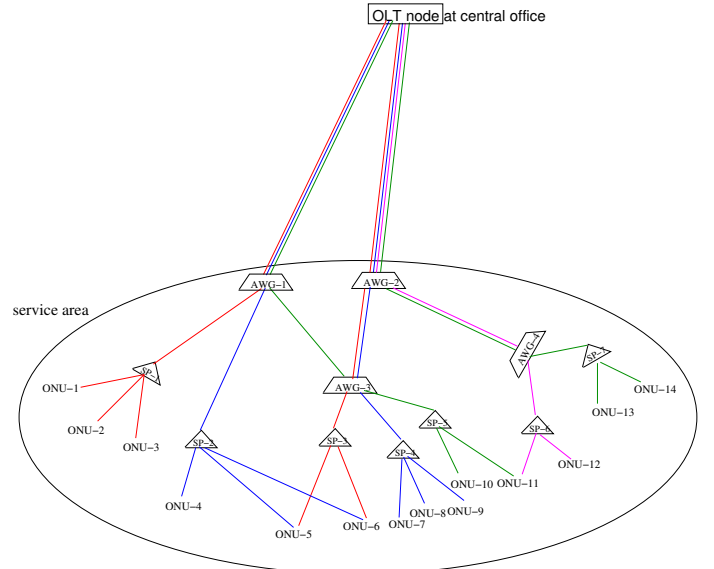


Fig. 1. Mesh hybrid WDM-TDM PON model.

PON splitters are usually arranged in star/tree; however, splitters and/or AWGs may be connected in a ring for providing better reliability [5]. ONUs and splitters can also be organized in a mesh topology as in the light-mesh model proposed in [6]. However, in this paper, we consider another mesh topology for deploying long-reach hybrid WDM-TDM PON, where AWG nodes can be connected to each other (see Fig. 1). This mesh topology has been initially proposed in [7]. In this topology, each AWG node has $N \times N$ ports (i.e., N in-ports and N out-ports). Each port can receive and transmit a waveband instead of a single wavelength. In addition, each AWG node must be capable to forward wavelengths in a relatively arbitrary way between in-ports and out-ports. Although conventional $N \times N$ AWG proposed by Dragon in [8] (see Fig. 2(b) for an example) can demultiplex wavelengths from an input waveband to different out-ports, it does not allow arbitrary wavelength commutation. We will show in Section II that by combining several conventional $1 \times N$ AWGs (see Fig. 2(a)) and $N \times N$ AWGs together in cascade, we can produce a totally *passive* waveband MUX/DEMUX that performs an expected wavelength commutation. Such waveband MUX/DEMUX should be used instead of AWG in the mesh WDM-TDM PONs. Readers are referred to references [2], [9], and [10] for waveband MUX/DEMUXs

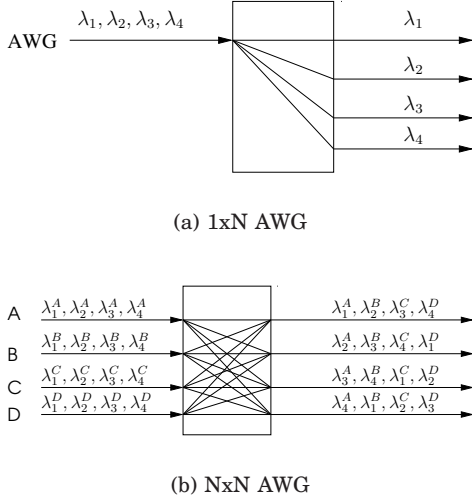


Fig. 2. (a) Conventional 1x4 AWG and (b) conventional 4x4 AWG

with more restricted routing functions.

Two main reasons bring us to consider mesh topology for long-reach PON: 1) the robustness of the mesh structure; and 2) shorter total length of fiber deployment that leads to lower network installation and maintenance costs.

Indeed, the mesh topology is a robust structure that enables network survivability against failures. Survivability means that whenever there is a failure in the network, for example a fiber cut, all working traffic can still be continuously transmitted via deviation routes, thanks to some protection schemes. Although the protection issue of PON has not received much attention in research and development, it should be carefully considered, mostly for large PON, since a failure may affect hundreds of customers due to its high split ratio. Mesh topology allows many backup choices to a connection between an OLT and an ONU because there exist multiple paths between them. This characteristic is absent in the star/tree topology since there exists uniquely one path between a pair of OLT and ONU. Even though it is possible to add backup ability to star PON by connecting each ONU to two different splitters, the choice of backup connection remains limited.

Concerning the network installation and maintenance costs, our arguments are as follows. Mesh topology allows reducing the total length of fiber deployment in long-reach PON. Since in mesh topology, AWGs can feed each other, less fiber cable (in length) needs to be run between CO and service areas for serving AWGs. Indeed, let us consider a branch of PON composed of an OLT and a remote service area. There are two typical cases of connections between an OLT and a service area as shown in Fig. 3:

- All AWGs are fed independently by the OLT.
- Only some AWGs are directly fed by the OLT (AWG-1 and AWG-2 in the figure), the other AWGs (AWG-3 in the figure) are indirectly fed through these AWGs (AWG-2 in the figure). Since the service area diameter is several times smaller than the distance from the service area to the OLT, less fiber needs to be used in case (b) than in case (a).

Clearly, when the number of splitters and ONUs increases, using links between AWGs as in case (b) helps to save more

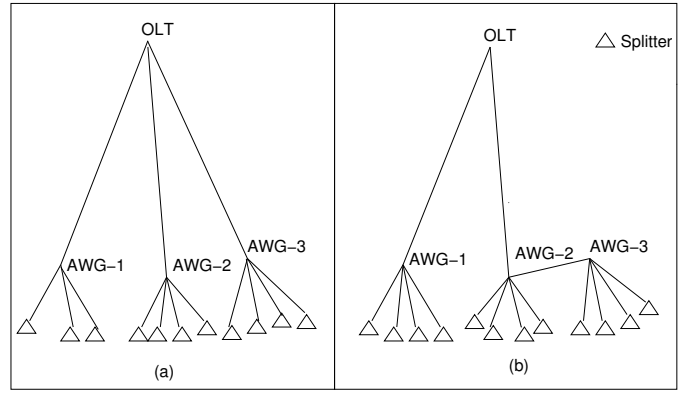


Fig. 3. Two typical connections of an OLT and a service area (ONUs are not shown).

fiber. More complex PON with more OLTs and service areas can be seen as a combination of these simple cases.

Less fiber deployment saves not only fiber cost itself but also fiber installation and maintenance costs. Fiber installation cost includes labor expenses for conduit designing, ground trenching and conduit and fiber placing. The fiber maintenance cost is the cost to inspect conduit and fiber regularly along their path. Both fiber installation and maintenance costs are proportional with fiber length. Therefore, minimizing the total length of fiber deployment could be, to some extent, considered as a valid strategy to reduce the total installation cost of LR-PON [11]. It is also worth noting that in optical networks, beside the fiber, fiber installation and maintenance costs which take about 90% of overall capital investment for the network, there is also equipment cost. However, the equipment cost takes only 10% of overall capital investment [6]. Table I shows fiber related costs given by the US Department of Transportation Research and Innovative Technology Administration in 2005 [12] and the update in 2011 [13]. Table II shows the device costs of PON. We can easily remark that these costs belong to different scales.

In summary, mesh topology can make long-reach WDM-TDM PONs more robust and helps to save the fiber installation and maintenance costs. In this paper we will show that it is indeed possible to build a mesh long-reach hybrid TDM-WDM PON. We will also illustrate through the experimental tests that the mesh topology actually saves fiber for *survivable* long-reach hybrid TDM-WDM PONs. The path protection scheme described in subsection I-A will be used for making the PON survivable. We will propose several algorithms that design the topology for this network with minimal fiber length. The design problem is set as follows: given a set of ONUs to be served, sets of possible OLTs, AWGs and splitters, the objective is to trace out a network topology and routings for all ONUs such that (i) all connections are survivable against single failures and (ii) the total fiber length to be used is minimal. The problem will be described more clearly in Section III.

A. Protection scheme

While some studies focus only on protecting the long distance part between CO and services areas (for example [11]), we are interested in making the whole PON including service areas survivable under any single failure. Similar

Trenching (per mile)	52,000 ~ 77,000 \$ [13]
Conduct & Fiber laying (per mile)	21,000 ~ 54,000\$ [13]
Maintenance (per mile, per year)	3,000 \$ [12]
Fiber (per mile)	1,000 ~ 2,500 \$ [12]

TABLE I
FIBER INSTALLATION AND MAINTENANCE COSTS .

OLT (per unit)	2,500 \$ [14]
ONU (per unit)	50 \$ [15]
Splitter (1x8)	50 \$ [15]
AWG (per unit port)	500 ~ 1000 \$ [16]

TABLE II
PON DEVICE COSTS.

to a large number of studies on network survivability, we consider the single failure scenario where there is at most one failure in the entire network. The failure is assumed to be repaired before other failures may occur. In addition, it is assumed that equipment (at OLT and ONU) is fully protected, i.e. only failure caused by fiber cut is considered.

There are several choices of protection scheme for mesh WDM networks. These schemes include link-based protection, segment-based protection, path-based protection [17] [18]. In link-based protection, each link of the *working connection* (i.e. the connection to be protected) will be replaced by a *backup segment* when the link fails. Consequently, every node along the *working connection* must be capable to switch traffic from the *working connection* to the *backup segments*. Similarly, segment-based protection backs up each *working segment* separately by a *backup segment*, thus the segment end nodes must be capable to switch traffic. In path-based protection, the end-to-end *working path* is protected by an end-to-end *backup path*, thus only the source and the destination nodes need to have the switching ability. Since it is difficult to integrate the switching ability to passive devices of PON such as AWGs and splitters, we decide to use a dedicated path protection scheme for protecting the whole PON. A *working connection* between an OLT and an ONU will be backed up *dedicatedly* by another link-disjoint *backup connection*. When a failure occurs on a fiber link of the *working connection*, the OLT and the ONU, which are active devices, are requested to make switches for diverting the affected traffic to the *backup connection*. AWGs and splitters are not involved in the traffic switching. The requirement of link-disjoint between a working connection and its backup is crucial in order to ensure that at least one of them is in operation when there is a single failure in the network.

Fig. 4 shows an example of two choices of backup connection in a mesh PON where the working connection is OLT→AWG-1→SP-1→ONU-1 and the two choices of backup connection are OLT→AWG-2→AWG-3→SP-2→ONU-1 and OLT→AWG-3→SP-2→ONU-1. Note that in this example, AWG-2 and AWG-3 are in fact waveband MUX/DEMUXs. They should be pre-configured in a way that one of two path choices for backup connection is established.

B. Related works

Although topology design for optical networks has been widely studied, there is little attention on designing PON and mostly long-reach PON with survivable capability. Most existing works such as those in [19], [20], and [21] focus

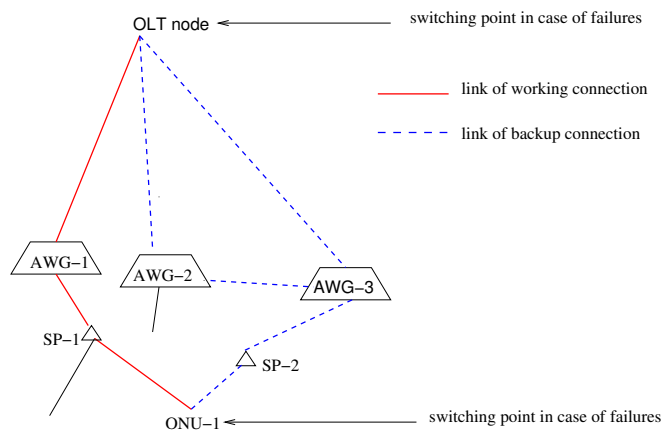


Fig. 4. An example of path protection scheme in mesh PON.

on optical backbone where all nodes have equal roles and can be arbitrarily connected to each other. However, topology design for PON concerns various devices such as OLTs, AWGs, splitters and ONUs with different communication roles. In addition, there are constraints on how different types of devices can be connected. Indeed, OLTs connect only to AWGs, while ONUs connect to splitters. Furthermore, the design problem for mesh PON is subject to the passive nature of PON equipment. For example, the number of intermediate AWGs and the fiber length between OLTs and splitters should be restricted in order to limit end-to-end power loss.

Several studies specifically on PON topology design are presented in [14], [22], and [23] but they focus on star TDM PONs without survivability. Optimal and heuristic solutions have been proposed in [24] for planning long-reach TDM PON with high availability. Automatic protection for long-reach PON in [25] makes use of highly sensitive and fast-response protection modules in order to achieve very fast traffic diversion onto the protection paths upon failure. However, the study of automatic protection does not describe how the working and protection paths are designed. Some other solutions in [16], [26], and [27] design WDM PON or hybrid WDM-TDM PON without survivability. To the best of our knowledge, except our initial work in [7], no other research has been reported in designing mesh long-reach hybrid WDM-TDM PON with end to end protection.

The remaining of the paper is organized as follows. Section II explains how waveband MUX/DeMUX nodes can be built and used for replacing conventional AWGs in the proposed mesh hybrid WDM-TDM PONs. Section III states the topology design problem for survivable mesh hybrid WDM-TDM PONs and discusses its parameters. Section IV describes an optimal design based on an ILP. In Section V, we propose a heuristic algorithm for designing the PON without considering the links between AWGs. Section VI presents an efficient design algorithm, which takes into account the links between AWGs. The numerical results are shown in Section VII. Finally, Section VIII concludes the paper.

II. $\mathbb{N} \times \mathbb{N}$ WAVEBAND MUX/DEMUX ARCHITECTURE

To deploy mesh topology in hybrid WDM-TDM PONs, one needs to use waveband MUX/DeMUXs instead of con-

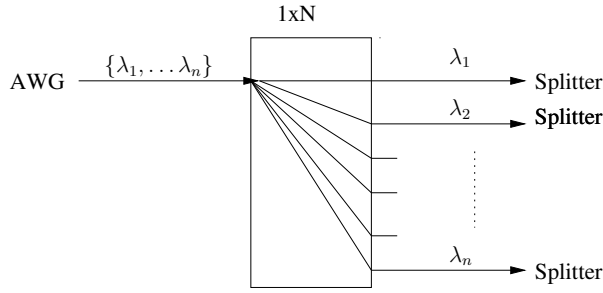


Fig. 5. A node with one waveband input - multiple single wavelength outputs can be realized by a single $1 \times N$ AWG

ventional AWGs wherever a complex routing function is required.

Although the term routing is used, it should be understood that waveband MUX/DeMUXs and AWGs still operate passively once they are configured (e.g. wired together) according to a static routing. This static routing is identified in the network design step by the design algorithms that will be presented in subsequent sections.

In the current section, we propose a way to build $N \times N$ waveband MUX/DeMUX nodes for mesh hybrid WDM-TDM PON using conventional $1 \times N$ or $N \times N$ AWGs. The proposed architectures are not necessarily the best ones, but we use them to show that it is feasible to build $N \times N$ waveband MUX/DeMUX nodes for our mesh PON from conventional AWGs.

We consider 4 types of wavelength routings that may occur in intermediate nodes of a mesh WDM-TDM PON.

A. Type 1 - One waveband input, many single wavelength outputs

This type of node is fed by an OLT or an AWG with a waveband. It then routes wavelengths of the band separately to splitters. A single conventional $1 \times N$ AWG can be used to perform the function of this node (see Fig. 5).

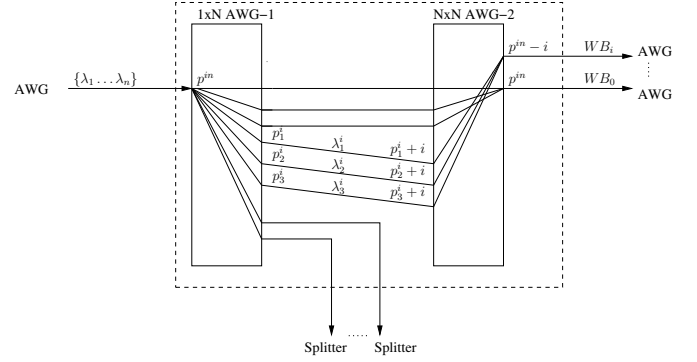
B. Type 2 - One waveband input, many waveband and single wavelength outputs

This node is fed by an OLT or an AWG with a waveband. Then, it routes some sub-wavebands to the next stage AWGs and some single wavelengths to splitters. This node must be a waveband MUX/DeMUX. This section explains how to build this node. Readers are referred to Fig. 6 for an illustration.

Let us denote the set of wavelengths in the input waveband as $\{\lambda_1, \lambda_2, \dots, \lambda_n\}$. Wavelengths $\lambda_k, \dots, \lambda_n$ need to be dropped to splitters while other wavelengths $\lambda_1, \dots, \lambda_{k-1}$ are expected to get out in $m+1$ sub-wavebands at $m+1$ ports that connect with $m+1$ AWGs (or waveband MUX/DeMUXs) of the next stage. We index sub-wavebands by $i \in \{0 \dots m\}$ and denote sub-waveband index i by $WB_i = \{\lambda_1^i \dots \lambda_{b_i}^i\}$. Then:

$$\{\lambda_1 \dots \lambda_n\} = \bigcup_{m}^{i=1} WB_i \cup \{\lambda_k\} \dots \cup \{\lambda_n\}$$

Without loss of generality, we assume that the ranges of sub-wavebands are strictly disjoint with each other and the frequencies in WB_i are greater than those in WB_{i-1} .



$$WB_i = \{\lambda_1^i, \dots, \lambda_{b_i}^i\}$$

Fig. 6. A waveband MUX/DeMUX node with one waveband input - many sub-waveband and single wavelength outputs

First of all, let the input waveband enters a conventional cyclic $1 \times N$ AWG, called AWG-1, at port p^{in} for demultiplexing wavelengths. Then, wavelengths $\lambda_k, \dots, \lambda_n$ are dropped to splitters while the others continue to go to a conventional cyclic $N \times N$ AWG, called AWG-2, for being regrouped to expected sub-wavebands. Now, we will show that it is possible to connect AWG-1 to AWG-2 in some way such that sub-waveband WB_i goes out of AWG-2 at port $(p^{in} - i) \bmod N$ for all $i \in \{1 \dots m\}$.

The correspondence between the input port and the output port of a wavelength when it passes through a conventional cyclic $1 \times N$ AWG or $N \times N$ AWG is given by Kakehashi *et al.* in [10] as following:

$$port_{in} = 1 + (\text{wavelength index} - port_{out}) \bmod N \quad (1)$$

Readers are referred to [28] for more detailed computation and explanation.

Symmetrically, if wavelengths in sub-waveband WB_i get out of AWG-1 at ports p_1^i, p_2^i, \dots and then enter AWG-2 at the same port indexes, they will get out of AWG-2 all together at the port index p^{in} as they have entered AWG-1. However, if these wavelengths enter AWG-2 at ports shifted i indexes, i.e., ports $p_1^i + i, p_2^i + i, \dots$, they will all get out of AWG-2 at port index $(p^{in} - i) \bmod N$. Therefore, in order to direct sub-waveband WB_i to go out at port $(p^{in} - i) \bmod N$ of AWG-2, we need to connect their outgoing ports of AWG-1 with corresponding i -shifted index incoming ports of AWG-2. For example, in Fig. 6, wavelengths of WB_i get out of AWG-1 at outgoing ports p_1^i, p_2^i, p_3^i , these ports need to be connected with incoming ports $p_1^i + i, p_2^i + i, p_3^i + i$ of AWG-2 respectively in order to make WB_i get out of AWG-2 at port $(p^{in} - i) \bmod N$.

Following this method, we can distribute wavelengths from the input port p^{in} into sub-wavebands $WB_i, i = 0 \dots m$ and direct each sub-waveband to output port $(p^{in} - i) \bmod N$.

C. Type 3 - Many waveband inputs, many waveband and single wavelength outputs

This type of node receives multiple wavebands from different AWG/OLTs and produces multiple sub-wavebands to different AWGs (or waveband MUX/DeMUX) in addition to multiple single wavelength outputs to splitters. In this case, we assume that each sub-waveband is composed of wavelengths that come from a single AWG. The node must be a waveband MUX/DeMUX.

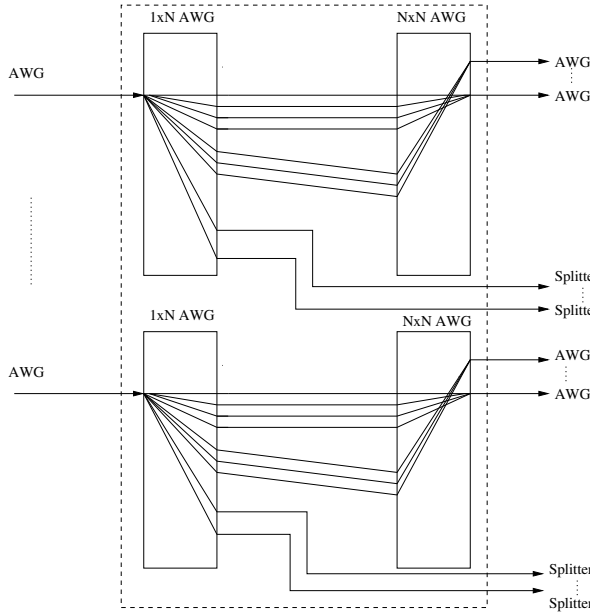


Fig. 7. A waveband MUX/DEMUX node with many waveband inputs - many sub-waveband and single wavelength outputs

This node can be built by repeating the architecture of Type 2 for each waveband input as in Fig.7. In that case, the number of component AWGs does not exceed two times the number of input wavebands. Of course, better architecture may require fewer AWGs.

D. Type 4 - Many waveband inputs, many waveband outputs with mixed bands and single wavelength outputs

This type of node is similar to Type 3 but a sub-waveband output could be composed of wavelengths from multiple AWGs. The node can be built using a similar architecture as Type 3 where an $1 \times N$ AWG receives an input waveband in order to demultiplex its wavelengths. Then the wavelengths to be dropped to splitters are left out. The wavelengths to be regrouped to sub-wavebands enter a set of $N \times N$ AWGs for multiplexing. In order to reduce the number of $N \times N$ AWGs to be used, we should try to multiplex the sub-wavelengths whose ranges are disjoint to each other by the same $N \times N$ AWG.

For example, consider a node to be built that receives 2 input wavebands $\{\lambda_1^A \dots \lambda_{n_A}^A\}$ and $\{\lambda_1^B \dots \lambda_{n_B}^B\}$ respectively from AWG^A and AWG^B . These wavelengths need to be routed to output ports as sub-wavebands: $WB_1 = \{\lambda_1^A \dots \lambda_{i_1}^A, \lambda_{i_2}^B \dots \lambda_{i_3}^B\}$, $WB_2 = \{\lambda_{i_1+1}^A \dots \lambda_{i_2-1}^A\}$, $WB_3 = \{\lambda_1^B \dots \lambda_{i_1}^B, \lambda_{i_3+1}^A \dots \lambda_n^A\}$ where $1 \leq i_1 \leq i_2 \leq i_3$. Wavelengths with the same index have the same frequency. Sub-wavebands with WB_1 and WB_2 can be multiplexed by the same $N \times N$ AWG since they share no common wavelength. Formula (1) should be used again for identifying to which ports of $N \times N$ AWG the wavelengths of WB_1 and WB_2 need to enter, so that each sub-waveband gets out at a distinct port. Similarly, WB_2 and WB_3 could also be multiplexed by the same $N \times N$ AWG, but WB_1 and WB_3 cannot because they share frequencies indexed from $1 \dots i_1$. Fig. 8 illustrates this example.

For this type of node, it is rather complex to determine how many $N \times N$ AWGs are needed. However, the maximum

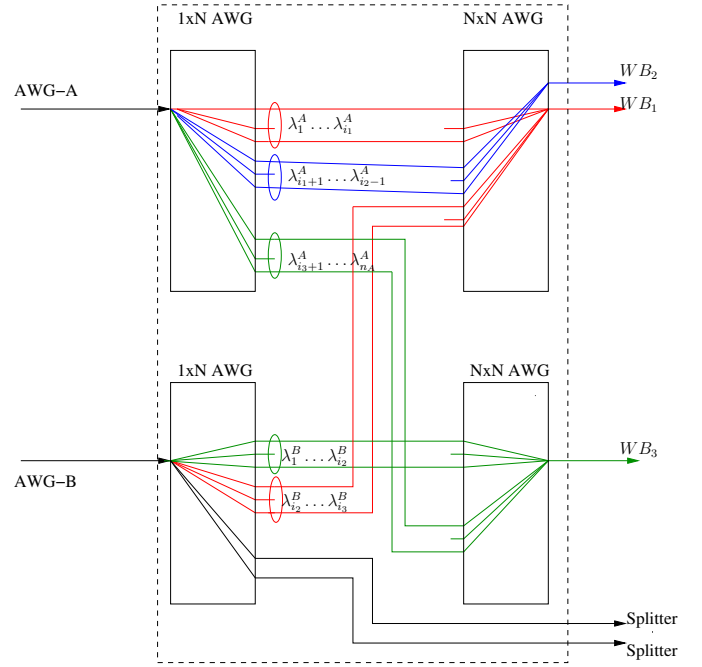


Fig. 8. (Color online) A waveband MUX/DEMUX node with many waveband inputs - many sub-waveband outputs with mixed bands and single wavelength outputs.

number of $N \times N$ AWGs to be used is the minimal number of groups of disjoint output sub-wavebands. In a such group, sub-wavebands share no common wavelengths.

III. SURVIVABLE MESH HYBRID WDM-TDM PON DESIGN PROBLEM STATEMENT

In this paper, a PON is made survivable by using a dedicated path protection scheme, *i.e.*, each working connection between an OLT and an ONU is protected by a link-disjoint backup connection.

The problem of designing a survivable mesh hybrid WDM-TDM PON is stated as follows. *Given* a set of possible locations for OLTs, AWGs or waveband MUX/DEMUXs, splitters, ONUs, and the possible length of fiber needed for connecting any two of them; *the design goal* is to connect these devices together, and to identify for each ONU an upstream/downstream working connection and a link-disjoint upstream/downstream backup connection from a common OLT *such that* the total fiber length is minimized. The minimal fiber length objective comes from the expectation to reduce the fiber installation and maintenance costs. We do not consider the device costs in this design problem. Since we focus on the mesh connection between AWGs, in the current design problem we consider that signal can be routed through several AWGs but split only once by an optical power splitter along the way from OLT to ONU. Each fiber can carry W wavelengths. The design is subject to several constraints due to the characteristic of PON:

- C1 Each splitter connects to one AWG or one waveband MUX/DEMUX by using a single wavelength.
- C2 The wavelength that enters a splitter can serve at most n_{split} ONUs, where n_{split} is split ratio of the splitter.
- C3 Connections between OLTs and ONUs should not be longer than L km.

Descriptions	Notations	Values
Fiber loss (per kilometer)	L_{fiber}	0.2 dB
AWG insertion loss (per unit)	L_{AWG}	4 dB [29]
Splitter excess loss (per unit)		0.5 ~ 1.5 dB [29]
Splitting loss (per unit)	L_{SP}	$10 \lg n_{split}$ dB
Power budget		32 ~ 37 dB [30]
Connection length (kilometer)	ℓ	
Hop count of the connection	h	
Nb. of conventional AWGs along the connection	n_{AWG}	
Nb. of waveband MUX/DEMUX along the connection	n_{WB}	

TABLE III
UNIT LOSSES AND NOTATIONS.

C4 Connections between OLTs and ONUs should not take more than \mathbb{H} hops.

The solution of this problem draws out the physical topology of the PON, routes and assigns wavelengths for connections between OLTs and ONUs. The solution identifies also the wavelengths to come in and to go out each AWG port or waveband MUX/DEMUX port. The OLTs, AWGs, splitters and ONUs need to be configured/wired statically afterwards according to the topology and the routing and wavelength assignment given by design solution.

Parameters \mathbb{L} and \mathbb{H} should be set carefully in order to keep signal at acceptable power level when arriving to ONUs. In the next subsection, we discuss how to set these parameters so that the power loss of end-to-end connections is acceptable.

A. Power loss of end-to-end connections

The power loss of a connection from an OLT to an ONU in decibels is the sum of the *fiber loss* from the OLT to the ONU and the total *insertion loss* at intermediate devices along the connection. Table III lists unit loss values and notations used in the following power loss computation for a connection.

The *fiber loss* of a connection is proportional with its length:

$$\text{Fiber loss} = L_{fiber} * \ell \text{ (dB)}$$

where ℓ is the total fiber length run from the OLT to the ONU. The attenuation coefficient L_{fiber} is equal to 0.2 dB/km for standard single mode fiber at the wavelength of 1550nm.

The total *insertion loss* is composed of the insertion losses of AWGs, of waveband MUX/DEMUXs and of splitters along the connection. The insertion loss of a waveband MUX/DEMUX is equivalent to the total loss caused by its component AWGs. Although the waveband MUX/DEMUXs in types 2, 3 and 4 may be built from more than two AWGs, they cause at most insertion loss equivalent to that caused by a sequence of two AWGs. This is because each wavelength travels through at most two AWGs inside a proposed waveband MUX/DEMUX. Thus, the total insertion loss of an end-to-end connection is:

$$\text{Insertion loss} = n_{AWG} \times L_{AWG} + 2 * n_{WB} \times L_{AWG} + L_{SP} \text{ (dB)}$$

Note that in our hybrid WDM-TDM PON architecture, there is only one splitter along each connection, thus L_{SP} is counted once.

Split ratio	\mathbb{L} (km)	Maximum number of equivalent AWGs
2	162.5	8.125
4	147.5	7.375
8	132.5	6.625
16	117.5	5.875
32	102.5	5.125

TABLE IV
UPPER BOUND OF THE MAXIMUM NUMBER OF EQUIVALENT AWGS AND CONNECTION LENGTH \mathbb{L} FOR A GIVEN SPLIT RATIO.

The insertion loss L_{AWG} of a conventional AWG is about 4 dB regardless the number of channels [2] [29]. The insertion loss for an optical splitter is composed of excess loss, which is 0.5 ~ 1.5 dB [29], and a large splitting loss, which is $10 \lg n_{split}$ dB. Thus, the insertion loss of a splitter is:

$$L_{SP} = 1.5 + 10 \lg n_{split} \text{ (dB)}$$

Consequently, the end-to-end power loss of a connection is:

$$\text{Power loss} = 0.2 * \ell + 4(n_{AWG} + 2n_{WB}) + 1.5 + 10 \lg n_{split} \text{ (dB)}$$

According to an NTT technical review [30], end-to-end power budget for a connection in long-reach PON is about 37 dB. Then, we need to set the following in-equation for all connections:

$$0.2 * \ell + 4(n_{AWG} + 2 * n_{WB}) + 1.5 + 10 \lg n_{split} \leq 37 \quad (2)$$

Let us refer to $(n_{AWG} + 2 * n_{WB})$ as the equivalent number of AWGs along a connection. Table IV shows the upper bound of ℓ and the upper bound of the equivalent number of AWGs when they are estimated independently given a split ratio n_{split} . However, (2) shows that ℓ and the equivalent number of AWGs depend on each other. The greater the number of equivalent AWGs a connection goes through, the shorter the connection should be in order to keep the end-to-end loss under the power budget. It can be seen that, adding an AWG along the connection from OLT to ONU trades off for 20 km shorter of connection length.

In order to simplify the network design problem, we will use two thresholds: maximum connection length \mathbb{L} and maximum hop count \mathbb{H} for controlling the power loss. Since a connection contains one OLT, multiple conventional AWGs and waveband MUX/DEMUXs, one splitter and one ONU, then the hop count of the connection is $h = n_{AWG} + n_{WB} + 2$. Let us consider three cases:

- If no waveband MUX/DEMUX is used along the connection, then $n_{AWG} + 2 * n_{WB} = h - 2$. Thus (2) becomes $(0.2 * \ell + 4(h - 2) + 1.5 + 10 \lg n_{split}) \leq 37$, and then we should set \mathbb{L} and \mathbb{H} so that $(0.2 * \mathbb{L} + 4(\mathbb{H} - 2) + 1.5 + 10 \lg n_{split}) \leq 37$.
- If no AWG is used, all intermediate nodes are waveband MUX/DEMUXs, then $n_{AWG} + 2 * n_{WB} = 2 * (h - 2)$. Consequently, we should set $(0.2 * \mathbb{L} + 8(\mathbb{H} - 2) + 1.5 + 10 \lg n_{split}) \leq 37$.
- If only one waveband MUX/DEMUX is used along the connection, then the equivalent number of AWGs is $h - 1$. Thus, we should set $(0.2 * \mathbb{L} + 4(\mathbb{H} - 1) + 1.5 + 10 \lg n_{split}) \leq 37$.

Table V shows the values of \mathbb{H} calculated in the three cases for given split ratios and given values of \mathbb{L} .

In order to compensate for the power loss due to long transmission distance and high split ratio, optical amplifiers

Split ratio	$\mathbb{L} = 80$ km	$\mathbb{L} = 70$ km	$\mathbb{L} = 60$ km	$\mathbb{L} = 50$ km
No waveband MUX/DEMUX				
2	6.125	6.625	7.125	7.625
4	5.375	5.875	6.375	6.875
8	4.625	5.125	5.625	6.125
16	3.875	4.375	4.875	5.375
32	3.125	3.625	4.125	4.625
Only waveband MUX/DEMUXs				
2	4.063	4.313	4.563	4.813
4	3.688	3.938	4.188	4.438
8	3.313	3.563	3.813	4.063
16	2.938	3.188	3.438	3.688
32	2.563	2.813	3.063	3.313
One waveband MUX/DEMUX				
2	5.125	5.625	6.125	6.625
4	4.375	4.875	5.375	5.875
8	3.625	4.125	4.625	5.125
16	2.875	3.375	3.875	4.375
32	2.125	2.625	3.125	3.625

TABLE V
HOP COUNT THRESHOLD \mathbb{H} FOR GIVEN SPLIT RATIOS AND
CONNECTION LENGTH THRESHOLDS \mathbb{L} .

can be used at CO or at the local exchange in users' area [31]. An erbium-doped-fiber amplifier (EDFA) or semiconductor optical amplifier (SOA) can compensate for up to 30 dB power loss, which is equivalent to seven additional AWGs or 3.5 additional waveband MUX/DEMUXs or more than 100 km of fiber or much higher split ratio. As a result, greater hop count limit \mathbb{H} and greater connection length threshold \mathbb{L} than those shown in Table V can be experienced. For example, with split ratio 32, one amplifier allows to extend connection lengths to $\mathbb{L} = 100$ km while the number of hops can be $\mathbb{H} = 5 \sim 8$.

From now on, for the sake of simplifying the presentation we refer to both AWGs and waveband MUX/DEMUXs by AWGs because they are treated in the same way in the proposed topology design algorithms.

IV. OPTIMAL DESIGN

Since designing survivable hybrid WDM-TDM PON is a complex problem, we use Integer Linear Programming (ILP) to compute optimal solutions. The ILP based model will be named by OPT. For each ONU, the upstream connection is assumed to follow the same route as the downstream connection but over a different wavelength. Thus, only downstream connections need to be taken into account in the model. Moreover, half the number of wavelengths per link as well as half the number of AWG ports are reserved for upstream connections. The network is modeled as a directed graph where OLTs, AWGs, splitters (abbreviated by SPs) and ONUs are vertices. A fiber between these devices is modeled by two directed edges. Since a wavelength from an OLT to a SP is split by the splitter for serving different ONUs, these ONUs can be seen as sharing a single lightpath from the OLT to the SP. The model uses the following binary decision variables:

- oa_{ij} , aa_{ij} , as_{ij} and sn_{ij} will take value 1 if links (OLT_i, AWG_j) , (AWG_i, AWG_j) , (AWG_i, SP_j) and (SP_i, ONU_j) should be included in the topology respectively, and 0 otherwise.
- $oa_{ij\lambda}^{sk}$, $aa_{ij\lambda}^{sk}$ and $as_{jk\lambda}^{sk}$ will take value 1 if the lightpath from OLT_s to SP_k uses wavelength λ and goes through

link (OLT_i, AWG_j) , (AWG_i, AWG_j) and (AWG_i, SP_j) respectively, and 0 otherwise.

- f_i^{sk} and $f_i^{sk}(b)$ will take value 1 if the lightpath from OLT_s to SP_k serves ONU_i in working and backup connections respectively, and 0 otherwise.

Parameters doa_{ij} , daa_{ij} , das_{ij} , dsn_{ij} express respectively the real lengths of the paths that would be used for running fiber between OLT_i and AWG_j , AWG_i and AWG_j , AWG_i and SP_j , SP_i and ONU_j . The values of these parameters should be obtained from the deploying maps considered by a network provider. In so doing, the model is configured with the practical distances of fiber lengths to be installed.

A. Constraints forming lightpaths between OLTs and splitters

The following constraints form lightpaths between OLTs and splitters such that there is at most one lightpath to each splitter. Constraints (3) and (5) enforce that the total number of lightpaths ending at SP_k does not exceed 1. Since AWGs are intermediate nodes of lightpaths, the flow conservation constraint (4) ensures that whenever a wavelength enters an AWG, it goes out from the same AWG.

$$\sum_{s,j,\lambda} oa_{sj\lambda}^{sk} \leq 1 \quad (\forall k), \quad (3)$$

$$oa_{si\lambda}^{sk} + \sum_j (aa_{ji\lambda}^{sk} - aa_{ij\lambda}^{sk}) - as_{ik\lambda}^{sk} = 0 \quad (\forall s, k, \lambda, i), \quad (4)$$

$$\sum_{s,j,\lambda} as_{jk\lambda}^{sk} \leq 1 \quad (\forall k). \quad (5)$$

Constraints (6) and (7) guarantee that each ONU is served by one lightpath in its working connection and another one in its backup connection. Constraint (8) allows a lightpath to be shared amongst at most n_{split} ONUs.

$$\sum_{s,k} f_d^{sk} = 1 \quad (\forall d), \quad (6)$$

$$\sum_k f_d^{sk} - \sum_{k'} f_d^{sk'}(b) = 0 \quad (\forall s, d), \quad (7)$$

$$\frac{1}{n_{split}} \times \sum_{s,d} (f_d^{sk} + f_d^{sk}(b)) - \sum_{s,j,\lambda} as_{jk\lambda}^{sk} \leq 0 \quad (\forall k). \quad (8)$$

Constraints C1 and C2 in Section III are assured by (5) and (8), respectively.

B. Link disjointedness between a working connection and its backup connection

The following constraints ensure that no link is shared between a working connection from OLT_s to ONU_d and its backup connection. Constraints (9), (10), (11), (12) forbid the two connections from sharing a link between OLTs and AWGs, between AWGs, between AWGs and splitters, and between splitters and ONUs respectively.

$$\sum_{\lambda} (oa_{s_j\lambda}^{sk} + oa_{s_j\lambda}^{sk'}) + f_d^{sk} + f_d^{sk'}(b) \leq 3, \quad (\forall s, d, k \neq k', j) \quad (9)$$

$$\sum_{\lambda} (aa_{ij\lambda}^{sk} + aa_{ij\lambda}^{sk'} + aa_{ji\lambda}^{sk'}) + f_d^{sk} + f_d^{sk'}(b) \leq 3, \quad (\forall s, d, k \neq k', i, j) \quad (10)$$

$$\sum_{\lambda} (as_{ik\lambda}^{sk} + as_{ik\lambda}^{sk'}) + f_d^{sk} + f_d^{sk'}(b) \leq 3, \quad (\forall s, d, k \neq k', i) \quad (11)$$

$$f_d^{sk} + f_d^{sk'}(b) \leq 1(\forall s, d, k). \quad (12)$$

C. Constraints verifying if a link should be included in the topology

Constraints (13), (14), (15), (16) ensure that: if there is a connection going through a link between OLTs and AWGs, or between AWGs, or between AWGs and splitters, or between splitters and ONUs, these links must be included in the PON topology:

$$\sum_{s,k,\lambda} oa_{s_j\lambda}^{sk} \leq \mathbb{Z}.oa_{s_j}, \quad \forall (s, j), \quad (13)$$

$$\sum_{s,k,\lambda} aa_{ij\lambda}^{sk} \leq \mathbb{Z}.aa_{ij}, \quad \forall (i, j), \quad (14)$$

$$\sum_{s,\lambda} as_{ik\lambda}^{sk} \leq \mathbb{Z}.as_{ik}, \quad \forall (i, k), \quad (15)$$

$$\sum_s (f_d^{sk} + f_d^{sk'}(b)) \leq \mathbb{Z}.sn_{kd}, \quad \forall (k, d), \quad (16)$$

\mathbb{Z} is a sufficiently large constant such that whenever a sum on the left-hand side of an inequality is positive, the inequality will hold if the right-hand side variable is set to 1. For example, \mathbb{Z} can be the product of the number of OLTs, the number of ONUs in the network and $\mathbb{W}/2$.

D. Wavelength unity constraints

Since a lightpath takes entirely a wavelength, there should be at most one lightpath using a given wavelength on a fiber link. Constraints (17), (18), (19) ensure that this requirement is satisfied on links between OLT and AWG, AWG and splitter, splitter and ONU respectively.

$$\sum_k oa_{s_j\lambda}^{sk} \leq 1 \quad (\forall s, j, \lambda), \quad (17)$$

$$\sum_{s,k} (aa_{ij\lambda}^{sk} + aa_{ji\lambda}^{sk'}) \leq 1 \quad (\forall i, j, \lambda), \quad (18)$$

$$\sum_s as_{ik\lambda}^{sk} \leq 1 \quad (\forall i, k, \lambda). \quad (19)$$

E. Constraints on the number of ports of AWGs

Each AWG has $\mathbb{N} \times \mathbb{N}$ ports. Since half the number of ports of each AWG is reserved for the upstream, the number of incoming ports and outgoing ports of AWGs must be restricted to $\mathbb{N}/2$.

$$\sum_i oa_{ij} + \sum_i aa_{ij} \leq \mathbb{N}/2 \quad (\forall j) \quad (20)$$

$$\sum_j aa_{ij} + \sum_j as_{ij} \leq \mathbb{N}/2 \quad (\forall i) \quad (21)$$

F. Constraint on the number of ports of OLTs

The total number of links from an OLT must not be greater than the number of ports n_0 of each OLT.

$$\sum_j oa_{ij} \leq n_0 \quad (\forall i) \quad (22)$$

G. Constraints on hop count

In order to reduce power loss, every connection must be limited by \mathbb{H} hops (constraint C4 in Section III). The first hop is from an OLT to the first AWG, the last two hops are from the last AWG to a splitter and then an ONU. Therefore, the number of remaining hops between the first and the last AWG should not exceed $(\mathbb{H} - 3)$. The following constraint limits the number of hops for the working connections. A similar constraint should be applied as well to the backup connections.

$$\sum_{i,j,\lambda} aa_{ij\lambda}^{sk} \leq \mathbb{H} - 3, \quad (\forall s, k). \quad (23)$$

H. Distance constraints

Again, in order to reduce power loss, the lengths of working and backup connections must be limited by \mathbb{L} (constraint C3 in Section III). The following constraint is for the working connections. Backup connections need similar constraints.

$$\sum_{j,\lambda} oa_{s_j\lambda}^{sk} \times doa_{s_j} + \sum_{i,j,\lambda} aa_{ij\lambda}^{sk} \times daa_{ij} + \sum_{i,\lambda} as_{ik\lambda}^{sk} \times das_{ik} + f_d^{sk} \times dsn_{kd} \leq \mathbb{L}, \quad (\forall s, k, d). \quad (24)$$

I. Objective function

The objective of topology design is to minimize the total length of fiber. It can be expressed by:

$$\begin{aligned} \text{minimize } & \sum_{i,j} oa_{ij} \times doa_{ij} + \sum_{i,j} aa_{ij} \times aa_{ji} \times daa_{ij} + \\ & \sum_{i,j} as_{ij} \times das_{ij} + \sum_{i,j} sn_{ij} \times dsn_{ij}. \end{aligned} \quad (25)$$

Note that the product $aa_{ij} \times aa_{ji}$ can be easily linearized by using supplementary binary variables.

The ILP model of OPT provides optimal solutions but the model size grows up quickly when the number of network equipment, number of wavelengths over a fiber \mathbb{W} and splitting ratio n_{split} increase. The model can actually run for small size networks. To solve the design problem for larger size networks, we will propose two heuristics in the following sections.

V. STAR DESIGN

In this section we propose a heuristic for designing a survivable hybrid WDM-TDM PON without considering the links between AWGs. The network has a star structure except that each ONU connects to two splitters in order to be reachable by an OLT through two link-disjoint paths for survivable purpose. A path is taken by the working connection and the other is for the backup connection. The algorithm examines different combinations of ONUs, splitters, AWGs and OLT for choosing the best one according to following steps:

- 1) For each pair of splitters SP_x, SP_y :

- a. Find the two best AWG_i, AWG_j and an OLT_u so that the total fiber length running along $OLT_u-AWG_i-SP_x$ and along $OLT_u-AWG_j-SP_y$ is minimal. These paths have to satisfy constraints on wavelengths, hop count and fiber length. Let us denote the total fiber length by δ_1 .
 - b. Select a group of n_{split} ONUs that has the smallest total distance to the two splitters. Let us denote the total distance by δ_2 .
- 2) Select the pair of splitters that minimizes the sum $\delta_1 + \delta_2$. Connect the splitters with the two AWGs, the OLT and the n_{split} ONUs that made the minimum $\delta_1 + \delta_2$ while checking the wavelength availability and port availability. Remove the selected splitters and ONUs from the list of devices to be considered in the next rounds.
 - 3) Repeat Step 1 and 2 with the remaining splitters and ONUs until there is no more ONU to be considered.

Fig. 9a illustrates a combination of OLT, AWGs, splitters and ONUs that is selected by the algorithm. Fig. 9b shows the result of the algorithm.

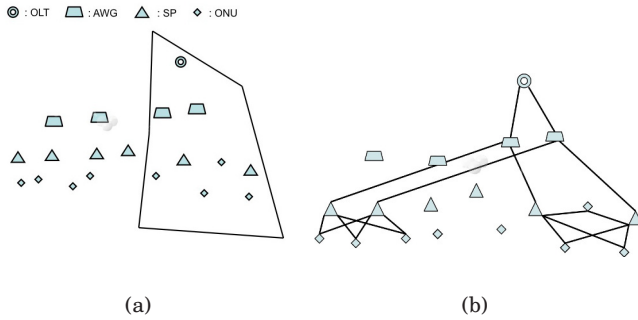


Fig. 9. Illustration of star design.

VI. MESH DESIGN

In this section, we propose a more efficient heuristic algorithm called MeshLIP, which designs a true mesh WDM-TDM PON by using the links between AWGs when it is necessary. The major advantage of MeshLIP is its polynomial running time, thus it can be used to design large size PONs. MeshLIP starts from a feasible network topology and then improves it by local improvement procedures. The algorithm is as flows:

- **[Initial solution calculation phase]** An initial solution can be any feasible solution that satisfies all the problem constraints. Star design can be used for generating an initial solution.
- **[Local improvement phase]** The initial solution is improved by changing the linkages between devices in such a way that the total fiber length is reduced.

We propose 5 following local improvements. These improvements are applied successively, each one improves a little bit the topology.

- 1) **[Switch ONUs to available SPs]:** for each pair of available SPs, change some ONUs to connect to these SPs if that leads to a reduction of the total fiber length. See Algorithm 1 for more details and Fig. 10 for an illustration.

- 2) **[Switch between current ONU-SP links]:** for each pair of links $ONU_{x_1}-SP_{y_1}$ and $ONU_{x_2}-SP_{y_2}$, permute the linkages to obtain the pair $ONU_{x_1}-SP_{y_2}$ and $ONU_{x_2}-SP_{y_1}$ if that leads to a reduction of the total fiber length. See Algorithm 2 for more details and Fig. 11 for an illustration.
- 3) **[Switch between current SP-AWG links]:** for each pair of links $SP_{x_1}-AWG_{y_1}$ and $SP_{x_2}-AWG_{y_2}$, permute the linkages to obtain the pair $SP_{x_1}-AWG_{y_2}$ and $SP_{x_2}-AWG_{y_1}$ if that leads to a reduction of the total fiber length. See more details in Algorithm 3 and Fig. 12 for an illustration.
- 4) **[Switch SPs to available AWGs]:** for each SP, find an alternative AWG to link with, if that leads to a reduction of the fiber length. In this case, when possible, the algorithm uses the short direct connection between the alternative AWG and in-use AWGs to prevent establishing new long OLT-AWG links. See Algorithm 4 for more details and Fig. 13 for an illustration.
- 5) **[Switch AWG-OLT links to AWG-AWG-OLT links]:** Change an AWG from directly linking with an OLT to indirectly connecting with the same OLT through an intermediate AWG, if that leads to a reduction of the fiber length. The two AWGs must not link to splitters that link to common ONUs. Otherwise, the working and backup connections of these ONUs will not be link-disjoint. See Algorithm 5 for more details and Fig. 14 for an illustration.

In all improvement procedures, all problem constraints are always checked at appropriate steps.

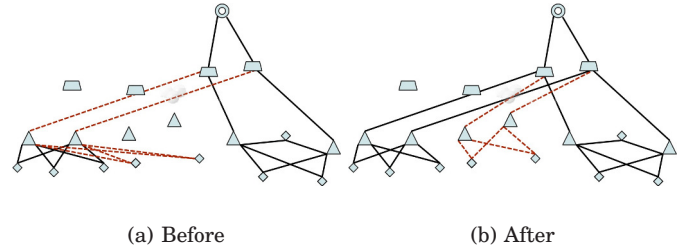


Fig. 10. Illustration of Improvement 1.

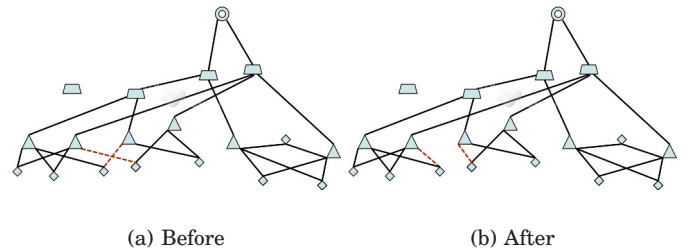


Fig. 11. Illustration of Improvement 2.

VII. NUMERICAL RESULTS

The proposed PON design algorithms have been implemented. OPT is implemented using ILOG CPLEX Academic edition [32]. Heuristics Star and MeshLIP are implemented in C. The algorithms are tested with different network

Algorithm 1: IMPROVEMENT 1

input : current topology
output: new improvement if $\delta_{max} > 0$

Min2Paths(SP_x, SP_y): finds OLT_z which minimizes two link disjoint paths from it to SP_x and SP_y and returns this minimal value;

MaxONUs(SP_x, SP_y): finds a group of maximum n_{split} ONUs which maximizes the amount of cable length saving if switching these ONUs to SP_x, SP_y ;

Max(α, β): returns α if $\alpha > \beta$ and returns β otherwise;

```

1  $\delta_{max} = 0$ ;
2 foreach free pair ( $SP_x, SP_y$ ) do
3    $\delta_1 = \text{Min2Paths}(SP_x, SP_y)$ ;
4    $\delta_2 = \text{MaxONUs}(SP_x, SP_y)$ ;
5    $\delta_{max} = \text{Max}(\delta_{max}, \delta_2 - \delta_1)$ ;
6 if  $\delta_{max} > 0$  then
7   Determine  $n_{split}$  ONUs and the free pair SPs leading to
    $\delta_{max}$ , then switch current links of these ONUs to this
   pair SPs and link these SPs to the corresponding OLT;

```

Algorithm 2: IMPROVEMENT 2

input : current topology
output: new improvement for each $\delta > 0$

Distance(A, B): returns the cable length linking device A to device B ;

```

1 foreach pair ( $ONU_{x_1}, ONU_{x_2}$ ) do
2    $SP_{y_1} \leftarrow$  a current link to  $ONU_{x_1}$ ;
3    $SP_{y_2} \leftarrow$  a current link to  $ONU_{x_2}$ ;
4    $\delta =$ 
   ( $\text{Distance}(ONU_{x_1}, SP_{y_1}) + \text{Distance}(ONU_{x_2}, SP_{y_2})$ ) -
   ( $\text{Distance}(ONU_{x_2}, SP_{y_1}) + \text{Distance}(ONU_{x_1}, SP_{y_2})$ );
5   if  $\delta > 0$  then
6     Remove links:  $ONU_{x_1} \rightarrow SP_{y_1}, ONU_{x_2} \rightarrow SP_{y_2}$ ;
7     Connect links:  $ONU_{x_1} \rightarrow SP_{y_2}, ONU_{x_2} \rightarrow SP_{y_1}$ ;

```

Algorithm 3: IMPROVEMENT 3

input : current topology
output: new improvement for each $\delta > 0$

```

1 foreach pair ( $SP_{x_1}, SP_{x_2}$ ) do
2    $AWG_{y_1} \leftarrow$  a current link to  $SP_{x_1}$ ;
3    $AWG_{y_2} \leftarrow$  a current link to  $SP_{x_2}$ ;
4    $\delta =$ 
   ( $\text{Distance}(SP_{x_1}, AWG_{y_1}) + \text{Distance}(SP_{x_2}, AWG_{y_2})$ ) -
   ( $\text{Distance}(SP_{x_2}, AWG_{y_1}) + \text{Distance}(SP_{x_1}, AWG_{y_2})$ );
5   if  $\delta > 0$  then
6     Remove links:  $SP_{x_1} \rightarrow AWG_{y_1}, SP_{x_2} \rightarrow AWG_{y_2}$ ;
7     Connect links:  $SP_{x_1} \rightarrow AWG_{y_2}, SP_{x_2} \rightarrow AWG_{y_1}$ ;

```

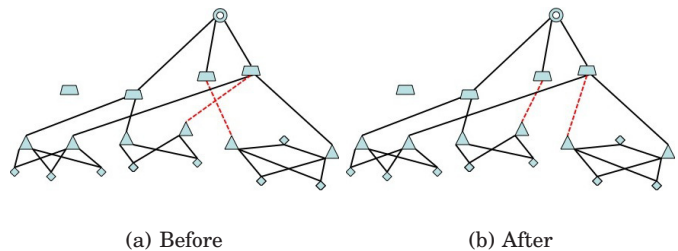


Fig. 12. Illustration of Improvement 3.

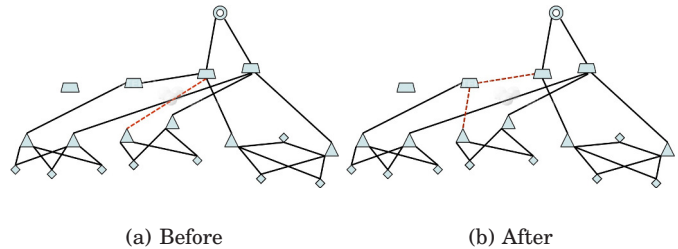


Fig. 13. Illustration of Improvement 4.

instances in order to evaluate their performances as well as to prove the advantages of the mesh topology for long-reach hybrid WDM-TDM PON.

Each network instance is characterized by the coordinates of PON devices (i.e. OLTs, AWGs, SPs and ONUs) in a 2D plan and parameters $\mathbb{W}, \mathbb{L}, \mathbb{H}, n_{split}, \mathbb{N}$. It is generally expected that connections of long-reach PON go up to 100km, then \mathbb{L} is set to 100km. A connection in the proposed mesh architecture can go zigzag through multiple AWGs, thus the distance between an OLT and a service area should be around 80 km. Consequently, the coordinates of OLTs are generated so that the OLTs are in about 80 km from the center of service areas. Since in LR-PON, the service area size is much smaller than its distance to the Central Office, we limit the service area diameter in 6km. According to the

Algorithm 4: IMPROVEMENT 4

input : current topology
output: new improvement if $\delta_{max} > 0$

```

1  $\delta_{max} = 0$ ;
2 foreach in-use  $AWG_x$  do
3   foreach free  $AWG_y$  do
4      $\delta = 0$ ;
5     foreach  $SP_z$  do
6       if
        $\text{Distance}(AWG_x, SP_z) > \text{Distance}(AWG_y, SP_z)$ 
       then
7          $\delta = \delta + \text{Distance}(AWG_x, SP_z) -$ 
          $\text{Distance}(AWG_y, SP_z)$ 
8          $\delta_{max} = \text{Max}(\delta_{max}, \delta_2 - \text{Distance}(AWG_x, AWG_y))$ ;
9 if  $\delta_{max} > 0$  then
10  Determine in-use  $AWG_x$ , free  $AWG_y$  and SPs leading to
     $\delta_{max}$ , then Switch current links of these SPs to  $AWG_y$ 
    and Connect  $AWG_x$  to  $AWG_y$ ;

```

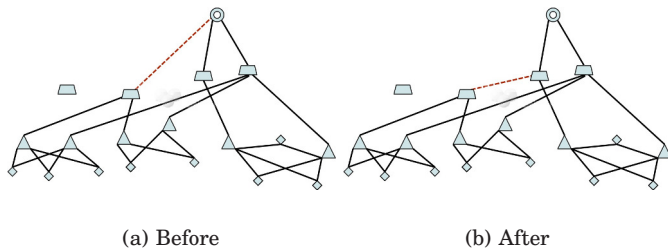


Fig. 14. Illustration of Improvement 5.

Algorithm 5: IMPROVEMENT 5**input** : current topology**output**: new improvement if $\delta_{max} > 0$

```

1  $\delta_{max} = 0$ ;
2 foreach  $OLT_z$  do
3   foreach in-use pair  $(AWG_x, AWG_y)$  linking to  $OLT_z$  do
4     if
5        $Distance(AWG_x, OLT_z) > Distance(AWG_y, OLT_z)$ 
6       then
7         | Exchange the role of  $x$  and  $y$ ;
8         |  $\delta =$ 
9         |  $Distance(AWG_x, OLT_z) - Distance(AWG_x, AWG_y)$ ;
10        |  $\delta_{max} = \text{Max}(\delta_{max}, \delta)$ ;
11 if  $\delta_{max} > 0$  then
12   Determine pair  $AWG_x, AWG_y, OLT_z$  leading to  $\delta_{max}$ ,
13   then Remove link  $AWG_x \rightarrow OLT_z$  and Connect  $AWG_x$  to
14    $AWG_y$ ;

```

computation in Section III, with no more than one amplifier along a connection, when $\mathbb{L} = 100$, the split ratio n_{split} can be set to 32, \mathbb{H} can be set to 5. The AWGs, SPs and ONUs are distributed randomly in service areas. Let us denote the size of a network instance by #OLTs-#AWGs-#SPs-#ONUs (# stands for *the number of*). We generated three datasets for testing the proposed algorithms:

- Dataset 1: 130 network instances with sizes varying from 1-3-8-8 to 1-7-24-24, $\mathbb{W} = 16$, number of ports of an AWG $\mathbb{N} = 8$, $n_{split} = 2$, $\mathbb{L} = 100$ km, $\mathbb{H} = 5$.
- Dataset 2: 130 network instances with sizes varying from 1-3-8-16 to 1-7-24-48, $\mathbb{W} = 16$, $\mathbb{N} = 8$, $n_{split} = 4$, $\mathbb{L} = 100$ km, $\mathbb{H} = 5$.
- Dataset 3: 1430 network instances with sizes varying from 1-8-48-624 to 1-10-74-1184, $\mathbb{W} = 32$, $\mathbb{N} = 16$, $n_{split} = 32$, $\mathbb{L} = 100$ km, $\mathbb{H} = 5$.

Although the proposed algorithms are ready for multiple OLTs, we currently test with single OLT networks. Tests with more OLTs are unnecessary since different OLTs are usually asked to serve different service areas.

Star and MeshLIP provide design results instantly for each network instance. OPT takes times varying from several seconds to several hours for each network in Datasets 1 and 2; and even cannot terminate for a network of Dataset 3. Fig. 15 presents an example of a PON, where OLT is at point (0, 0) and other devices are in the remote service area.

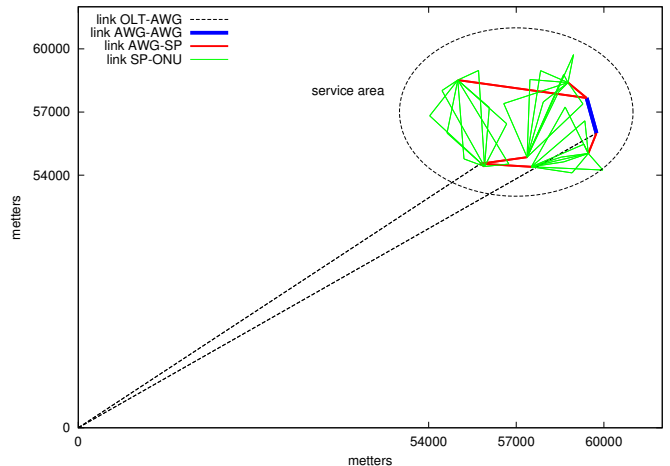


Fig. 15. Example of a survivable long-reach hybrid WDM-TDM PON designed by Local-Search. Links between OLT and AWGs are dash black lines, between AWGs are blue thickest lines, between AWGs and SPs are red medium lines, between SPs and ONUs are green thin lines.

A. Gaps between Star, MeshLIP and OPT

We evaluate the performance of the proposed algorithms by making comparison between the total fiber lengths that Star, MeshLIP and OPT propose for each network instance in the three datasets. Due to the high computational effort of OPT, the tests can be performed only on networks with sizes up to 1-5-14-14 of Dataset 1 and sizes up to 1-4-14-28 of Dataset 2. Two versions of MeshLIP have been tested:

- MeshLIP Impr. 1-2-3: In this version, only improvements 1, 2 and 3 are applied subsequently in this order during the local improvement procedure. Each improvement is performed once.
- MeshLIP Impr. 1-2-3-4-5: In this version, all improvements are applied subsequently in this order. Each improvement is performed once. Note that the improvements 4 and 5 consider the use of links between AWGs while the others do not.

We have also tried to repeat the five improvements more than once in order to see if they could improve further the design. We have remarked that the next round of five-improvement provides usually the same results with the previous one. This phenomenon reveals that MeshLIP converges usually right after the first round of five-improvement.

Table VI shows the average relative gaps between the total fiber lengths given by the proposed heuristics and those given by OPT for the same network instances. The gap between a solution of an algorithm X and OPT is computed as:

$$\frac{\text{fiber length in X} - \text{fiber length in OPT}}{\text{fiber length in OPT}}, \quad (26)$$

where fiber lengths are the total lengths of fiber to be used in the topologies designed by algorithm X and by OPT.

Star and MeshLIP Impr. 1-2-3 do not use links between AWGs in their designs. Although MeshLIP provides better gaps than Star when Improvements 1, 2 and 3 are used, it provides even much smaller gaps when Improvements 4 and 5 are added. This is explained by the fact that Improvements 4 and 5 use links between AWGs, which leads to the

	Star (%)	MeshLIP Impr. 1-2-3 (%)	MeshLIP Impr. 1-2-3-4-5 (%)
Dataset 1	65.74	46.16	16.7
Dataset 2	46.87	24.38	15.56

TABLE VI

AVERAGE RELATIVE GAPS BETWEEN THE PROPOSED ALGORITHMS AND OPT.

	MeshLIP Impr. 1-2-3 (%)	MeshLIP Impr. 1-2-3-4-5 (%)
Dataset 1	-14.41	-30.74
Dataset 2	-15.06	-29.19
Dataset 3	-11.75	-19.75

TABLE VII

AVERAGE RELATIVE GAPS BETWEEN MESH LIP AND STAR.

reduction of the total fiber length. Consequently, the optimal solutions are approached.

For comparing MeshLIP with Star only, we have run all test cases of the three datasets. Then, we compute the relative gaps between them according to the following formula:

$$\frac{\text{fiber length in X} - \text{fiber length in Star}}{\text{fiber length in Star}} \quad (27)$$

Table VII shows the relative gaps of MeshLIP over Star. The negative gaps indicate that MeshLIP saves more fiber than Star in average. The gaps in Table VII shows that Star is improved approximately from 12% to 15% by performing Improvements 1-2-3, and is about twice greater improved when links between AWGs are allowed by adding Improvements 4-5 afterwards (here we refer to the gaps between 19.75 % and 30.74%).

B. Pertinence of links between AWGs

For analyzing the pertinence of links between AWGs, we counted the percentage of network instances that use links between AWGs out of all network instances. The first two columns of Table VIII shows the percentages for MeshLIP and OPT. We remark that about 73% up to nearly 100 % of networks designed by MeshLIP use links between AWGs, whereas for OPT the percentage is around 86%. That means 86% of networks really need to use links between AWGs for achieving less fiber usage and thus less fiber installation and maintenance cost.

In order to evaluate the level of fiber saving, we created a variation of OPT called OPT-star where links between AWGs are not allowed (i.e., variable aa with different indexes are removed from all equations). The third column in Table VIII shows the average fiber saving level of OPT, which is the percent reduction in cost of the optimal OPT designs compared to the optimal OPT-star designs. The saving level

	Use links btw. AWGs		Fiber saving	
	OPT (%)	MeshLIP (%)	OPT (%)	MeshLIP (%)
Dataset 1	86.27	73.33	39.61	-
Dataset 2	85.71	73.33	22.86	-
Dataset 3	-	99.79	-	9.05

TABLE VIII

PERCENTAGES OF CASES THAT MESH LIP IMPR. 1-2-3-4-5 AND OPT USE LINKS AWG-AWG AND THE FIBER SAVING LEVEL OF THOSE CASES.

	Dataset 1	Dataset 2	Dataset 3
Avg. of all conn. lengths	84246	84350	83216
Avg. of all hop counts	4.24	4.23	4.26
Avg. length of longest conn.	89478	89920	89864
Length of the longest conn.	94804	95682	97500

TABLE IX

STATISTICS ON CONNECTION LENGTH AND HOP COUNT GIVEN BY MESH LIP IMPR. 1-2-3-4-5.

is significant. Up to 39.61% less fiber is used when links between AWGs are used. As a result, up to 39.61% of fiber installation and maintenance costs are saved thanks to link between AWGs. For large networks in Dataset 3, we evaluate the fiber saving level through the reduction in cost of MeshLIP Impr. 1-2-3-4-5 in comparison with MeshLIP Impr. 1-2-3. The saving is in average 9.05%. The smaller fiber saving level in Dataset 3 in comparison with Dataset 1 and 2 can be explained as follows. In Dataset 3, due to very high split ratio (32 versus 2 or 4) and number of wavelengths (32 versus 16), the amount of fiber running within the service area for connecting AWGs, splitters and ONUs takes a more important part of the total fiber length. However, mesh topology reduces mainly the amount of long distance fiber connecting OLTs and AWGs.

C. Hop count and path length

The hop count threshold \mathbb{H} and the length threshold \mathbb{L} have been considered in all proposed algorithms in order to keep end-to-end power loss for connections between OLTs and ONU under power budget.

Table IX shows the statistics on hop counts and lengths of connections designed by MeshLIP with all improvements. For each dataset, the numbers in the first two rows are the average connection length and the average hop count of all connections in all network instances. The number in the third row is the average length of the longest connections of all network instances. The number in the fourth row is the length of the longest connection of all network instances in a dataset. The table shows that the hop counts respect the hop limit constraint, so do the connection lengths.

Since MeshLIP Impr.1-2-3 does not consider links between AWGs while MeshLIP Impr. 1-2-3-4-5 does, we analyse the impact of links between AWGs on connection length and on hop count by comparing the values of these parameters in the two cases. In Table X, column ‘‘Hop count overhead’’ shows how many hops, in average, that connections given by MeshLIP Impr. 1-2-3-4-5 take more than those given by MeshLIP Impr. 1-2-3. We can see that, in average, a connection has from 0.23 to 0.26 hops more due to the links between AWGs. Similarly, column ‘‘Path length overhead’’ shows that, in average, a connection given by MeshLIP Impr. 1-2-3-4-5 trends to be under 1% longer than those given by MeshLIP Impr.1-2-3 due to links between AWGs.

Hence, the use of links between AWGs does not have much impact on the optical connection lengths and hop counts. Consequently, it may not influence the optical transmission quality.

VIII. CONCLUSIONS

With the increasing bandwidth demands from customers, the long-reach PON plays more and more important role in

	Hop count overhead (hops)	Path length overhead (%)
Dataset 1	0.24	0.85
Dataset 2	0.23	0.89
Dataset 3	0.26	0.79

TABLE X

HOP COUNT AND PATH LENGTH OVERHEADS DUE TO THE USE OF LINKS BETWEEN AWGS IN MESH LIP 1-2-3-4-5

access network deployment. In this paper, we have shown that the use of the hybrid WDM-TDM PON architecture with mesh links between AWGs in service areas is feasible when using the proposed Waveband MUX/DEMUXs. Moreover, the use of mesh links between AWGs helps reduce the fiber installation and maintenance costs of long-reach access networks since it allows to avoid unnecessary long fiber between CO and service areas. We have also developed efficient heuristic algorithms for designing the topology of the PON following this architecture such that all connections between OLTs and ONUs are survivable upon any single failure. According to the experiments, about 86% of optimal network topologies should use links between AWGs. The experimental results also show that the heuristic algorithms find solutions very close to optimal ones.

ACKNOWLEDGEMENTS

The work of the first author is supported by Vietnam's National Foundation for Science and Technology Development (NAFOSTED) under the grant number 102.01.13.09. The authors would like also to thank Dr. Ngoc T. Dang from the Post and Telecommunications Institute of Technology of Vietnam for his fruitful discussions and comments for the paper and Quang Huy Duong from Hanoi University of Science and Technology for his implementation of MeshLIP.

REFERENCES

- [1] C. Bock, J. Prat, and S. Walker, "Hybrid WDM/TDM PON using the AWG FSR and featuring centralized light generation and dynamic bandwidth allocation," *Journal of Lightwave Technology*, pp. 3981 – 3988, Dec 2005.
- [2] H. Venghaus, Ed., *Wavelength Filters in Fibre Optics*, ser. Springer Series in Optical Sciences. Springer, 2010.
- [3] G. Talli and P. D. Townsend, "Hybrid DWDM - TDM Long-Reach PON for Next-Generation Optical Access," *Journal of Lightwave Technology*, vol. 24, no. 7, pp. 2827–2834, July 2006.
- [4] D. Shea and J. Mitchell, "Long-reach optical access technologies," *IEEE Network*, vol. 21, no. 5, pp. 5–11, 2007.
- [5] F.-T. An, K. S. Kim, D. Gutierrez, S. Yam, E. S.-T. Hu, and F. I. F. Osa, "SUCCESS: A Next-Generation Hybrid WDM/TDM Optical Access Network Architecture," *Journal of Lightwave Technology*, vol. 22, no. 11, pp. 2557–2569, 2004.
- [6] A. Gumaste, D. Diwakar, A. Agrawal, A. Lodha, and N. Ghani, "Light-mesh - a pragmatic optical access network architecture for ip-centric service oriented communication," *Optical Switching and Networking*, vol. 5, no. 2-3, pp. 63–74, 2008.
- [7] D.-L. Truong and A. T. Pham, "A model for designing survivable mesh optical access networks," in *International Conference on Advanced Technologies for Communications (ATC)*, Aug 2011, pp. 156–160.
- [8] C. Dragone, "An N*N optical multiplexer using a planar arrangement of two star couplers," *IEEE Photonics Technology Letters*, vol. 3, no. 9, pp. 812–815, 1991.
- [9] S. Kakehashi, H. Hasegawa, K. Sato, O. Moriwaki, S. Kamei, Y. Jinnouchi, and M. Okuno, "Performance of Waveband MUX/DEMUX Using Concatenated AWGs," *IEEE Photonics Technology Letters*, vol. 19, no. 16, pp. 1197 – 1199, Aug. 2007.
- [10] S. Kakehashi, H. Hasegawa, K. ichi Sato, O. Moriwaki, and S. Kamei, "Analysis and development of fixed and variable waveband mux/demux utilizing awg routing functions," *Journal of Lightwave Technology*, vol. 27, no. 1, pp. 30–40, Jan 2009.
- [11] M. Ruffini, D. Mehta, B. O'Sullivan, L. Quesada, L. Doyle, and D. B. Payne, "Deployment Strategies for Protected Long-Reach PON," *Journal of Optical Communication Networking*, vol. 4, no. 2, pp. 118–129, Feb 2012.
- [12] U.S. Department of Transportation Research and Innovative Technology Administration, "Its unit costs database," Oct. 2010.
- [13] —, "Intelligent Transportation Systems Benefits, Costs, Deployment, and Lessons Learned: 2011 Update," Oct. 2010.
- [14] J. Li and G. Shen, "Cost Minimization Planning for Greenfield Passive Optical Networks," *Journal of Optical Communication Networking*, vol. 1, pp. 17–29, 2009.
- [15] "AliExpress website," <http://www.aliexpress.com>, 2013.
- [16] G. Maier, M. Martinelli, A. Pattavina, and E. Salvadori, "Design and cost performance of the multistage WDM-PON access networks," *Journal of Lightwave Technology*, vol. 18, no. 2, pp. 125–143, 2000.
- [17] J. Zhang and B. Mukherjee, "A review of Fault Management in WDM Mesh networks: Basic Concept and Research Challenges," *IEEE Network*, vol. 18, no. 2, pp. 41–48, Mar. 2004.
- [18] D.-L. Truong and B. Jaumard, "Recent progress in dynamic routing for shared protection in multidomain networks," *Communications Magazine, IEEE*, vol. 46, no. 6, pp. 112–119, 2008.
- [19] H. Luu and F. Tobagi, "Physical topology design for all-optical networks," in *International Conference on Broadband Communications, Networks and Systems (BROADNETS)*, Oct. 2006, pp. 1–10.
- [20] Y. Xin, G. Rouskas, and H. Perros, "On the physical and logical topology design of large-scale optical networks," *Journal of Lightwave Technology*, vol. 21, no. 4, pp. 904 – 915, 2003.
- [21] R. M. Krishnaswamy and K. N. Sivarajan, "Design of logical topologies: a linear formulation for wavelength-routed optical networks with no wavelength changers," *IEEE/ACM Trans. Netw.*, vol. 9, no. 2, pp. 186–198, 2001.
- [22] B. Latic and M. Hajduczenia, "On optimized Passive Optical Network (PON) deployment," in *Second International Conference on Access Networks and Workshops*, Ottawa, Canada, Aug 2007, pp. 1–8.
- [23] A. Agata and Y. Horiuchi, "PON Network Designing Algorithm for Suboptimal Deployment of Optical Fiber Cables," in *Asia Communications and Photonics Conference and Exhibition*, Shanghai, China, November 2009, pp. 1–2.
- [24] B. Kantarci and H. Mouftah, "Optimization models for reliable long-reach pon deployment," in *IEEE Symposium on Computers and Communications (ISCC)*, July 2011, pp. 506 – 511.
- [25] E. Wong and K.-L. Lee, "Automatic protection, restoration, and survivability of long-reach passive optical networks," in *IEEE International Conference on Communications (ICC)*, July 2011, pp. 1–6.
- [26] J. Zhang and N. Ansari, "Minimizing the arrayed waveguide grating cost and the optical cable cost in deploying wdm passive optical networks," *Journal of Optical Communications and Networking*, vol. 1, no. 5, pp. 352–365, 2009.
- [27] B. Jaumard and R. Chowdhury, "Location and allocation of switching equipment (splitters/awgs) in a wdm pon network," in *Proceedings of 20th International Conference on Computer Communications and Networks (ICCCN)*, 2011, pp. 1–8.
- [28] B. Glance, I. KAMINOW, and R. Wilson, "Applications of the integrated waveguide grating router," *Lightwave Technology, Journal of*, vol. 12, no. 6, pp. 957–962, 1994.
- [29] A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, and B. Mukherjee, "Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review," *Journal of Optical Networking*, vol. 4, no. 11, pp. 737–758, Nov 2005.
- [30] H. Kimura, T. Matsumoto, S. Shimazu, S. Yamashita, and J. Yamasaki, "Optical power budget enhancement technologies for long-reach ge-pon system," *NTT Technical Review*, vol. 9, no. 10, pp. 1–5, 2011.
- [31] H. Song, B. whi Kim, and B. Mukherjee, "Long-reach optical access networks: A survey of research challenges, demonstrations, and bandwidth assignment mechanisms," *IEEE Communications Surveys Tutorials*, vol. 12, no. 1, pp. 112–123, 2010.
- [32] IBM Academic Initiative, "ILOG CPLEX Optimization Studio," http://www-03.ibm.com/ibm/university/academic/pub/page/ban_ilog_programming.

Dieu Linh Truong is currently working as assistant professor in the Department of Data Communications and Computer Networks, School of Information and Communication Technology, Hanoi University of Science and Technology, Vietnam. She received the PhD degree from the Department of Computer Science and Operations Research, Université de Montréal, Canada in 2007, the Master degree from Institute de la Francophonie pour l'Informatique, Vietnam in 2001 and the Engineer degree from Hanoi University of Technology in 1999. Her interests include multidomain networks, optical networks and survivable network design problems.

Phan Thuan Do is currently working as assistant professor in the Department of Computer Science, School of Information and Communication Technology, Hanoi University of Science and Technology. He received the PhD degree from the University of Burgundy, France in 2008, the Master degree from the University of Paris 7, France in 2005 and the Engineer degree from Hanoi University of

Technology in 2003. His interests include algorithms, combinatorics and survivable network design problems.

Anh T. Pham received the B.E. and M.E. degrees, both in Electronics Engineering from the Hanoi University of Science and Technology, Vietnam in 1997 and 2000, respectively, and the PhD degree in Information and Mathematical Sciences from Saitama University, Japan in 2005. From 1998 to 2002, he was with the NTT Corp. in Vietnam. Since April 2005, he has been on the faculty at the University of Aizu, where he is currently a senior associate professor at the Computer Communications Laboratory, the School of Computer Science and Engineering. His present research interests are in the broad areas of communication theory and networking with a particular emphasis on modeling, design and performance evaluation of wired/wireless communication systems and networks. Dr. Pham is senior member of IEEE. He is also member of IEICE and OSA.