A Local Improvement Approach for Survivable Long-reach Hybrid WDM-TDM PON Design

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***Abstract*—Long-reach hybrid WDM-TDM PONs connect far away service areas to center offices of service providers. Typically, multiples fiber cables run from the center office side to each service area in order to feed the service area with data flows. We believe that mesh topology in service areas allows AWGs feeding each other and consequently less fiber cables need to be run between center offices and service areas. In this paper, we show some typical cases where mesh connections between AWGs are useful. We propose also an efficient algorithm based on Local improvement approach for designing survivable long-reach hybrid WDM-TDM PONs where mesh topology between AWGs is allowed. The experimental results show that a large percentage of PONs should use mesh topology in service areas in order to minimize the total PON deployment cost.**

I. Introduction

PON is a promising technology for deploying access networks since it allows sharing access lines amongst multiple buildings with low cost. A major advantage of PON technology is that it makes use of passive splitters for spliting signal on the way from the center office (CO) to multiple end users. The passive devices do not require power supply thus allows eliminating electrical/electronic related installation and maintenance activities which are costly. Recently hybrid WPON-TPON [1] has been introduced where multiple wavelengths over the same fiber are exploited to carry traffic from Optical Line Terminal (OLT) in CO to a point close to customer area. There, an Arrayed Waveguide Grating (AWG) demultiplexes the signal into different wavelengths, each one goes to a direction. Each wavelength is splitted again by a passive power Splitter before ending at Optical Network Unit (ONU) in customer premises.

Long-reach PON [2] [3] refers to the PON that covers a long distance from 20km to 100km. In such a PON, customers are regrouped in service areas which are far away from the center offices. They share extended fibers to connect to CO. Hybrid long-reach WDM-TDM PON (LR-PON) [4] covers at the same time long distance and serves numerous customers thanks to multiple wavelength. The OLTs remains in the CO on the service provider sides while AWGs, Splitters and the ONUs resides in service area. The services area diameters could be in few kilometres.

PON splitters are usually arranged in star/tree but sometimes Spliters and/or AWGs are connected in ring for providing reliability [5]. In this paper, we consider mesh topology for deploying long-reach hybrid WDM-TDM PON (see Fig.1) where AWGs can be connected to each other. The mesh topology between AWGs has been proposed in [6] where each AWG are assumed to have $N \times N$ ports. An advantage of mesh topology is the robust network structure with protection capability against failures, which is totally absent in the star/tree topology since in the latter there exists uniquely one path between an OLT and an ONU. In long-reach PON, mesh topology allows AWG feeding each other and consequently less fiber cables need to be run between center offices and service areas for serving AWGs. Indeed, let us consider a branch of PON composed of an OLT and a far away service area. In order to make the PON survivable against any failure on fiber link, each working flow from the OLT to an ONU is backed up by another link-disjoint flow. Therefore the OLT should connect to the service area by at least two AWGs. Fig. 2 illustrates typical connections between an OLT and a service area:

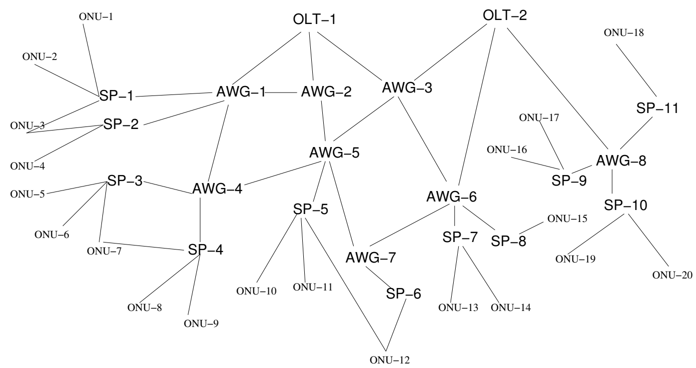


Fig. 1. Mesh hybrid WDM-TDM PON model

a) There are a small number of Splitters and ONUs to be served. Two AWGs have enough ports to serve all Splitters. The two AWGs are fed independently by the OLT.
b) There are more Splitters and ONUs to be served than in case a) thus more than two AWGs are required. All these AWGs are fed independently by the OLT.
c) There are more Splitters and ONUs to be served than in case a) and more than two AWGs are required. Only some AWG are fed directly by the OLT and the other AWGs

are fed indirectly through these AWGs. Since service area diameter is much smaller than the distance between the service area to the OLT (about 10 times smaller) then this case uses less fiber than the case b).

Clearly, when the number of Splitters and ONUs is increasing, links between AWGs as in case c) leeds to less fiber using.

More complex PON with more OLTs and service areas can be seen as a combination of these simple cases thus links AWG-AWG would be more useful. The light-mesh model in [7] proposed also to use mesh topology but for the part between ONUs and Spliters instead of between AWGs.

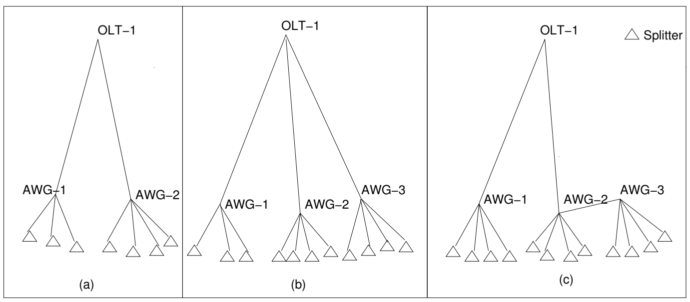


Fig. 2. Three typical connections of an OLT and a service area (ONUs are not shown)

In this paper we focus on survivable long-reach hybrid WDM-TDM PON with mesh connection between AWGs. We aim to prove that the mesh topology between AWGs helps to save fiber running between CO and service areas and thus reduces the long-reach PON deployment and maintenance cost which is proportional with fiber length. It is stated in [7] that for an optical network, 90% capital cost comes from fiber laying out and only 10% is due to equipment cost. Therefore, we will not consider the equipment cost of PON in this research. We are going to propose several algorithms to design long-reach hybrid WDM-TDM PON topology with objective to minimize the total fiber length to be used. By experimentation with these algorithms, we demonstrate that mesh connection between AWGs are necessary for reducing PON deployment and maintenance cost. The proposed algorithms are also very good tools for designing survivable long-reach hybrid WDM-TDM PON with low cost.

Although topology design for optical networks have been largely studied, there is not much attention for designing PON and mostly LR-PON with survivable capability. Most existing works such as those in [8], [9] and [10] focus on optical backbone where all nodes have equal roles and can be arbitrary connected to each other. Differently, topology design for PON concerns various devices such as OLTs, AWGs, Splitters and ONUs which have different communication roles and one device only connects to some other. Indeed, OLTs connect only to AWGs, Splitters connect to AWGs but not directly to OLTs. In addition, the design problem for Mesh PON is subjected to the passive nature of PON equipments, for example, the number of intermediate AWGs and the fiber length between OLTs and Splitters should be restricted in order to limit the insertion loss. Few researches are conducted on PON topology design. Some of them are presented in [11] [12] and [13] but they focus on TDM PON with star topology without survivability. An optimal and an heuristic solution has been proposed for planning long-reach TDM PON with high availability in [14]. Automatic Protection for long-reach PON solution in [15] make uses of highly-sensitive and fast-response protection module in order to achieve very fast traffic diversion onto the protection paths upon failure. However the work does not describe how the working and protection paths are designed. Some other solutions for designing hybrid WDM-TDM PON without survivability has also been proposed in [16]. To the best of our knowledge except the work in [6], there is no work on designing mesh Long-reach hybrid WDM-TDM PON with protection. In this paper, we will propose more efficient algorithms.

The paper is organised as follows. Section II states the problem of designing topology of survivable mesh hybrid WDM-TDM PON. Section III describes existing solutions for this problem proposed in [6] including an optimal design based on ILP and an greedy heuristic. In Section IV, we propose an efficient heuristic based on local search approach for this problem. The numerical results are shown in Section V. Finally, Section VI concludes the paper.

II. Survivable Mesh Hybrid WDM-TDM PON Design Problem Statement

In this paper, a PON is made survivable by using path protection scheme, *i.e.*, each working connection between OLT and ONU is protected by a link-disjoint backup connection. The two connections must be link-disjoint in order to have at least one connection available when there is a single failure in the network. Since the two ends of each connection – OLT and ONU – are active devices, it is possible to configure or add functionalities to these devices so that they are capable to switch traffic automatically from working connection to backup one when the former fails. The detail switching mechanism will not be addressed in this paper.

The problem of designing a survivable mesh hybrid WDM-TDM PON is stated as follows:

Given:

- OLTs, AWGs, Splitters, ONUs and their positions in 2D plan,
- $\mathbb{W}$: the maximum number of different wavelengths available over each link.

The goal of the design is:

- to connect the OLTs, AWGs, Splitters, ONUs together and to identify a working downstream, a working upstream, a backup downstream and a backup upstream flows between each ONU and an OLT. A backup stream must be link-disjoint with its working one.
- to minimize fiber length in order to minimize the deployment and maintenance cost.

The design is subject to several constraints due to the characteristic of PON:

C1 Each splitter connects to one AWG by one wavelength.
C2 Splitting ratio of each Splitter is $n_{splitting}$. That means at most $n_{splitting}$ ONUs can share a wavelength.
C3 Connections from OLTs to ONUs should not be longer than $\mathbb{L}$ km.
C4 Connections from OLTs to 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 flows between OLTs and ONUs. All AWGs are assumed $\mathbb{N}\times\mathbb{N}$ (*i.e.*, $\mathbb{N}$ in-ports and $\mathbb{N}$ out-ports) and they can route wavelengths independently from one incoming port to any outgoing port. Although an original $\mathbb{N} \times \mathbb{N}$ AWG does not allow arbitrary wavelength commutation matrix, but with the help of splitters and combiners or by combining several conventional $\mathbb{N} \times \mathbb{N}$ AWGs together we can produce AWGs with arbitrary wavelength commutation. A proposal for such an AWG is presented in [17] under the name Waveband MUX/DEMUX.

III. EXISTING SOLUTIONS

A. Optimal solution based on ILP

The problem of designing survivable hybrid WDM-TDM PON is complex. In [6], we have proposed an Interger Linear Programming (ILP) model for solving this problem. For each ONU, the upstream connection is assumed to follow the same route with the downstream connection but over another wavelength therefore only downstream connections are taken into account in the model. The network is modeled as a directional graph where OLTs, AWGs, Splitters (abbreviated by SP) and ONUs are vertexes. Fiber connecting a pair of these devices are modeled by two directional links, each one contains $\mathbb{W}$ wavelengths.

The model uses some per-link binary variables for expressing if a link or a fiber should be included in the topology or not. The model uses also some per-connection variables expressing if a wavelength in a link should be used for a working or backup connection between an OLT and an ONU or not. Based on these variables a set of constraints are defined:

- Flow conservation constraints: The constraints form the working and backup connections for each ONU.
- Disjointedness constraints: The constraints ensure that a working connection is link-disjoint with its backup one.
- Constraints verifying if a link is needed: The constraints ensure that a link is included in the PON topology uniquely when there is a connection going through the link by a wavelength.
- Constraint on the number of hops: The constraint ensures that the number of hops of a connection to be limited by $\mathbb{H}$ hops (constraint C4)
- Distance constraint: The constraint ensures that the length of a working or backup connection to be limited by $\mathbb{L}$ (constraint C3).
- And several constraints on the number of ports of AWGs or OLTs.

The objective of the model is to minimize the total fiber length to be used.

Solving the model provides optimal solution, however the model size explodes very fast when the size of PON grows leading to unacceptable running time. In this paper, we refer to this model by OPT.

B. Greedy solution without connection between AWGs

In [6], an efficient greedy solution for this survivable hybrid WDM-TDM PON design problem is also proposed. For each ONU, two disjoint connections to the same OLT are identified as the working and the backup flows. However the greedy does not take into account mesh connections between AWGs. In this paper we refer to this Greedy by NoMesh.

IV. LOCAL-SEARCH BASED APPROACH

Existing ILP model provides optimal solution but the model size grows up rapidly with the number of network equipments, the number of wavelengths per fiber and the splitting ratio of Splitters. The model can practically be used for small size networks such as of 1 OLT, 4 AWG, 8 Splitters and 16 ONU. In order to highlight the necessity of mesh topology in survivable hybrid WDM-TDM PON, we need to solve its design problem in larger network size and compare the results with those of NoMesh. For such purpose, we propose in this section an efficient heuristic for this design problem. The solution is based on local improvement procedure which takes into account the mesh connection between AWGs. The experimentation will show that the obtained results are very close to the global optimal solutions OPT and in many cases they reach the optimal ones. The major advantage of this local search based algorithm is polynomial running time, thus the algorithm can be used to design PONs of hundreds devices. In this paper, we refer to this algorithm as Local-Search. The algorithms is composed of two main processes:

- **[Initial solution]** By a greedy heuristic, we build a feasible solution satisfying all problem constraints.
- **[Local improvement procedure]** Improve the initial solution by switching some devices from their current links to connect to other devices so that the total fiber used is reduced. This strategy allows us to profit from connected AWG$-$OLT links instead of establishing new direct AWG$-$OLT links thanks to possibility to link directly AWGs together according to the characteristic of mesh topology.

The two processes are described in detail below.

A. Greedy heuristic for an initial solution

We create locally optimal group one by one. A locally optimal group contains $n_{splitting}$- ONUs, two SPs, two or more AWGs and one OLT that minimizes the total fiber lengths running between them. This process is repeated until no more group can be created. The devices are selected into a group by following steps:

- For all free pair (SP_x,SP_y) (have not connected yet to any ONU),
  - find the OLT_s which minimizes the total length of two link-disjoint paths from the considered OLT to

SP_x and SP_y (via AWGs). These paths have to satisfy constraints on wavelength, hops and fiber length. This minimal sum is denoted by σ_1;
  – find a group of $n_{splitting}$ free ONUs which minimizes the total length of all links from these $n_{splitting}$-ONUs to SP_x and SP_y. This minimal sum is denoted by σ_2;
- Choose the pair (SP_x,SP_y) and all devices OLT, AWGs, $n_{splitting}$-ONUs which minimizes the sum $\sigma_1 + \sigma_2$.

The chosen devices of each groups are connected to each other according to paths resulting the minimum sum. Fig. 3(a) illustrates the locally optimal group and Fig. 3(b) illustrates the connections between devices of the group.

B. Local improvement procedure

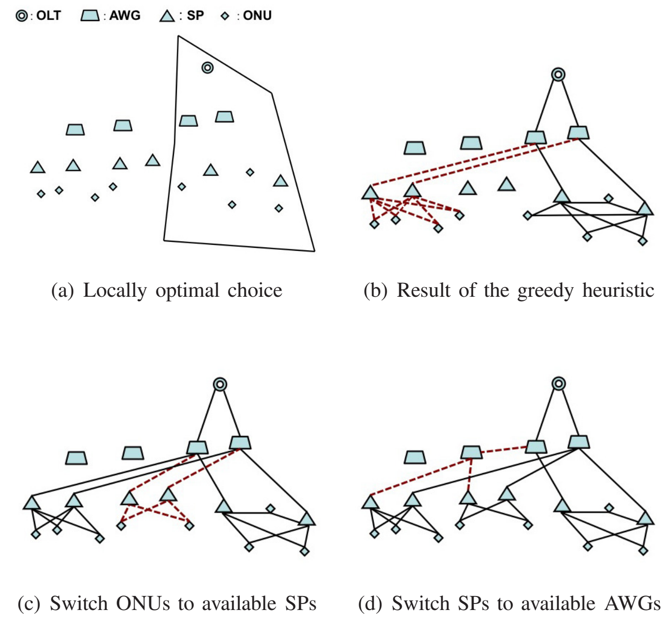
We adjust links by switching some ONUs, SPs, AWGs from their current links to newly connect to other devices while always satisfying all problem constraints such that the total fiber miles is reduced. The improvement procedure is implemented by four following processes. These processes are repeated until no more improvement found.

1) **[Switch ONUs to available SPs]**: find a new pair SPs to which some ONUs can switch from current connection and lead to a reduction of fiber length. See Fig. 3(c) for illustration.
2) **[Switch between current ONU−SP links]**: for each pair of links $\text{ONU}_{i_1} - \text{SP}_{j_1}$ and $\text{ONU}_{i_2} - \text{SP}_{j_2}$, permute the connections to obtain the pair $\text{ONU}_{i_1} - \text{SP}_{j_2}$ and $\text{ONU}_{i_2} - \text{SP}_{j_1}$ if that leads to shorter total fiber length.
3) **[Switch SPs to available AWGs]**: find a new AWG to which some SPs currently linking to another AWG can switch and lead to a reduction of fiber length. In this case, the algorithm should profit from the short direct connection between the new AWG and in-use AWGs to prevent establishing new long OLT−AWG links. See Fig. 3(d) for illustration.
4) **[Switch AWG−OLT links to AWG−AWG−OLT links]**: replace some long AWG−OLT links by some short AWG−AWG links which allows reducing fiber length. These replacements have to satisfy the condition that each new connected AWG−AWG pair has links only to SPs with no common ONUs. This guarantees the link-disjoint characteristic of two paths between an ONU and an OLT.

For the sake of brevity we do not discuss in detail the algorithms and complexity of each improvement process in this paper. Source code of our algorithm can be found at [18].

V. NUMERICAL RESULTS

The proposed design algorithm has been implemented and tested with different network instances in order to evaluate their performances as well as to prove the advantage of the mesh topology for long-reach hybrid WDM-TDM PON. Each network instance is characterized by the coordination of PON devices (OLTs, AWGs, Splitters and ONU) in two-dimension



(a) Locally optimal choice (b) Result of the greedy heuristic

(c) Switch ONUs to available SPs (d) Switch SPs to available AWGs

Fig. 3. Examples of Local-Search steps

plan and parameters such as: the number of wavelength per fiber $\mathbb{W}$, length threshold $\mathbb{L}$, the number of hops threshold $\mathbb{H}$, the splitting ratio $n_{splitting}$, the number of ports of AWGs $\mathbb{N}$. The coordination are generated so that OLTs are in 10 km or 20 km from service areas. The AWGs, Splitters and ONUs are distributed randomly in service areas of 3 km diameter. Let us denote the size of a network by the number of OLT-AWG-SP-ONU. In the current experiments, sizes of network instances vary from 1-3-6-6 to 1-10-20-80. Fig. 4 presents an example of a PON designed by Local-Search.

Since OPT can only be run on small network, we performed some tests on networks with sizes from 1-3-6-6 to 1-4-10-10 and $\mathbb{W} = 8$, $\mathbb{N} = 4$, $n_{splitting} = 2$. Table I presents the average relative difference between the total fiber length given by Local-Search and that given by OPT. The results show that Local-Search provides solutions very close to the optimal ones.

With certain datasets such as when the number of OLT-AWG-SP-ONU is 1-4-6-6, $\mathbb{W} = 8$, $n_{splitting} = 2$, distance between OLT and service area is about 10 km, all optimal topologies use 2 links between AWGs. Local-Search also finds that every solution uses links between AWGs. The average gap between Local-Search and OPT is 10%. We tested also the same dataset with NoMesh, note that in NoMesh no AWG-AWG link is allowed. NoMesh finally finds topologies with much more fiber lengths, the average gap with OPT is 50%. These figures show that for certain network sizes, the mesh

	Local-Search	NoMesh
Gap with OPT (%)	6.72	27.52

TABLE I
PERCENTAGE OF DIFFERENCE IN FIBER LENGTH IN COMPARISON WITH OPT

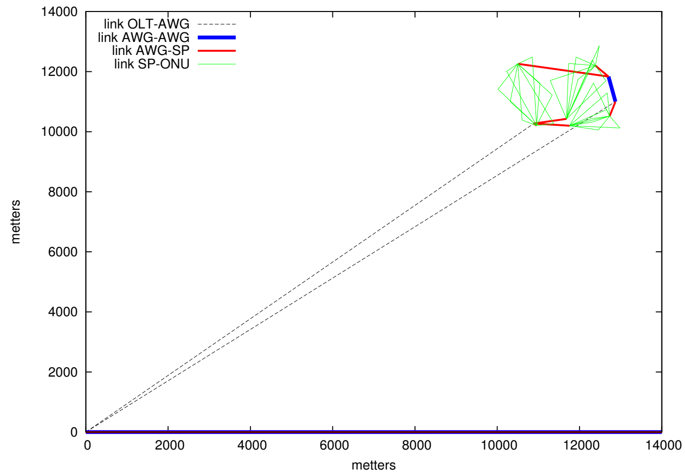


Fig. 4. Example of a survivable Long-reach hybrid WDM-TDM PON designed by Local-Search. Links between OLT and AWGs are dash black lines, links between AWGs are blue thickest lines, links between AWGs and Splitters are red medium lines, links between Splitters and ONUs are green thin lines

	Link AWG-AWG usage	Fiber saving over NoMesh
Dataset 1	44, 67%	21.79%
Dataset 2	35,71%	46.23%
Dataset 3	47,67%	31.80%

TABLE II
PERFORMANCE OF LOCAL-SEARCH

topology between AWGs are really necessary for saving fiber.

We performed further tests on larger networks in order to count the number of cases where links between AWGs are used in order to see the pertinence of the mesh topology between AWGs in service area. Since OPT takes too long running time for large networks, we tested only Local-Search and NoMesh with three datasets:

- Dataset 1: 150 networks with sizes vary from 1-3-5-5 to 1-7-18-18, distance between OLT and service area is 10 km, $\mathbb{W} = 8$, $\mathbb{N} = 4$, $n_{splitting} = 2$.
- Dataset 2: 150 networks with sizes vary from 1-3-5-5 to 1-7-18-18, distance between OLT and service area is 10 km, $\mathbb{W} = 8$, $\mathbb{N} = 4$, $n_{splitting} = 4$.
- Dataset 3: 300 networks with sizes vary from 1-2-4-8 to 1-10-20-80, distance between OLT and service area is 20 km, $\mathbb{W} = 8$, $\mathbb{N} = 8$, $n_{splitting} = 8$.

Table II shows the number of cases that Local-Search uses links between AWGs and fiber saving ability of Local-Search over NoMesh thanks to these links between AWGs. Note that in NoMesh, no links between AWGs are allowed. We remark that for large networks, a large percentage of networks designed by Local-Search uses links between AWGs. In the cases of experiments, these links between AWGs helps Local-Search to save from 21.79% upto 46.23% of fiber in comparison with NoMesh.

VI. CONCLUSIONS

With the increasing bandwidth demands from customer, long-reach PON playes more and more important role in access network deployment. In this paper, we have shown that the use of hybrid WDM-TDM PON architecture with mesh connection between AWGs in service areas helps to reduces the deployment and maintenance costs of long-reach access networks since it allows to limits long fiber running between CO and service areas. We have also developed a local search based algorithm for designing the topology of the PON following this architecture such that every connection between OLTs and ONUs are survivable upon any single failure. The experimental results show that the heuristic algorithm finds solutions very close to optimal ones. In addition, upto 47% best network topologies use links between AWGs proving the necessity of mesh connections between AWGs.

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