Survivable Physical topology design for All-optical Metro core networks

Hanh V. Nguyen, Dieu Linh Truong
School of Information and Communication Technology, Hanoi University of Science and Technology, Hanoi, Vietnam
viet.hanh@samsung.com; linhtd@soict.hut.edu.vn

***Abstract*: Along with the development of bandwidth consuming services, fiber optic is being widely used, especially in the metro core networks. Many solutions have been proposed for designing optical network topology. However, these solutions designed networks with a lot of fiber redundancy. This paper proposes a solution for designing physical topology of optical metro core networks with the objectives of (i) ensuring traffic requirements between the network nodes, (ii) minimizing fiber cost, and (iii) assuring the network survivability. The numerical results show that the proposed solution satisfies those objectives and save more fiber than existing solutions.**

Keywords: All-optical networks, survivable network, physical topology design, routing and wavelength assignment.

I. INTRODUCTION

Thanks to Wavelength Division Multiplexing (WDM) technology, a fiber can be exploited by multiple wavelengths; each one can carry generally 10Gbps of data. Today Dense WDM (DWDM) systems use 50 GHz or even 25 GHz channel spacing [1] result in up to 160 wavelengths in operation over the same fiber leading to a very large bandwidth capacity. The WDM technology becomes then an obvious choice for deploying backbone networks in general and metro core networks in particular. In the first generation of optical networks, optical signals are transmitted over fiber links and are converted to electrical form to be processed at network nodes. SONET/SDH is a typical architecture of this generation. The optical networks today are in the second generation where signal remains always in optical domain both along links and also at network nodes while being processing. The networks of the second generation are so called all-optical networks. All-optical networks remove electrical processing and electrical-optical conversion elements from the networks and therefore reduce the equipment cost.[1]

In all-optical networks, network nodes are optical cross-connects (OXCs) that switch a wavelength from one incoming port to an outgoing port. That means the smallest bandwidth-switching unit is a wavelength. Since all-optical networks do not process data electronically at nodes, a data flow entering an OXC by a wavelength generally gets out of the OXC using the same wavelength. Except when wavelength converter is used in the middle, a data flow must travel over the same wavelength from end-to-end. This condition is called *wavelength continuity constraint* and the wavelength path from end-to-end is called a *lightpath*. Over the same fiber link, two lightpaths cannot be assigned the same wavelength. In this research, we will not consider the use of wavelength conversion.

A physical topology is usually designed when an optical network provider builds a network according to a required traffic matrix. The physical topology of an optical network shows how OXCs interconnect to each other by fiber links. The traffic matrix describes amounts of bandwidth (in terms of wavelengths for example) that the network should transfer between each pair of network nodes. In this paper, we use the term *request* to refer to each such amount of bandwidth to be carried between a source and a destination node in the traffic matrix. Therefore, while designing physical topology of a network, it is

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[1] **A preliminary version of this paper has been presented in ComManTel'13, Ho Chi Minh city, Vietnam, January 2013**

sometimes necessary to perform a test routing to find out lightpaths for all requests in the traffic matrix in order to make sure that the designed network can carry all requests in its traffic matrix.

Routing in all optical networks is known as Routing and Wavelength Assignment (RWA) problem [2]. Routing is to find the path from a source node to a destination node for each request in the traffic matrix. Wavelength assignment is to find the same available wavelength on all links along the routed path for carrying the requested bandwidth. Such a RWA makes the physical topology design problem more complex since RWA is proved NP-hard [7].

In this paper, we focus on the problem of designing physical topology for all-optical network such that the network is survivable at any single failure. Survivability is the ability that a network can provide continuous service in the presence of failures. A failure may happen on network links because of fiber cuts or at network node due to equipment faults. Since the failure frequency is not very high and a failure usually be repaired before another one occurs, it is often assumed that there is a single failure in the network at a moment. Most modern network devices have built-in redundancy that greatly improves their reliability; consequently the main concern is on link failures. When there is a failure in the network, all connections going through the failure location will be affected. Basically, network recovery techniques deviate data flow from those affected connections to some alternative paths that avoid the failure location. The data communications can then continue over the alternative paths. Restoration is the class of recovery techniques where the alternative paths are looked for after failures thus the failure recovery is not guaranteed. Protection is another class of recovery technique where those alternative paths (called backup paths) are pre-planned before failures in order to be ready to replace the affected ones (called working paths) when failure occurs. In general, protection is preferred than restoration, however backup network resources need to be pre-planed once we design the network. There exist different protection scheme, for example link-based, path-based, segment-based protection [1]. We will use Path-based protection scheme in this research. In a path-based protection, a unique end-to-end backup connection is used for replacing the working one whatever the location of the failure on the latter. The backup connection needs to be disjoint with the working one in order to not fail simultaneously due to a failure at the common parts.

The problem of designing physical topology for survivable optical metro core networks is stated as follows:

Given:

- A set of core network nodes with their coordinates.
- A traffic matrix under the form of requests between pairs of network nodes such as: source, destination, bandwidth requirements.
- The maximum number of wavelengths per fiber.

The goal is to connect the set of network nodes in some topology such that:

- The network can carry all the traffic matrix,
- The network is survivable when there is a failure and
- The network uses the minimal fiber length.

In fact, 90% cost of optical networks is due to fiber installation cost and only 10% comes from equipment [4]. The fiber installation cost, i.e. cost of laying out the fiber underground or hanging the fiber over towers, is proportional with the fiber length. Therefore, in minimizing fiber length, the network cost tends also to be minimized.

There are many studies for designing physical network topology. Studies in [3],[5],[9],[14],[15],[16] focus on copper networks in general but do not recommend tailored solutions for all-optical networks. Study in [8] gives some formulas to estimate the needed fiber-to-node ratio for making survivable network but does not deal with a design solution. Studies in [10][11][12] perform Routing and Wavelength Assignment over an existing physical topology. Study in [17] gives some theorems, lemmas and methods that design survivable WDM physical topologies without taking into account if the designed network can carry a given network load (traffic matrix) or not. Some other researches focus on designing all-optical network such as Two-Stage Cut Saturation Algorithm and Benchmark Algorithm [6]. However, these solutions aim uniquely at minimizing fiber cost while ignoring the survivability.

In this paper, we propose a physical topology design solution to all-optical network with the aims of meeting the traffic matrix with the minimum fiber cost and assuring the network survivability against single failure. The proposed algorithm is compared to Benchmark algorithm. Although Two-Stage Cut Saturation Algorithm is claimed that it costs about 20% less fiber length than Benchmark algorithm, due to the complexity of the former algorithm, we will not make a comparison with it. However, in Section 4, we will see that in experimented cases the proposed algorithm is usually several times better than Benchmark algorithm in terms of fiber cost saving, so we also believe that it is possibly comparative or better than Two-Stage Cut Saturation.

The rest of the paper is organized as follows. Section 2 reviews Benchmark algorithm. In Section 3, we propose our new solution. In Section 4, we evaluate the complexity of the proposed solution and demonstrate its advantages over Benchmark through numerical results. Conclusions are given in Section 5.

II. BENCHMARK ALGORITHM

Benchmark algorithm designs the physical topology for all-optical network without reserving spare capacity for survivability purpose. This algorithm adds links to the network topology gradually until the network can meet all the lightpath requests in the traffic matrix.

The idea of the algorithm is as follows. Let N be the number of network nodes, there can be N(N-1)/2 direct links. These links are denoted by $l_1, l_2, \ldots, l_{N(N-1)/2}$. Links are sorted in ascending fiber cost order.

i) Let call LB and UB be the lower bound and upper bound of the number of links in the topology respectively. The algorithm starts with LB=0 and UB = N(N-1)/2.

ii) Compute mid = $\lfloor (LB+UB)/2 \rfloor$.

iii) Create initial network with links from l_1 to l_{mid} then perform Routing and Wavelength Assignment (RWA) to determine whether this network can meet all the lightpaths requests in the traffic matrix. If RWA step terminates successfully, then set UB = mid, otherwise LB = mid.

iv) If UB-LB >1, then go to iii); otherwise, the fiber cost of the network is equal to the sum of the fiber cost of l_1, l_2, …, l_{UB} and the algorithm stops.

RWA is performed in two steps for each request of the traffic matrix: routing then wavelength assignment. Routing is performed by using Dijkstra algorithm. When all requests have been routed successfully, the routed paths will be assigned wavelength using First-Fit strategy [7] (the number of assigned wavelengths depends on the bandwidth of each request). In First-Fit, wavelengths are numbered from low to high and the lowest index wavelength available is chosen to assign to a request.

In case of failure at the routing or wavelength assignment step, Benchmark adds about half of the remaining links to the current topology by increasing mid in iii) and performs again routing and wavelength assignment for the requests in the traffic matrix. The algorithm ends when all the requirements are routed and assigned wavelength successfully.

The fact that Benchmark algorithm begins by creating a topology with about half number of links between network nodes leads to large fiber cost even in the initial topology. Furthermore, Benchmark algorithm does not aim to design network topology to be fault tolerance, consequently the resulted topology may not be survivable at failures.

III. PROPOSED ALGORITHM

The objective of the proposed algorithm is to design the survivable physical topology that meets the traffic requirement with minimal fiber length. The proposed algorithm is called Survival.

The algorithm is inspired from the remark that a ring is the simplest 2-connected structure that guarantee that any connection along the ring perimeter be survivable when the network fails. Indeed, between any pair of nodes on ring, there are always two paths in clockwise and counter-clockwise on the ring for carrying traffic. So one path can be used for working and the other can be used for backup. Survival algorithm starts with creating a ring going through all network nodes then adds gradually cross-ring links to this ring until the current topology is capable to meet the requested traffic matrix. Fig. 1 illustrates Survival algorithm. It is composed of two following steps.

Step 1: Create an initial topology: The initial topology is the small ring going through all nodes. The problem of finding a smallest ring going through all nodes is a Travelling Salesman Problem [13], which is known as NP-hard. In this paper, we do not aim to find a smallest ring but just a relatively small ring going through all nodes in acceptable time. Therefore, we proposed the following heuristic algorithm:

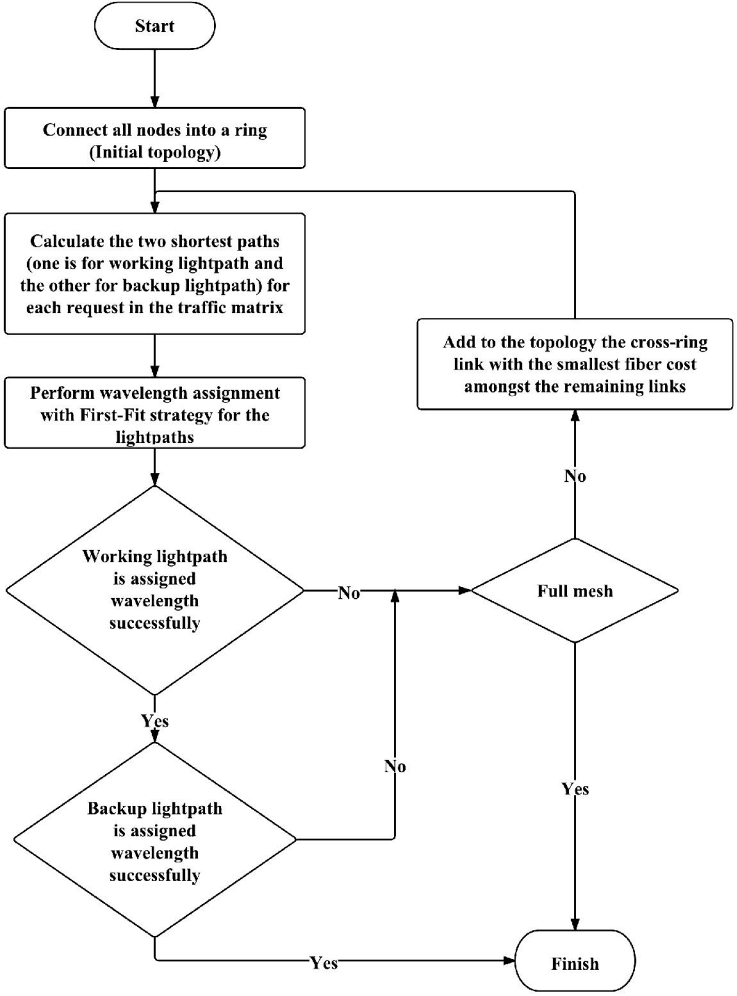

Figure 1. Flowchart of Survival algorithm

- Starting from any node, we remove this node from the node set, and add it to the ring. Then we select from the remaining node set the nearest node to the last added one. The selected node and its link with the last added node are added into the ring. After that the node is then removed from the node set.
- From the newly added node, we continue the same process until all nodes have been added into the ring.
- Finally, we add a link between the start node and the last node to close the ring.

Step 2: RWA is performed for all requests in the traffic matrix with the initial topology:

- Routing: we need to find two node-disjoint shortest lightpaths for each request in the traffic matrix. One path serves as working lightpath and the other serves as backup lightpath. The working lightpath is found by using Dijkstra algorithm. The backup lightpath is found by removing all links and nodes belonging to the working lightpath before running Dijkstra algorithm again.
- Wavelength Assignment: First-Fit is used to assign wavelengths to lightpaths. Requests are assigned wavelength one by one according to descending order of working lightpaths length for greater wavelength re-utilization.

For each request: we perform wavelength assignment on the working lightpath first, then for the backup lightpath. In case of failure in any step due to unavailable wavelength along the working or backup lightpath, the current topology is checked to see if it is already full mesh. If not, Survival adds the smallest fiber cost cross-ring link in the remaining links to the topology and performs RWA again. Note that cross-ring link is the link whose two end nodes are on ring; and fiber cost is canculated by the fiber length of the link. This task is repeated until all lightpaths are assigned wavelength successfully.

Algorithm stops when the topology meets all the requests in the traffic matrix or when it becomes full mesh.

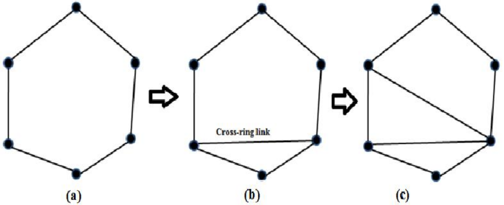

Figure 2. The designing process of Survival algorithm

Fig.2 illustrates the steps of Survival algorithm:,(a) describes an initial ring topology; (b) illustrates the first cross-ring link that is added to topology and (c) illustrates the next cross-ring link is added.

IV. NUMERICAL RESULTS

We have evaluated the complexity of Survival algorithm based on network size parameters: the number of nodes N, the number of links E of the topology and the number of wavelengths per fiber W. Survival algorithm can be seen as the iterations of the three main tasks:

- Making initial ring with complexity of $O(N^2)$
- Routing at the i^{th} iteration using Dijkstra with complexity of $O(N^2+E_i)$ where E_i is the number of links of the topology at the i^{th} iteration.
- Assigning wavelength at the i^{th} iteration using First-Fit with complexity of $O(WE_i)$.

Therefore, the complexity of Survival after k iteration is:

$$O\left(N^2\right)+O\left(\sum_{i=0}^{k}(N^2+E_i+WE_i)\right) \qquad (1)$$

Since at each iteration, Survival adds one edge to the topology then $E_{i+1} = E_i + 1$. Note also that E_0 is the number of edge of the initial links so $E_0 = N$. Therefore, by performing mathematical regression we get:

$$E_i = N + i \qquad (2)$$

By substituting (2) into (1), we obtain the complexity of Survival after k iteration as:

$$O\left(N^2\right)+O\left(\left(k+1\right)\left(N^2+N+WN\right)+\frac{k\left(k+1\right)}{2}\left(W+1\right)\right)$$

This expression is equivalent to:

$$O\left(\frac{k^2}{2}(W+1)+k\left(N^2+(W+1)N+\frac{W+1}{2}\right)+2N^2+(W+1)N\right)$$

In the best case, the algorithm finds the final topology right at the first iteration (case k=0). Thus the best computational complexity is $O(N^2 + (W+1)N)$.

The worst case happens when Survival has to add link by link to the topology and performs RWA iteratively until a full mesh topology is achieved. In that case the number of iterations can attain to $N(N-1)/2 - N$ or $N(N-3)/2$, and then the computational complexity of Survival in the worst case is in the order of $O(WN^4)$.

Benchmark and Survival algorithms have been implemented and tested with the same datasets. We generated several datasets similar to those used in [6] for testing Benchmark algorithm:

- Networks composed of N nodes uniformly distributed in two dimensions in a square of 800 x 800 units of length. The horizontal and vertical coordinates of each node are thus generated in range from 0 to 800.
- The numbers of requests in traffic matrix are entered in the range from N to $N(N-1)/2$.
- All links have homogeneous number of wavelengths: W. In the current experiments W varies from 32 to 128.
- Bandwidth requirement of requests in the traffic matrix are uniformly distributed in range [1: 5] wavelengths.

The experimental results in Fig. 3 and Fig. 4 show that Benchmark algorithm works well with small network sizes. When the number of nodes increases, Benchmark results in a network with increasing fiber cost. Both Benchmark and Survival algorithms depend strongly on the traffic matrix. However, we can see that, with the same node set when the number of requests in the traffic matrix increases, Benchmark algorithm provides unchanged result. This means the network is highly redundant. On the other hand, Survival algorithm results in fault-tolerant network topologies with different costs in those cases. That means Survival algorithm designs topologies with low redundancy. The cause of high redundancy in Benchmark is due to the fact that Benchmark algorithm initially adds about half of the possible links in the network. Therefore when the number of nodes in the network increases, Benchmark initiates a dense network topology with the huge fiber cost at the beginning. This topology itself can meet the traffic matrix, which is several times greater than the input matrix.

In contrast, Survival algorithm connects nodes into a ring initially. In so doing, when the number of nodes increases, fiber cost for initial topology does not increase much. Moreover, the ring topology ensures that there exist two disjoint paths for each source-destination pair in the traffic matrix. This is an important condition to make a network survivable when a fault occurs. If the initial topology cannot load all requests in the traffic matrix, Survival only adds links to the topology one by one (not half of links as Benchmark) and try RWA again. Some requests can be routed over the new links. Survival will stop right after the current topology has enough capacity for the traffic matrix.

Table 1 and Table 2 describe the ratio of fiber cost of Benchmark over that of Survival when the number of wavelengths per link are 64 and 128 wavelengths respectively. This ratio illustrates how many times Survival saves fiber in comparison with Benchmark.

Table 1. Fiber cost ratio of Benchmark in comparison with Survival when W = 64 wavelengths

Network size (nodes)	Cost ratio Benchmark /Survival
5	0.9058
10	1.2586
15	1.9807
20	2.6586
25	2.479

Table 2. Fiber cost ratio of Benchmark in comparison with Survival when W = 128 wavelengths

Network size (nodes)	30	35	40
Cost ratio Benchmark/Survival	4.9558	5.0904	5.6448

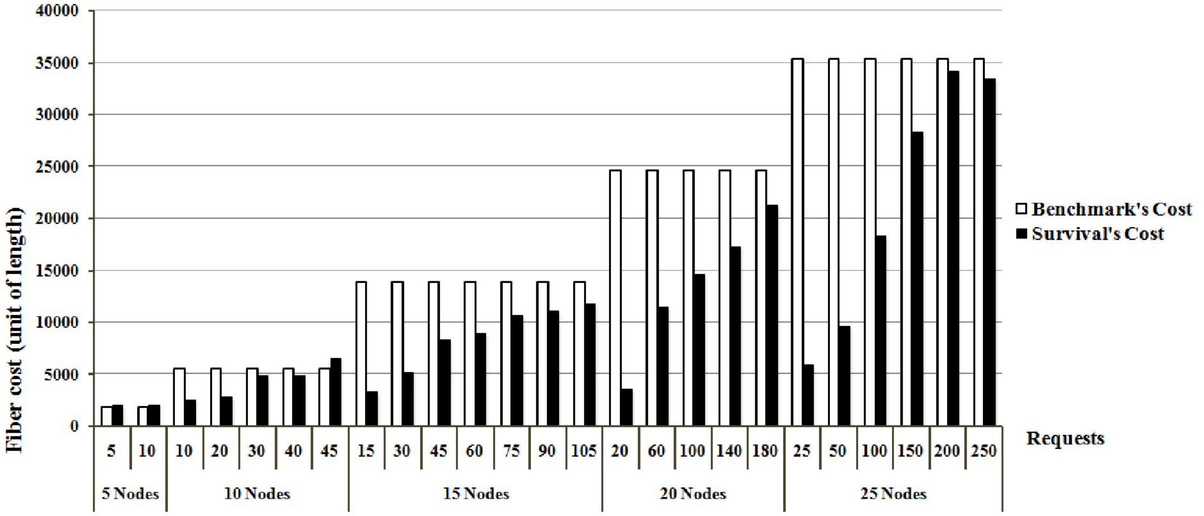

Figure 3.Fiber cost of network when W = 64 wavelengths

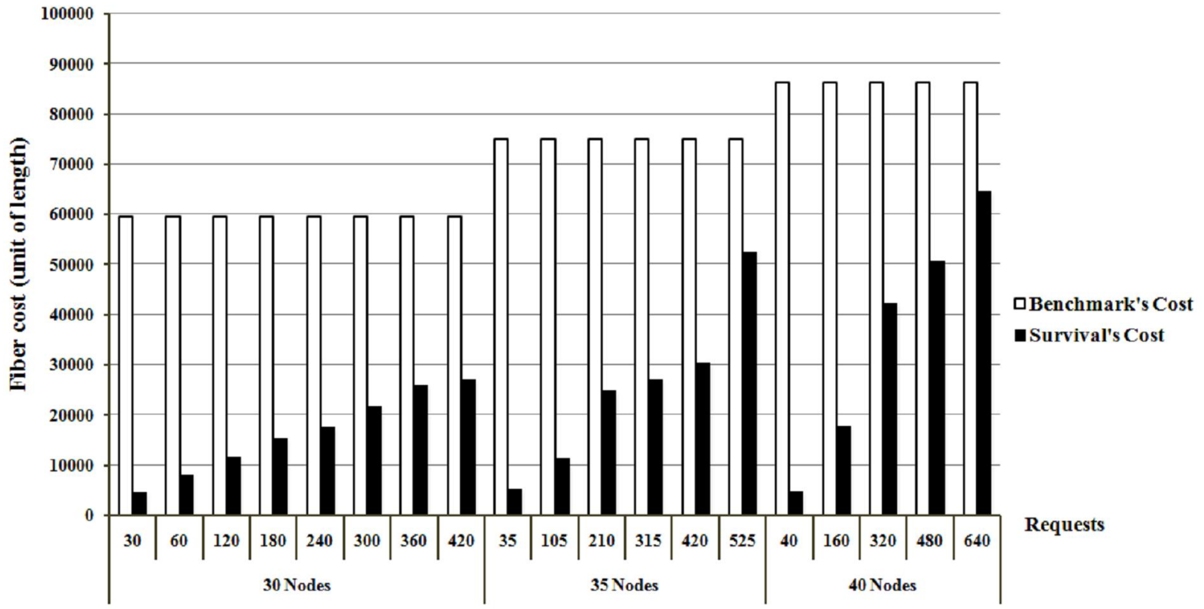

Figure 4. Fiber cost of network when W = 128 wavelengths

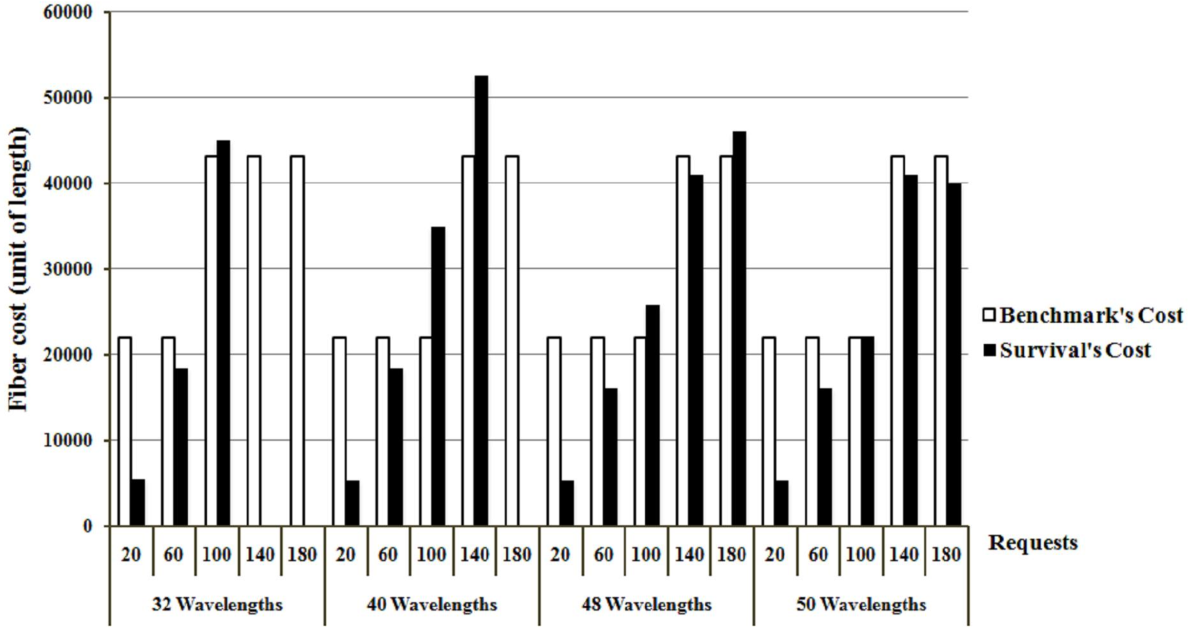

Figure 5. Fiber costs of Benchmark and Survival when the number of wavelengths per link increases.

In general, survival is several times betters than Benchmark in term of cost, mostly when the number of wavelengths per link is large. We can remark also in Fig.4 that with a network of 40 nodes, and the number of requests is 40, Survivable offers a topology with 18 times smaller cost than that of Benchmark.

Although in above tests, Benchmark gives the same result for all cases with the same number network nodes, we suspect that Benchmark would change the topology when network load becomes too large. Therefore, we tested Benchmark and Survival in case of 20 node, the network load varies amongst 20, 60, 100, 140 and 180 requests, and the number of wavelength per link varies from 32 to 50.

Fig.5 shows that not in all cases Benchmark algorithm gives the same topology result for the different traffic matrices. This is explained that, the number of wavelengths on each link is insufficient for Benchmark to perform routing and wavelength assignment for all requests on the initial topology so it adds new links to the topology. (In Fig. 3, when the number of wavelengths on each link is 64, the initial topology is sufficient to satisfy the traffic matrix.)

In some cases, the network costs of Survival algorithm are higher than those of Benchmark algorithm. Moreover, there are few cases where Benchmark algorithm can give solutions but Survival cannot. The reason is that, Survival algorithm has to find two paths (working and backup) for each request in the traffic matrix (due to survivable purpose), while Benchmark has to find only one. We can easily remark that Survival algorithm gives the better-resulted networks when the number of wavelengths on each link increases, while Benchmark results almost unchanged topology. When the number of wavelengths on each link reaches to a certain threshold, Survival algorithm gives the better network than Benchmark algorithm. This is also an advantage of Survival algorithm over Benchmark.

V. CONCLUSION

This paper proposes a solution to the physical topology design for all-optical networks. This solution has been implemented and experimented with multiple datasets. From the experimental results, we can be concluded that: (i) Survival algorithm can design effectively for all optical networks with low cost, (ii) Survival algorithm allows designing physical topology that ensuring the network survivability. The complexity evaluation of Survival shows that the algorithm has polynomial complexity and can be used for design large-scale networks.

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AUTHORS BIOGRAPHIES

Hanh V. Nguyen received his Engineer degree in Data Communications and Computer Networks from School of Information and Communication Technology, Hanoi University of Science and Technology in June 2012. Since then he has been working for Advanced Technology Part, Samsung Vietnam Mobile R&D Center. His interests include optical networks and survivable network design problems; context recognition, optical character recognition and peer-to-peer applications on mobile phones.

Linh T. D. 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 Technology. She received the Ph.D 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 Science and Technology in 1999. Her interests include multi-domain networks, optical networks and survivable network design problems.