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Auxiliary Graph-Based Protection Algorithm for Survivable Wireless-Optical Broadband Access Network

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Abstract—In Wireless-Optical Broadband Access Network (WOBAN), the Wireless Mesh Network (WMN) at front-end is self-healing, because its mesh topology can provide alternative routes. However, the Passive Optical Network (PON) at back-end has the tree topology, thus it cannot survive the failures of network components such as Optical Line Terminal (OLT) and Optical Network Unit (ONU). In this paper, we focus on the survivability of WOBAN against the single OLT failure and single ONU failure in the back-end PON. To tolerate single OLT failure, we deploy the backup fibers between different segments with the objective of Maximum Protection and Minimum Deployment Cost (i.e., the MPMDC problem). To tolerate single ONU failure, we assign each ONU several alternate ONUs in the same segment with the objective of Maximum Protection and Minimum Hops Number (i.e. the MPMHN problem). We propose an Auxiliary Graph-based Protection Algorithm (AGPA) to solve the MPMDC and MPMHN problems, so as to optimize the deployment of backup fibers and the assignment of alternate ONUs. The numerical results show that our AGPA is efficient in solving the MPMDC and MPMHN problems.

Keywords-Wireless-Optical Broadband Access Network; survivability; backup fibers; alternate ONUs

1. Introduction

Recently, the Wireless-Optical Broadband Access Network (WOBAN) was acknowledged as a promising architecture for future access networks because it integrates both the Passive Optical Network (PON) and Wireless Mesh Network (WMN) technologies [1-4]. A typical WOBAN architecture is composed of multiple segments. As shown in Fig. 1, it is a WOBAN with two segments, and each segment has a WMN at the front-end and a PON at the back-end. Compared to the traditional access technologies, WOBAN can provide the users with larger bandwidth, more flexible access, and higher Quality of Service (QoS) [5-8]. Therefore, WOBAN has become a hot topic in recent years.

The survivability of WOBAN is a key issue because many traffic flows may be interrupted by the failure of network components. In WOBAN, the front-end WMN is self-healing, because its mesh topology can provide alternative routes. However, the back-end PON cannot survive network component failures due to its tree topology [9, 10]. Thus, it is necessary to enhance the survivability of WOBAN against the failures in the back-end PON.

In this paper, we focus on the survivability of WOBAN against the single Optical Line Terminal (OLT) failure and the single Optical Network Unit (ONU) failure. To tolerate single OLT failure, we first employ one of the ONUs in each segment as the backup ONU. Then we selectively deploy the backup fibers between the backup ONUs in different segments. The segments that are connected by backup fiber can backup for each other. Once the OLT in one segment fails, all the traffic in the failed segment will be sent to the backup ONU via the front-end WMN, and then the traffic will be transmitted through the backup fibers to the other available segments. We focus on optimizing the deployment of backup fibers with the objective to maximize the amount of protected traffic and minimize the deployment cost. We formulate this objective as Maximum Protection and Minimum Deployment Cost (MPMDC) problem.

To tolerate single ONU failure, we assign each ONU several alternate ONUs (distinguished from the backup ONUs mentioned above) in the same segment. Once an ONU fails, the traffic carried by the failed ONU will be sent to its available alternate ONUs through the wireless multi-hops paths in the front-end WMN. We focus on optimizing the assignment of alternate ONUs with the objective to maximize the amount of protected traffic and minimize the number of wireless hops. We formulate this objective as Maximum Protection and Minimum Hops Number (MPMHN) problem.

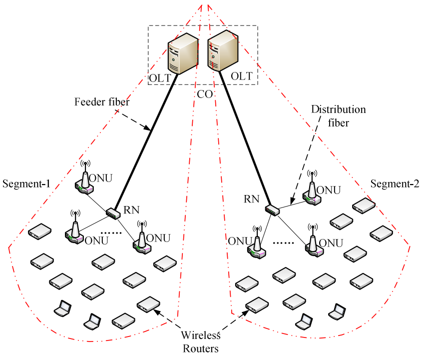


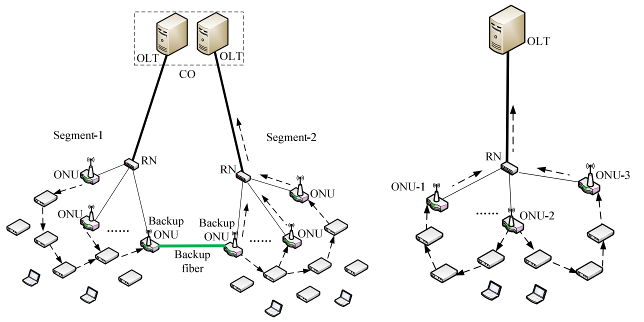
Figure 1. The WOBAN architecture with two segments

We propose an Auxiliary Graph-based Protection Algorithm (AGPA) to solve the MPMDC problem and the MPMHN problem. In AGPA, we first build two auxiliary graphs, one is for the MPMDC problem, and another one is for the MPMHN problem. Based on these two auxiliary graphs, both MPMDC and MPMHN problems can be converted to the Minimum Cost Maximum Flow (MCMF) problem in their respective auxiliary-graph. Then, we use the Shortest Path Faster Algorithm (SPFA) to find the MCMF in each one of the two auxiliary graphs. Finally, we can get the solutions to the MPMDC and MPMHN problems from their respective MCMF.

The remainder of this paper is organized as follows. In Section II, we formulate the MPMDC and MPMHN problems, respectively. In Section III, we present the proposed AGPA. The simulation results are given in Section IV. We finally conclude this paper in Section V.

2. Problem Formulation

It has been demonstrated that a distribution fiber failure is equivalent to an ONU failure and a feeder fiber failure is equivalent to an OLT failure [9, 10]. Thus, in this paper, we only consider the OLT failure and the ONU failure.



(a) Protection against OLT failure (b) Protection against ONU failure

Figure 2. Illustration of the protection scheme

1.1 Protection against Single OLT Failure

To protect WOBAN against the single OLT failure, we employ one of the ONUs as the backup ONU in each segment, and deploy backup fibers between the backup ONUs in different segments so that each segment is connected to at least one another segment. As shown in Fig. 2 (a), segment-1 and segment-2 are connected by backup fiber, thus they can backup for each other. Once segment-1 suffers from OLT failure, each ONU in segment-1 needs to transfer its traffic to the backup ONU. Then, the backup ONU in segment-1 sends the traffic to the backup ONUs in segment-2 through the backup fiber in between. The backup ONU in segment-2 will distribute the received traffic to the other ONUs in segment-2 via its front-end WMN, and each ONU in segment-2 can carry the received traffic by using its spare capacity. Thus, the amount of traffic that can be protected for segment-1 depends on the spare capacity of segment-2.

We focus on optimizing the deployment of backup fibers with the objective to maximize the amount of traffic that can be protected for all segments and minimize deployment cost.
We define this objective as the MPMDC problem, which can be formulated as follows.

We denote V as the set of segments and S_a as segment-a $(a = 1, 2, 3 \cdots |V|)$. For each $S_a \in V$, we denote $dem(S_a)$ and $cap(S_a)$ as the traffic demand and the spare capacity of S_a, respectively. For any pair of segments $S_a, S_b \in V \ \ (a, b = 1, 2, 3 \cdots |V|, \ \ a \neq b)$, we let $fee(S_a S_b)$ denote the cost for deploying a backup fiber between the backup ONUs in S_a and S_b. We denote E as the set of segment pairs, and each segment pair in E should be connected by backup fiber. Then, the total spare capacity of the backup segments for S_b can be represented as

$$Z_{OLT} = \sum_{(S_a, S_b) \in E} cap(S_a) \tag{1}$$

Thus, the amount of traffic in S_b that can be protected upon S_b fails is

$$W_{OLT} = \min\Big(\sum_{(S_a, S_b) \in E} cap(S_a), dem(S_b)\Big) \tag{2}$$

Our objective (i.e., the MPMDC problem) is to maximize

$$Q_{OLT} = \sum_{S_b \in V} \min\Big(\sum_{(S_a, S_b) \in E} cap(S_a), dem(S_b)\Big) \tag{3}$$

and minimize

$$M_{OLT} = \sum_{(S_a, S_b) \in E} fee(S_a S_b) \tag{4}$$

1.2 Protection against Single ONU Failure

To protect WOBAN against the single ONU failure, we assign each ONU several alternate ONUs in the same segment. When an ONU fails, the traffic carried by the failed ONU will be sent to its available alternate ONUs via the front-end WMN. As shown in Fig. 2 (b), ONU-2 is assigned ONU-1 and ONU-3 as alternate ONUs. Once ONU-2 fails, all traffic carried by ONU-2 will be sent to ONU-1 and ONU-3 through the wireless multi-hops path in the front-end WMN. Thus, the amount of traffic that can be protected for ONU-2 depends on the spare capacity of ONU-1 and ONU-3.

We focus on optimizing the assignment of alternate ONUs with the objective to maximize the amount of protected traffic for all ONUs and minimize the number of wireless hops. We define this objective as the MPMHN problem, which can be formulated as follows.

We denote O as the set of ONUs in a segment and N_i as ONU-i $(i = 1, 2, 3 \cdots |O|)$. For each $N_i \in O$, we denote $dem(N_i)$ and $cap(N_i)$ as the traffic demand and the spare capacity of N_i, respectively. For any pair of ONUs $N_i, N_j \in O \ (i, j = 1, 2, 3 \cdots |O|, \ \ i \neq j)$, we let $num(N_i N_j)$ denote the number of wireless hops from N_i to N_j. We denote $R(N_i)$ as the set of alternate ONUs for N_i. Then, the total spare capacity of the alternate ONUs for N_i can be represented as

$$Z_{ONU} = \sum_{N_j \in R(N_i)} cap(N_j) \tag{5}$$

The amount of traffic in N_i that can be protected upon N_i fails is

$$W_{ONU} = \min\Big(\sum_{N_j \in R(N_i)} cap(N_j), dem(N_i)\Big) \tag{6}$$

Our objective (i.e., the MPMHN problem) is to maximize

$$Q_{ONU} = \sum_{N_i \in O} \min(\sum_{N_j \in R(N_i)} cap(N_j), dem(N_i)) \tag{7}$$

and minimize the total number of wireless hops

$$M_{ONU} = \sum_{N_i \in O} \sum_{N_j \in R(N_i)} num(N_i, N_j) \tag{8}$$

3. The Proposed Agpa

In this section, we propose an efficient algorithm called AGPA to solve the MPMDC problem and the MPMHN problem. The AGPA can solve the MPMDC and MPMHN problems by two steps. In the first step, we build two auxiliary graphs, one is for the MPMDC problem, and another one is for the MPMHN problem. Based on the respective auxiliary-graph, both the MPMDC and MPMHN problems can be converted to the MCMF problem. In the second step, a heuristic algorithm called SPFA is used to find the MCMF on each one of the two auxiliary graphs. Finally, we can obtain the solutions to the MPMDC and MPMHN problems from their respective MCMF.

3.1 Auxiliary Graph for the MPMDC Problem

We denote G_{MPMDC} as the auxiliary graph for the MPMDC problem. G_{MPMDC} is a directed graph, and each edge in it is characterized by a cost and a capacity (denoted as (*cost*, *cap*)). The procedure of building G_{MPMDC} is described as follows.

1) Create a source vertex *S* and a destination vertex *D*.
2) For each pair of segments $S_a, S_b \in V$, if $cap(S_a) > 0$ or $cap(S_b) > 0$, create a vertex U_{ab} (called U-vertex).
3) For each segment $S_b \in V$, create a vertex V_b (called V-vertex).
4) For each U-vertex U_{ab}, create a directed edge from *S* to U_{ab} with (*cost*, *cap*)=($fee(S_a S_b)$, $+\infty$).
5) For each V-vertex V_b, create a directed edge from V_b to D with (*cost*, *cap*)=(0, $dem(S_b)$).
6) For each U-vertex U_{ab}, if $cap(S_a) > 0$, we create *m* directed edges from U_{ab} to V_b with (*cost*, *cap*)=(0,1), where $m = cap(S_a)$; if $cap(S_b) > 0$, we create *n* directed edges from U_{ab} to V_a with (*cost*, *cap*)=(0,1), where $n = cap(S_b)$.

For example, we assume a WOBAN with 3 segments S_1, S_2 and S_3. The traffic demands of S_1, S_2 and S_3 are $dem(S_1) = 3$, $dem(S_2) = 4$ and $dem(S_3) = 2$, respectively. The spare capacity of S_1, S_2 and S_3 are $cap(S_1) = 2$, $cap(S_2) = 3$ and $cap(S_3) = 4$, respectively. The cost of backup fibers between each pair of segments are $fee(S_1 S_2) = 2$, $fee(S_1 S_3) = 4$ and $fee(S_2 S_3) = 3$, respectively. According to the procedure mentioned above, we can build the auxiliary graph G_{MPMDC} as shown in Fig. 3.

Based on G_{MPMDC}, the MPMDC problem can be solved by finding the MCMF. Here, the MCMF in G_{MPMDC} refers to a flow from *S* to *D* which has the maximum throughput and the minimum cost. Specifically, there are multiple flows with the maximum throughput from *S* to *D*, while the MCMF is the one which has the minimum cost, where the cost of a flow is the cost sum over all edges traversed by the flow. From the MCMF in G_{MPMDC}, we can obtain the optimal solution *E* as follows. Initially, *E* is an empty set. For each U-vertex U_{ab}, if the flow from *S* to U_{ab} has the throughput larger than zero, we add (S_a, S_b) into *E*. For example in Fig. 3, we show its MCMF from *S* to *D* by displaying the throughput (denoted as *t*) of each edge that the MCMF traverses. We can see that the MCMF in Fig.3 has the maximum throughput of 9 and the minimum cost of 5. Since the flow from *S* to U_{12} and the flow from *S* to U_{23} have nonzero throughput, the optimal solution to the MPMDC problem in Fig. 3 is $\{(S_1, S_2), (S_2, S_3)\}$. This solution achieves the maximum protection of 9 with the minimum deployment cost of 5.

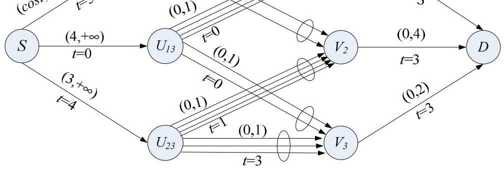


Figure 3. An instance of the auxiliary graph G_{MPMDC}

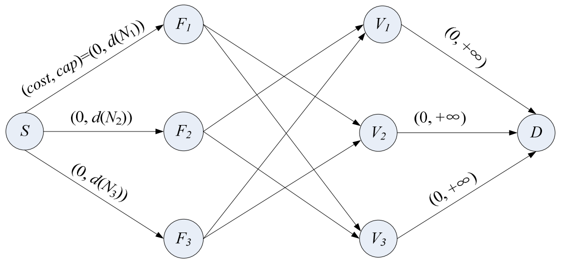
3.2 Auxiliary Graph for the MPMHN Problem

We denote G_{MPMHN} as the auxiliary graph for the MPMHN problem. Similar to G_{MPMDC} mentioned above, G_{MPMHN} is also a directed graph, and each edge in G_{MPMHN} is characterized by a cost and a capacity (denoted as (*cost*, *cap*)). However, the building of G_{MPMHN} has the different procedure from that of G_{MPMHN} , as follows.

1) For each ONU N_i $(i=1,2,3\cdots|O|)$, create a F-vertex F_i and a H-vertex H_i, respectively.
2) For each F-vertex F_i, create a directed edge from *S* to F_i with (*cost*, *cap*)=(0, $dem(N_i)$).
3) For each H-vertex H_i, create a directed edge from H_i to *D* with (*cost*, *cap*)=(0, $+\infty$)
4) For each vertex pair F_i and H_j $(i \neq j)$, create a directed edge from F_i to H_j with (*cost*, *cap*)= ($num(N_i N_j)$, $cap(N_j)$).

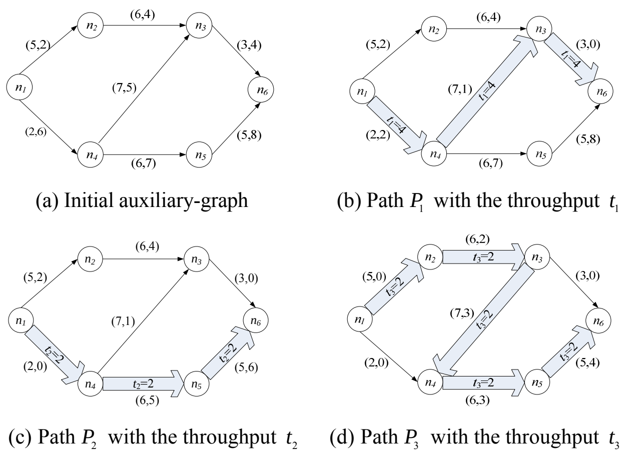
For example, Fig. 4 shows the G_{MPMHN} of the MPMHN problem about three ONUs denoted as N_1, N_2 and N_3.

Based on the MCMF in G_{MPMHN} , We can obtain the optimal solution to the MPMHN problem (i.e., $R(N_i)$ $(i=1,2,3\cdots|O|)$) as follows. Initially, $R(N_i)$ $(i=1,2,3\cdots |O|)$ is an empty set. If the flow on the edge from F_i to H_j has a nonzero throughput, this means that N_i needs to use the spare capacity of N_j to protect its traffic and N_j is an alternate ONU of N_i. Thus, we add N_j into $R(N_i)$.



The (*cost*, *cap*) of the edge from F_i to H_j (i, j=1,2,3; $i \neq j$) is ($num(N_iN_j)$, $cap(N_j)$).

Figure 4. An instance of the auxiliary graph G_{MPMHN}



(a) Initial auxiliary-graph (b) Path P_1 with the throughput t_1

(c) Path P_2 with the throughput t_2 (d) Path P_3 with the throughput t_3

Figure 5. An instance of the SPFA for finding the MCMF

3.3 The Heuristic Algorithm for the MCMF Problem

It is notable that more segments and more ONUs will produce the larger-scale G_{MPMDC} and G_{MPMHN} respectively, thus the larger complexity for solving the MCMF problem. Therefore, we use a heuristic algorithm called SPFA to find the MCMF in each one of G_{MPMDC} and G_{MPMHN} . In SPFA, we first find a path which has the minimum cost from the source vertex *S* to the destination vertex *D.* Then, we assign this path the maximum throughput. Thus, we can get a path from *S* to *D* with the minimum cost and the maximum throughput. We repeat this step until the flow from *S* to *D* gets the maximum throughput. Finally, we will find the MCMF from *S* to *D*.

We take an example in Fig. 5. The initial auxiliary-graph is shown in Fig. 5 (a), which includes 6 vertices (i.e., $n_1 \sim n_6$). Each edge is characterized by two numbers in a bracket: the first number denotes its cost per unit capacity and the second number denotes its capacity. We aim to find the MCMF from n_1 to n_6 .

In Fig. 5 (b), because the cost of the edge $(n_3 \to n_6)$ is 3 and the cost of the edge $(n_5 \to n_6)$ is 5, we choose the edge $(n_3 \to n_6)$. In the same way, we choose the edge $(n_1 \to n_4)$ instead of $(n_1 \to n_2)$. To connect the edge $(n_1 \to n_4)$ and the edge $(n_3 \to n_6)$, we choose the edge $(n_4 \to n_3)$. Then, we find the path $(n_1 \to n_4 \to n_3 \to n_6)$ denoted as P_1. We assign P_1 the maximum throughout $t_1 = 4$ and update the capacity of each edge in P_1. Thus, the cost of P_1 is $4 \times (2+7+3) = 48$.

In Fig. 5 (c), we continue to find the next path with the minimum cost from n_1 to n_6. Because the edge $(n_3 \to n_6)$ has no spare capacity, we choose the edge $(n_5 \to n_6)$. Thus, we can find the path $(n_1 \to n_4 \to n_5 \to n_6)$ denoted as P_2, which has the maximum throughout $t_2 = 2$ and the minimum cost $2 \times (2+6+5) = 26$. Then, we update the capacity of each edge in P_2.

In Fig. 5 (d), because the edge $(n_1 \to n_4)$ has no spare capacity, we choose the edge $(n_1 \to n_2)$. Thus, we can find the path $(n_1 \to n_2 \to n_3 \to n_4 \to n_5 \to n_6)$ denoted as P_3, which has the maximum throughout $t_3 = 2$ and the minimum cost $2 \times (5+6+(-7)+6+5) = 30$ (It is notable that the edge $(n_3 \to n_4)$ has the opposite direction of edge $(n_4 \to n_3)$, thus its cost is -7).

Since the flow from n_1 to n_6 reaches its maximum throughout, the SPFA stops. Finally, by combining the three paths P_1, P_2 and P_3, we can obtain the MCMF which has the maximum throughput $t_1 + t_2 + t_3 = 4 + 2 + 2 = 8$ and the minimum cost $48 + 26 + 30 = 104$.

4. Numerical Results

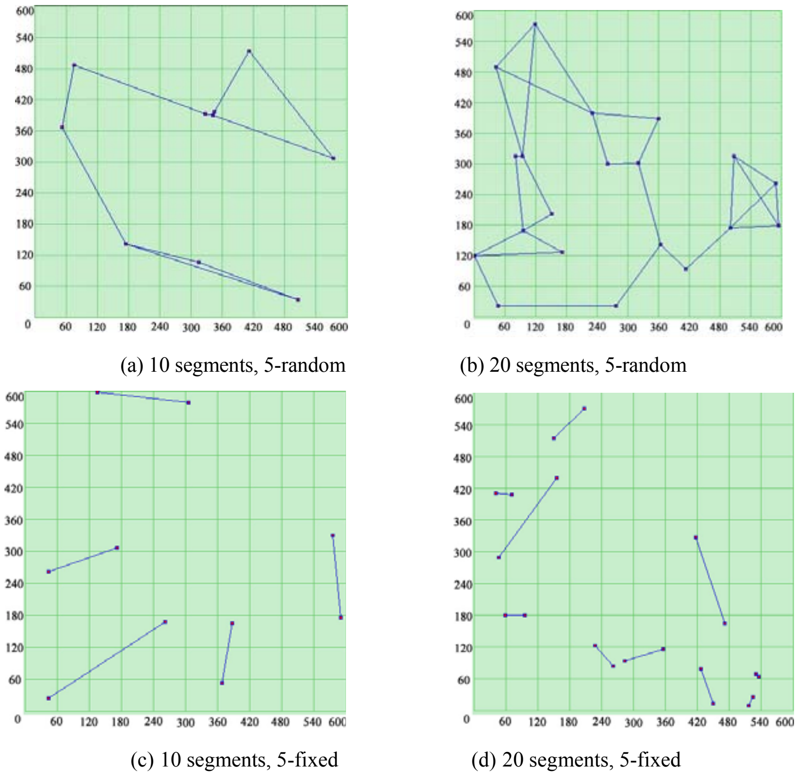
In this section, we evaluate the performance of our AGPA by considering different instances of the MPMDC and MPMHN problems.

We generate the instances of the MPMDC problem as follows. We randomly distribute $|V|$ segments in a $600m \times 600m$ square area. All segments have the same capacity of 10 units. The deployment cost of the backup fibers between the backup ONUs in two segments is set to the Euclidean distance and rounded to the nearest integer. $|V|$ is set to 10 or 20. Each segment is assigned the demand in random or fixed way. Thus, we can set four instances: (a) 10 segments, random demands; (b) 20 segments, random demands; (c) 10 segments, fixed demands; (d) 20 segments, fixed demands.

Based on these four instances, we evaluate the Deployment Cost (DC) and the Number of Backup Fibers (NBF) for the optimal solutions to the MPMDC problems in different instances, as shown in Table I. Here, "*k*-random" $(k \in \{5,6,7,8\})$ means that each segment is randomly assigned the demand within the range from *k* units to 10 units. "*k*-fixed" means that all segments are assigned a fixed demand of *k* units. For all instances shown in Table I, there always exists $\sum_{S_a \neq S_b \in V} cap(S_a) \geq dem(S_b)$ for each segment $S_b \in V$, thus each segment can be fully protected. We can see that, both *k*-fixed and *k*-random instances have the larger DC and NBF when the demand (i.e., *k*) increases. However, *k*-fixed instance always has lower DC and NBF than *k*-random instance. This is because the total demand of all segments in *k*-fixed instance is lower than that in *k*-random instance. Furthermore, we also display the deployment of backup fibers for different instances of MPMDC problem in Fig. 6, where the backup ONUs and the backup fibers are designated as dots and lines, respectively.

TABLE I. DEPLOYMENT COST (DC) AND NUMBER OF BACKUP FIBERS (NBF) FOR THE OPTIMAL SOLUTIONS TO THE MPMDC PROBLEMS IN DIFFERENT INSTANCES

	$\|V\|$=10		$\|V\|$=20	
Demands	DC(*km*)	NBF	DC(*km*)	NBF
5-random	2060	15	4096	33
6- random	3134	19	5191	38
7- random	6153	30	8863	56
8- random	9445	35	16855	80
5-fixed	640	7	913	13
6- fixed	1541	12	2339	24
7- fixed	2264	18	4508	38
8- fixed	4368	26	6012	47



(a) 10 segments, 5-random (b) 20 segments, 5-random

(c) 10 segments, 5-fixed (d) 20 segments, 5-fixed

Figure 6. The deployment of backup fibers for different instances of the MPMDC problem

We generate the instances of the MPMHN problem as follows. We set a $600m \times 600m$ square area and divide it into 16 cells. Each cell includes a segment composed of 4 ONUs which have the same capacity of 10 units. Each ONU is assigned the demand in random or fixed way. Table II shows the optimal solutions to different instances of the MPMHN problem. Due to the space limitation, we choose one of the 16 segments (including 4 ONUs) as a sample. In this table, "N_i (5-random)" $(i = 1, 2, 3, 4)$ means that N_i is randomly assigned the demand within the range from 5 units to 10 units. "N_i (5-fixed)" $(i = 1, 2, 3, 4)$ means that N_i is assigned the fixed demand of 5 units. For each instance, we show the alternate ONUs set and the average number of wireless hops. We can see that, each ONU is assigned more alternate ONUs in the 5-random instance than in the 5-fixed instance, thus a larger average hops number.

TABLE II. OPTIMAL SOLUTIONS TO DIFFERENT INSTANCES OF THE MPMHN PROBLEM

ONU	Alternate ONUs	Average hops number
N_1 (5-random)	N_2 N_3 N_4	9
N_2 (5-random)	N_1 N_3	7
N_3 (5-random)	N_1 N_2 N_4	8
N_4 (5-random)	N_1 N_3	7
N_1 (5-fixed)	N_2	4
N_2 (5-fixed)	N_1	4
N_3 (5-fixed)	N_4	6
N_4 (5-fixed)	N_3	6

5. Conclusion

In this paper, we aim to protect WOBAN against the single OLT failure by optimizing the deployment of backup fibers, and against the single ONU failure by optimizing the assignment of alternate ONUs. We formulate the objectives of deploying backup fibers and assigning alternate ONUs as the MPMDC problem and the MPMHN problem, respectively. A novel and efficient algorithm, called AGPA, is proposed to solve the MPMDC and MPMHN problems. In AGPA, we first build two auxiliary graphs, one is for the MPMDC problem, and another one is for the MPMHN problem. Then, both MPMDC and MPMHN problems can be converted to the MCMF problem based on their respective auxiliary-graph. We use the SPFA to find the MCMF in each one of the two auxiliary graphs. Finally, we can get the solutions to the MPMDC and

MPMHN problems from their respective MCMF. The numerical results demonstrate that our AGPA is efficient in solving the MPMDC and MPMHN problems.

6. Acknowledgement

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