Impact of Mesh topology in cost reduction of Survivable Hybrid WDM-TDM PON networks

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ABSTRACT

Along with the development of the Fiber-to-the-Home (FTTH) networks, the Passive Optical Network (PON) is largely studied. PON technology is known as optical access network technology that uses fiber optic and passive devices to connect service providers and end users. Some models for deploying PON have been proposed. In this paper we focus on mesh and star topology for hybrid WDM-TDM PON. We propose three design methods for the two models and compare them to each other in order to see the advantage of mesh topolgy with links between AWGs. These methods are also compared with the solution in [11]. The results show that the proposed methods gains better performance and the use of link between AWGs allows saving a noticeable fiber amount.

Keywords

Optical network design, PON design, survivable network, mesh network, heuristic algorithm.

1. INTRODUCTION

Passive Optical Network (PON) is a promising technology for deploying access networks since it allows sharing access lines amongst multiple buildings with low cost and power consumption. PON makes use of passive devices (without power supply) for splitting signal on the way from the service provider Center Offices (CO) to multiple end users. Hybrid WDM-TDM PON [10] refers to a type of Passive Optical Networks where Wavelength Division Multiplexing and Time Division Multiplexing technologies are both employed for exploiting fiber capacity. In these networks, fibers are run from the Optical Line Terminals (OLT) in CO to Array Waveguide Gratings (AWG) near to the customer areas. The fiber carry multiple wavelengths and each one can be used to transport Gibabits data from CO. This bundle of wavelengths is then demultiplexed by AWG according to WDM principle so that each wavelength goes towards a customer group. Then the wavelength is splitted by a passive power Splitter before ending at Optical Network Unit (ONU) in customer premises. Figure 1 shows an example of Hybrid WDM-TDM PON network. Long-reach and large scale PON can cover a distance of 100 km from OLT to ONU [3] and can serve more than 4000 customers [10]. PONs are usually deployed in Star (tree-like) topology where OLTs, AWGs, SPs and ONUs are arranged as branches of tree with OLTs in roots and ONUs in leaves. Some research such as [1] proposed to deploy Hybrid WDM-TDM PON in ring where CO and AWGs or Splitters are connected in a cycle. In [11], a Mesh architecture for Hybrid WDM-TDM PON has been explicitly introduced where AWGs can connect to each other and the optical data from an OLT may travel through two or more AWGs before going to an Splitter and end at an ONU. All AWGs in this case are assumed to be $N \times N$ (i.e., N in-ports and N out-ports) and they can route wavelengths independently from one in-port to any out-port. Although conventional $N \times N$ AWG does not allow arbitrary wavelength commutation, but the work in [4] proved that an Waveband MUX/DEMUX built from concatenated conventional $N \times N$ AWGs can perform the required wavelength commutation at each node. For the sake of simplification those Waveband MUX/DEMUXs are referred in this paper also as $N \times N$ AWGs.

The advantage of the Mesh topology are the survivable ability and efficient wavelength utilization. Indeed, Mesh topology provides the possibility integrating protection models in the networks since there can exist more than one path between two nodes thus one can serve as working path and the other serves as backup path. The backup path will be used for replacing the working one in case of failure of the latter due to a failure in the network. This feature is totally absent in the tree-like topology. Ring topology allows also protection but it is known that Ring uses wavelengths inefficiently due to the fact that a dedicated wavelength around the ring is required for transmission between each pair of nodes.

We believe that the presence of links between AWGs in Mesh topology of Hybrid WDM-TDM PON will allows to create a robust topology for serving a large number of customers with less fiber requirement. We believe also that, the main capital investment on PON network is on fiber itself and on fiber installation (laying out the fiber underground or hanging fiber). Some researches stated that fiber layout take 90% the capital cost, only 10% are due to network equipment [2]. Since the fiber installation cost is proportional with fiber length, therefore, if Mesh topology can help to reduce the total fiber length, *i.e.* the fiber running from OLTs

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to ONUs, it results in a less expensive PON.

In this paper, we will evaluate the pertinence of the Mesh topology in reduction of fiber installation cost for Hybrid WDM-TDM PON. Since this cost is proportional with the fiber length, we will then evaluate the fiber consuming level of Mesh topology with links between AWGs over the Star topology without links between AWGs. For this purpose we develop some polynomial iterative methods for designing survivable Hybrid WDM-TDM PON using Star and Mesh topologies. Then we compare the total fiber length used in both topologies. It is expected that the Mesh topology saves fiber more than Star topology. A major advantage of the proposed methods is polynomial running time, thus the methods can be used to design PONs of hundreds devices.

In fact, the Star topology is a special case of the Mesh topology where no links are allowed between AWGs. Therefore, the problem of designing Star PON and Mesh PON with minimal fiber length can be stated commonly as following: Given a set of OLTs, AWGs, Splitters, ONU and given that all fiber links have equal number of wavelengths per fiber. The goal of the design is:

- To connect the OLTs, AWGs, Splitters, ONUs together.
- To route a working downstream, a working upstream, a backup downstream and a backup upstream connection to between each ONU and an OLT. A backup stream must be link-disjoint with its working one in order to be able to survive the traffic on the working one in case of failure.
- To minimize the total cable length.

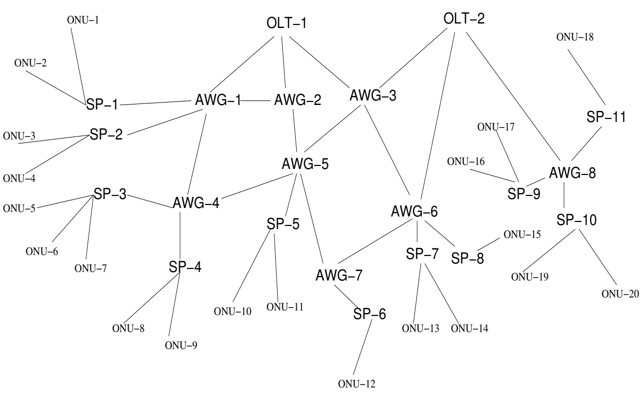

Figure 1: Example of a Mesh Hybrid WDM-TDM PON

The design is subject to several constraints due to the characteristics of Mesh PON and the passive nature of PON devices:

- A Splitter can receive at most one wavelength from an unique AWG.
- A Splitter can split wavelength for at most *n_splitting* ONUs.
- The number of intermediate AWGs and the fiber length between an OLT and an ONU should be limited in order to limit the signal power attenuation.

Although there are a lot of research on designing optical core networks, for example in [5, 8, 12], there are few works on designing PON networks such as those in [3,6,7,9]. Moreover, those works either focus on TDM PON, either does not aim to design a survivable network.

The study in [11] has proposed the optimal solution for designing a survivable Mesh Hybrid WDM-TDM PON using Integer Linear Programming model and a Greedy heuristic solution for designing Survivable Star Hybrid WDM-TDM PON. However, these two methods are not sufficient to make a comparison of Mesh and Star topologies since the former takes too long time to give the results when the number of network devices increases and the latter can still be improved. Therefore, in this paper, we will propose a less time consuming heuristic algorithm for Mesh topology and another better quality heuristic algorithm for Star topology.

The remaining of the paper is organized as follows: In Section 2 and 3, we propose two design methods for Star topology without links between AWGs. In Section 4, we propose a design solution based on local improvement procedures for Mesh topology with links between AWGs. The numerical results are shown in Section 5. Finally, some concluding remarks are given in Section 6.

2. STAR DESIGN METHOD 1 (STAR-1)

In the survivable Star topology, each ONU needs to connect to the same OLT by two disjoint paths via two Splitters and two AWGs so that one path plays the role of working connection and the other is backup connection. In order to satisfy this requirement, in the Greedy algorithm given in [11], Splitters and AWGs are regrouped in groups of two Splitters and two AWGs, then ONUs are distributed into the closest groups. Each ONU in the group connect to the same OLT by two disjoint branches ONU-Splitter-AWG-OLT via two pairs of Splitter-AWG in the group. In fact, the way to distribute ONUs to the closest group help to obtain short paths between ONUs and OLTs. However, on the way from an ONU to an OLT, the farest segment is between the OLT and AWG, therefore the more ONUs sharing the same OLT-AWG segment, the less long fiber needs to be run between AWG and OLT and consequently the more total fiber length is saved. Inspired from this remark, we propose to improve Greedy by changing the way distributing ONUs into groups. The ONUs will be distributed in groups so that each group is saturized with *n_spliting* ONUs and thus the same AWG-OLT segment is shared in maximum amongst ONUs. See Figure 2 for an illustration of grouping process. The detail method is as follows:

1. Put Splitters in pairs: The two Splitters closest to each other are put in pair first then the remaining Splitters are put in pairs recursively.
2. For each pair of Splitters SP_x, SP_y:
   a. Find the AWG_i closest to SP_x and the AWG_j closest to SP_y that still have available ports. Find and an available OLT_u so that the total fiber length running between OLT_u-AWG_i-SP_x and OLT_u-AWG_j-SP_y is minimal.
   b. Select a group of *n_spitting* ONUs that have the smallest total distance to the two Splitters.

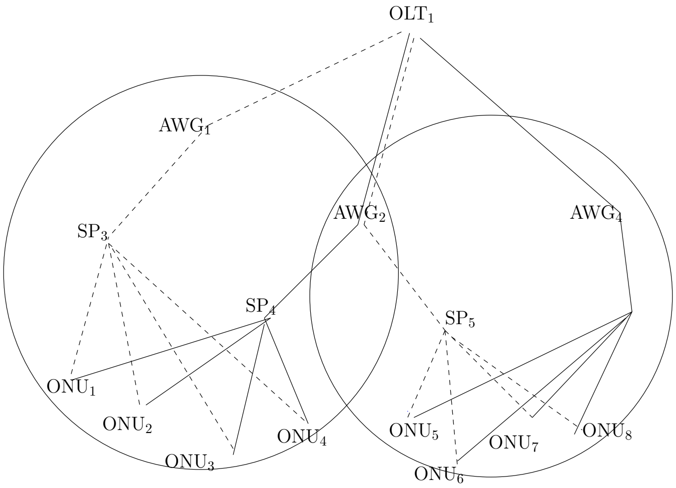

Figure 2: Illustration of device grouping process. A cycle represents a group with *n_splitting* ONUs. Dashed lines are backup connections, continuous lines are working connections.

3. Connect the selected ONUs to both Splitters. Connect SP_x to AWG_i and SP_y to AWG_j and both AWGs to OLT_u.

4. Repeat above steps with the remaining ONUs until there are no more ONUs to connect.

3. STAR DESIGN METHOD 2 (STAR-2)

In Star-1, the Splitters are made in pair if they are closest to each other. The two Splitters always connect with the two closest available AWGs then the closest OLT to the latter two. However, in so doing, it is not guarantee that the chosen AWGs and OLT make the total fiber length through them smallest. In this Section we propose an improved algorithm where we examine more combinations of ONUs, Splitters, AWGs and OLT before choosing a best one. The detail method is as follows:

1. For each pair of Splitters $\mathrm{SP}_x, \mathrm{SP}_y$:

   a. Find the two best $\mathrm{AWG}_i, \mathrm{AWG}_j$ and an OLT_u so that the total fiber length running between OLT_u-AWG_i-SP_x and OLT_u-AWG_j-SP_y is minimal. Let us denote the total fiber length by δ_1.

   b. Select a group of *n_spitting* ONUs that have the smallest total distance to the two Splitters. Let us denote the total distance by δ_2.

2. Select the pair of Splitters that have the smallest $\delta_1 + \delta_2$. Connect the Splitters with two AWGs, OLT and *n_spitting* ONUs that made the minimum while checking the wavelengths availability and port availability. Remove the selected Splitters and ONUs from the list of device to be considered.

3. Repeat Step 1 with the remaining Splitters and ONUs until there are no more ONUs.

4. MESH DESIGN USING LOCAL IMPROVEMENT PROCEDURES (MESH-LIP)

The solutions given by Star-1 and Star-2 do not consider the links between AWGs. In this Section, start from the topology given by Star-2, we perform successively following local modifications, each one improves a little bit the topology. We adjust some 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 five following processes. These processes are repeated until no more improvement is possible.

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 more detail in Algorithm 1. See Fig. 3(a) for 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 connections to obtain the pair ONU_{x_1}-SP_{y_2} and ONU_{x_2}-SP_{y_1} if that leads to shorter total fiber length. See more detail in Algorithm 2.

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 more detail in Algorithm 3. See Fig. 3(b) for illustration.

4. [**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 connections to obtain the pair SP_{x_1}-AWG_{y_2} and SP_{x_2}-AWG_{y_1} if that leads to shorter total fiber length. See more detail in Algorithm 4.

5. [**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 from each ONU to a OLT. See more detail in Algorithm 5.

It is noticeable that in all improvement procedures, all problem constraints on maximal path length, two link disjoint paths from each ONU to a OLT, number of splittings, number of hops and wavelength are always checked at appropriate steps.

5. NUMERICAL RESULTS

The three proposed algorithms and the Greedy heuristic solution in [11] have been implemented and tested with the same dataset in order to compare their performance and then evaluate the impact of Mesh topology in the reduction of the total fiber installation cost. The algorithms are tested with two dataset.

Algorithm 1: Improvement 1

input : current links of OLTs, AWGs, SPs, ONUs
output: new improvement if $\delta_{max} > 0$

`Min2Paths`($\mathrm{OLT}_z, \mathrm{SP}_x, \mathrm{SP}_y$): finds OLT_z which minimizes two link disjoint paths from it to SP_x and SP_y and returns this minimal value;

`MaxONUs`($\mathrm{SP}_x, \mathrm{SP}_y$): finds a group of maximum *n_splitting* ONUs which maximizes the saving amount of cable length if switching these ONUs to $\mathrm{SP}_x, \mathrm{SP}_y$;

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

$\delta_{max} = 0$;
foreach *free pair* (SP_x, SP_y) **do**
  $\delta_1 =$ `Min2Paths`($\mathrm{OLT}_z, \mathrm{SP}_x, \mathrm{SP}_y$);
  $\delta_2 =$ `MaxONUs`($\mathrm{SP}_x, \mathrm{SP}_y$);
  $\delta_{max} =$ `Max`($\delta_{max}, \delta_2 - \delta_1$);
if $\delta_{max} > 0$ **then**
  Determine *n_splitting* ONUs and the free pair SPs leading to δ_{max}, then Switch current links of these ONUs to this pair SPs;

Algorithm 2: Improvement 2

input : current links of OLTs, AWGs, SPs, ONUs
output: new improvement for each $\delta > 0$

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

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foreach *pair* (ONU_{x1}, ONU_{x2}) **do**
  $\mathrm{SP}_{y1} \leftarrow$ a current link to ONU_{x1};
  $\mathrm{SP}_{y2} \leftarrow$ a current link to ONU_{x2};
  $\delta =$
  (`Distance`($\mathrm{ONU}_{x_1}, \mathrm{SP}_{y_1}$) + `Distance`($\mathrm{ONU}_{x_2}, \mathrm{SP}_{y_2}$)) −
  (`Distance`($\mathrm{ONU}_{x_2}, \mathrm{SP}_{y_1}$) + `Distance`($\mathrm{ONU}_{x_1}, \mathrm{SP}_{y_2}$));
  if $\delta > 0$ **then**
    Remove links: $\mathrm{ONU}_{x_1} \rightarrow \mathrm{SP}_{y_1}$, $\mathrm{ONU}_{x_2} \rightarrow \mathrm{SP}_{y_2}$;
    Connect links: $\mathrm{ONU}_{x_1} \rightarrow \mathrm{SP}_{y_2}$, $\mathrm{ONU}_{x_2} \rightarrow \mathrm{SP}_{y_1}$;

Algorithm 3: Improvement 3

input : current links of OLTs, AWGs, SPs, ONUs
output: new improvement if $\delta_{max} > 0$

$\delta_{max} = 0$;
foreach *in-use* AWG_x **do**
  foreach *free* AWG_y **do**
    $\delta = 0$;
    foreach SP_z **do**
      if
      `Distance`(AWG_x, SP_z) > `Distance`(AWG_y, SP_z)
      then
        $\delta = \delta +$ `Distance`($\mathrm{AWG}_x, \mathrm{SP}_z$) −
        `Distance`($\mathrm{AWG}_y, \mathrm{SP}_z$)
      $\delta_{max} =$
      `Max`($\delta_{max}, \delta_2 -$ `Distance`($\mathrm{AWG}_x, \mathrm{AWG}_y$));
if $\delta_{max} > 0$ **then**
  Determine in-use AWG_x ,free AWG_y and SPs leading to δ_{max}, then Switch current links of these SPs to AWG_y and Connect AWG_x to AWG_y;

Algorithm 4: Improvement 4

input : current links of OLTs, AWGs, SPs, ONUs
output: new improvement for each $\delta > 0$

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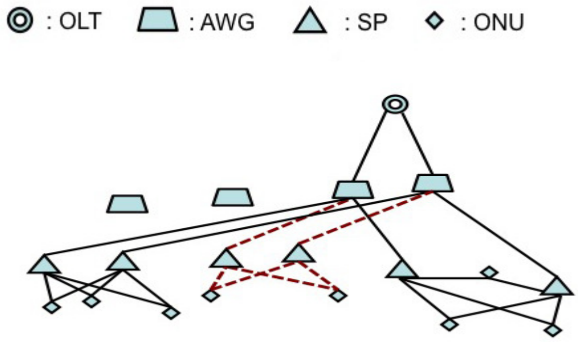
foreach *pair* (SP_{x1}, SP_{x2}) **do**
  $\mathrm{AWG}_{y1} \leftarrow$ a current link to SP_{x1};
  $\mathrm{AWG}_{y2} \leftarrow$ a current link to SP_{x2};
  $\delta =$
  (`Distance`($\mathrm{SP}_{x_1}, \mathrm{AWG}_{y_1}$) + `Distance`($\mathrm{SP}_{x_2}, \mathrm{AWG}_{y_2}$)) −
  (`Distance`($\mathrm{SP}_{x_2}, \mathrm{AWG}_{y_1}$) + `Distance`($\mathrm{SP}_{x_1}, \mathrm{AWG}_{y_2}$));
  if $\delta > 0$ **then**
    Remove links: $\mathrm{SP}_{x_1} \rightarrow \mathrm{AWG}_{y_1}$, $\mathrm{SP}_{x_2} \rightarrow \mathrm{AWG}_{y_2}$;
    Connect links: $\mathrm{SP}_{x_1} \rightarrow \mathrm{AWG}_{y_2}$, $\mathrm{SP}_{x_2} \rightarrow \mathrm{AWG}_{y_1}$;

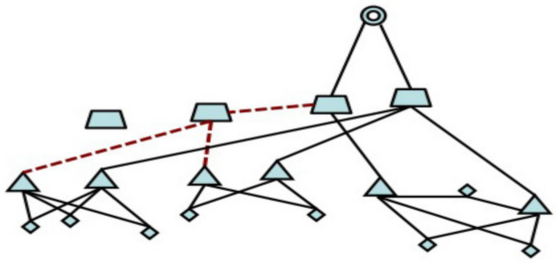
Algorithm 5: Improvement 5

input : current links of OLTs, AWGs, SPs, ONUs
output: new improvement if $\delta_{max} > 0$

$\delta_{max} = 0$;
foreach OLT_z **do**
  foreach *in-use pair* (AWG_x, AWG_y) *linking to* OLT_z
  do
    if
    `Distance`(AWG_x, OLT_z) > `Distance`(AWG_y, OLT_z)
    then
      Exchange the role of x and y;
    $\delta =$
    `Distance`($\mathrm{AWG}_x, \mathrm{OLT}_z$) − `Distance`($\mathrm{AWG}_x, \mathrm{AWG}_y$);
    $\delta_{max} =$ `Max`(δ_{max}, δ);
if $\delta_{max} > 0$ **then**
  Determine pair $\mathrm{AWG}_x, \mathrm{AWG}_y, \mathrm{OLT}_z$ leading to δ_{max}, then Remove link $\mathrm{AWG}_x \rightarrow \mathrm{OLT}_z$ and Connect AWG_x to AWG_y;



(a)



(b)

Figure 3: Illustration of local improvement procedures

- Dataset 1: Network instance sizes vary from 1 OLTs-3 AWGs -4 SPs to 1 OLTs-7 AWGs-18 Splitters and the number of ONUs varies upto 18. Splitting ratio $n\_splitting = 4$. The devices are distributed randomly in a region of 10km × 10km. Connection length threshold is set to 10km. The number of hops per connection is limited by 5 hops.

- Dataset 2: Network instance sizes vary from 1 OLTs-2 AWGs -4 SPs to 1 OLTs-10 AWGs- 20 Splitters and the number of ONUs varies upto 80. Splitting ratio $n\_splitting = 8$. The devices are distributed randomly in a region of 10km × 10km. Connection length threshold is set to 20km. The number of hops per connection is limited by 5 hops.

The splitting ratio in Dataset 1 is smaller than that in Dataset 2 results in smaller network sizes.

We compare the results of three algorithms Star-1, Star-2 and Mesh-LIP with the results of Greedy in order to demonstrate the performance of newly proposed algorithms. Table 1 and 2 show the reduction of fiber length of the proposed algorithms in comparison with Greedy. The fiber length reduction of a solution S is computed as:

$$\frac{\text{Fiber length of S} - \text{Fiber length of Greedy}}{\text{Fiber length of Greedy}}$$

The reduction numbers in the Tables are counted as the average reduction given from network instances with the same number of AWGs. The negative values mean the proposed algorithms provide solutions with less fiber. The results

Nb. of AWGs	Star-1 (%)	Star-2 (%)	Mesh-LIP (%)
3	-16.78	-17.69	-19.23
4	-26.51	-27.74	-29.19
5	-28.17	-29.12	-34.34
6	-25.69	-26.62	-38.10
7	-22.99	-24.00	-36.05

Table 1: Reduction of fiber length in comparison with Greedy in Dataset 1

Nb. of AWGs	Star-1 (%)	Star-2 (%)	Mesh-LIP (%)
2	0.67	-0.14	-2.19
3	-10.09	-12.96	-15.99
4	-18.12	-19.33	-24.13
5	-8.26	-9.79	-21.29
6	-7.44	-9.64	-22.34
8	-16.00	-17.48	-22.84
10	-18.03	-18.50	-25.99

Table 2: Reduction of fiber length in comparison with Greedy in Dataset 2

show that all Star-1, Star-2 and Mesh-ILP are much better than Greedy. While Star-2 is slightly better than Star-1, Mesh-ILP is more clearer better than Star-2 mostly when the number of AWGs increases.

We take a deeper look insides Star-2 and Mesh-LIP. In fact, Mesh-LIP is the results of applying successively different local improvements to Star-2. These local improvements includes re-arranging the ONUs, Splitters and profiting of links between AWGs in order to enhance the sharing level of the common fibers between AWG and OLTs. Table 3 and 4 show the average fiber reduction resulted from the improvements in Mesh-LIP. Negative numbers mean the total fiber length to be used are reduced. Those improvement allows to save upto 15.65% of fiber in the testing cases. In addition, in both Datasets, about 43-44% of cases links between AWGs are chosen by Mesh-LIP in order to reduce fiber costs. This number prove that the Mesh topology with links between AWGs are necessary for saving fibers.

In both tested Datasets, the number of ONUs and Splitters are generated proportional with the number of AWGs, therefore when the number of AWGs increases, the network size increases also. In general, the fiber saving level of Mesh-LIP over Star-2 increases when the network size increase (see Table 3 and 4). However, in the case of the Dataset 2, when the number of AWGs are 8 and 10 respectively, the fiber saving level is even smaller than when network has only 6 AWGs. This is explained that performance of Mesh over Star topology does not only depending on the network size but also on the distribution of network node locations.

Nb. of AWGs	Fiber reduction of Mesh-LIP over Star-2 (%)
3	-1.81
4	-1.98
5	-6.29
6	-14.72
7	-15.65

Table 3: Improvement of Mesh over Star-2 in Dataset 1

Nb. of AWGs	Fiber reduction of Mesh-LIP over Star-2(%)
2	-1.99
3	-3.39
4	-5.76
5	-12.04
6	-13.93
8	-6.49
10	-8.99

Table 4: Improvement of Mesh over Star-2 in Dataset 2

6. CONCLUSIONS

In this paper we have proposed some polynomial running-time solutions for designing survivable PON access networks according to Star and Mesh topologies. In the later case, links between AWGs are allowed. The proposed solution illustrates better performance in comparison with the existing one. The experiment results show that the Mesh topology allows to save a considerable amount of fiber in comparison with Star topology. However, the fiber saving level depends not only to the network size but also the distribution of the locations of network devices.

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