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Physical Topology Design for Survivable Optical Networks with Shared Risk Group Consideration

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Abstract

The problem of physical topology design for optical networks has been studied over years. Some studies consider the survivability aspect of the networks while designing. In this paper, we push the study on survivable optical network design further by considering in addition the possibility that fiber cables connecting different fiber nodes may be bundled together in the same conduit, thus, they share the same risk when the conduit fails. Since the considering design problem is NP-hard, we propose an heuristic for solving the problem. The objective of the design is minimising the total network cost. The results show that the heuristic solutions are about 12% different from the optimal ones.
Keywords: Optical networks, topology design, survivable networks, Shared Risk Group.

1 Introduction

Physical and logical topology design has been largely studied in many researches, for example in [1–10]. These studies focus on designing the optical networks but ignore the survivability aspect of the networks. In other words, data connections in the designed networks could not be survivable under fiber cuts or network node failures. Differently, we are interested in designing the optical networks with survivability.

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. 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. Protection is a 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. The backup path must not fail when the working path fails. Since the failures do not occur frequently, it is often assumed that there is a single failure in the network at a moment, and the failure is repaired before another one occurs. Under this assumption, the working path and the backup path of a connection need only to be disjoint in order to not fail in the same time.

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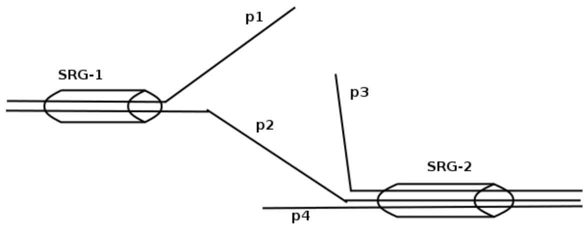

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Fig. 1. Example SRGs: SRG-1 $= \{p1, p2\}$ and SRG-2 $= \{p2, p3, p4\}$

The work in [2] has already consider the topology design problem for survivable networks. However, this work and many others have not considered the possibility that different fiber links between different pairs of optical nodes may be bundled together in the same conduit in certain segments. Therefore, these links share the same risk when the common conduit fails. The group of physical fibers that share the same risk when a conduct fails is called a Shared Risk Group (SRG). Figure 1 shows an example of SRGs in a practical fiber cable layout. Here, the fiber links $p1, p2$ are in SRG-1 while $p2, p3, p4$ are in SRG-2. Therefore, SRG-1 $= \{p1, p2\}$ and SRG-2 $= \{p2, p3, p4\}$. When a cut happens on conduit corresponding to SRG-1 then both $p1$ and $p2$ fail. Similarly, when a cut happen in the conduit corresponding to SRG-2 then $p1, p2$ and $p3$ fail altogether. In this research, we will try take into account of SRGs while designing optical networks. The research problem is stated as follows:

Given:

- A set of network nodes $\mathbb{N}$ and a pre-defined path for running fiber between each pair of nodes in $\mathbb{N}$.
- The maximum capacities of a fiber links in terms

of number of wavelengths $\mathbb{W}$.

- The traffic matrix $\mathbb{M}$ that defines a set of connection requests between nodes that the network must carry. $\mathbb{M} = \{(s, d, bw^{sd}) : \forall s, d \in \mathbb{N}\}$ where (s, d, bw^{sd}) is a request of connection from node s to node d with the requested bandwidth bw^{sd}.
- The set of SRGs $\mathbb{R} = \{r\}$, each risk group r lists all the links that share the same risk because they are bundled together along a segment.

We need to identify:

- A physical topology that can accommodate all connection requests in the traffic matrix with the lowest network cost. The network cost that we consider here includes the optical fiber cost, installation and maintenance cost and the optical node cost.
- Each connection requests must be allocated a working path and a backup path for the survivable purpose.

Both optical fiber cost and fiber installation and maintenance cost are proportional with the total fiber length. We consider that the optical node cost is proportional with the number of used optical interfaces on it. Therefore, minimising the total network cost would be equivalent to minimising both the fiber length and the number of used interfaces.

In order to make sure that a physical topology can accommodate all connection requests in the traffic matrix, we need to find a feasible resource allocation for all requests. A connection in Wavelength Division Multiplexing (WDM) optical networks makes use of a wavelength a long each fiber link. With the objective to avoid costly wavelength converters, a connection must use the same wavelength along its path. In optical networks, this resource allocation is known as Routing and Wavelength Assignment (RWA) problem [11]. 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 a wavelength that is available on all links along the routed path for carrying the requested bandwidth. Since the RWA problem is proven NP-hard, considering physical topology design and RWA together should be also NP-hard. Linear Programming can be used for modelling the optimal solution, however, the results cannot be obtained in reasonable delay for large size networks. For that reason, in this paper we will propose an heuristic solution to solve the problem.

The remaining of the paper is organised as follows. Section 2 proposes an heuristic solution for solving the problem. Section 3 presents an experimental evaluation of the proposed heuristic. Finally, Section 4 concludes the paper.

2 Proposed heuristic solution

Given the set of optical network node $\mathbb{N}$, and the traffic matrix $\mathbb{M} = \{(s, d, bw^{sd})\}$, we need to identify the topology that can accommodate all connection requests in $\mathbb{M}$ and minimizing the total used fiber lengths, denoted by $\mathbb{L}$, and total number of used optical interfaces. Since the set of optical nodes is given, the remaining task is to identify the set of links, denoted by $\mathbb{E}$, between the these optical nodes. It worth to note that, in this paper, in order to make the design problem practical, if a fiber need to be run between a pair of optical nodes, it must follow a predefined path and thus the length of the fiber link is known in advance. Let us denote de length of a fiber link between node i and node j by d_{ij}. The total fiber length used in the topology is:

$$\mathbb{L} = \sum_{(i,j)\in\mathbb{E}} d_{ij} \tag{1}$$

Although a fiber link between i and j can have $\mathbb{W}$ wavelengths, the link (i, j) uses only 2 optical interfaces (or ports), one at node i and another one at node j. Therefore the objective of minizing the network cost can be expressed as:

$$\min \sum_{(i,j)\in\mathbb{E}} (\mu_1 \times d_{ij} + \mu_2 \times 2) \tag{2}$$

where μ_1 and μ_2 are coefficients balancing the fiber related cost and the interface cost. We can remark easily that each link $(i, j) \in \mathbb{E}$ incures a cost:

$$c_{ij} = (\mu_1 \times d_{ij} + \mu_2 \times 2) \tag{3}$$

The main idea of our proposed topology design is that: we assign to each link (i, j) a weight c_{ij} then we route requests in the traffic matrix $\mathbb{M}$ though the weighted shortest path, i.e. the least cost path. When a link is used by at least one request, it will be added into the final topology and its cost is counted only once although the link may be reused later. Therefore, we encourage to reuse existing links for routing other requests by adjusting the link's weight to 0. We present in the following the steps of the heuristic:

Step 1 : Let $\mathbb{G}_f = (\mathbb{N}, \mathbb{E}_f)$ be a full mesh graph with the set of nodes is $\mathbb{N}$ and the set of edge $\mathbb{E}_f$

contains all pairs of nodes in $\mathbb{N}$ according to the pre-defined optical paths. Each edge $(i, j) \in \mathbb{E}_f$ is assigned a weight c_{ij} given in (3). Let $\mathbb{G} = (\mathbb{N}, \mathbb{E})$ is the graph representing the topology to be built, $\mathbb{G}$ has the same set of nodes $\mathbb{N}$ but initially, its set of nodes $\mathbb{E}$ is empty.

Step 2 : Sort connection requests in the traffic matrix $\mathbb{M}$ in descending order of the requested bandwidths. The requests will be handled one after another in this order in the next step.

Step 3 : For each connection request, find a working path as the least cost path in $\mathbb{G}_f$ by using a modified Dijkstra algorithm (see Alg. 1 for details). In the modified Dijikstra algorithm, whenever an edge is considered, it is tested if it has enough available wavelengths for the connection request first (line 9 in Alg. 1). Then, the found shortest path will be assigned the first wavelength available along the path according to First-Fit strategy [12].

In order to find a backup path for the request, we remove from $\mathbb{G}_f$ all edges that share the same SRG with any edge in the working path. Note that a SRG lists all the edge sharing a common risk. This step allows avoiding that the working and the backup paths would fail simultaneously when there is failure in the networks. The backup path will then found by using the modified Dijkstra algorithm again in the residual graph. The backup path is also assigned the first wavelength available along it according to First-Fit strategy.

The edges of the working and backup paths are inserted to $\mathbb{E}$.

Step 4 : Insert back the edges of the working and backup path to $\mathbb{G}_f$ but this time their weights are set to 0 in order to encourage other requests to reuse those edges. Repeat Step 3 until there is no more request left.

The pseudo-code of the algorithm is shown in Alg. 2. Resulted $\mathbb{E}$ is the set of links of the topology to be designed.

3 Experiments

The proposed heuristic has been implemented in Java. Regarding the computational time, the heuristic gives results immediately. Regarding the quality of solution, we would like to see how the heuristic solutions are closed to the optimal solutions. Since the design problem is NP-hard, we have developed an Integer Linear Program (ILP) which model the optimal solution. Due to the limited scope of this paper, the ILP is not shown. Cplex [13] tool has been used for solving

Algorithm 1: Modified Dijkstra

Input: graph $\mathbb{G}_f$, request $m = (s, d, bw^{sd})$
Output: shortest path from s to d with available bandwidth $\geq bw^{sd}$

for *vertex* $v \in \mathbb{G}$ **do**
1 dist[v] $\leftarrow \infty$; /* Unknown distance from s to v */
2 previous[v] $\leftarrow$ undefined ;
3 dist[s] $\leftarrow 0$;
4 **while** $\mathbb{E}_f \neq \emptyset$ **do**
5 $u \leftarrow$ vertex in $\mathbb{E}_f$ with smallest distance in dist[] ;
6 $\mathbb{E}_f = \mathbb{E}_f - \{u\}$;
7 **if** *dist[u]* = ∞ **then**
break;
8 **foreach** v *is neighbor of* u **do**
9 **if** *nb-avail-wavelength*$(v, u) \geq bw^{sd}$ **then**
10 $alt \leftarrow dist[u] + c_{uv}$;
11 **if** *alt < dist[v]* **then**
/* Relax(u,v,a) */
12 dist[v] $\leftarrow$ alt ;
13 previous[v] $\leftarrow$ u ;
14 **return** *previous[]*;

Algorithm 2: Physical topology design

Output: set of edges $\mathbb{E}$ of the topology
First-Fit(p): Assign the first available wavelength to p;

$\mathbb{E} \leftarrow \emptyset$;
Sort requests in $\mathbb{M}$ in descending order of requested bandwidth bw^{sd};
foreach $m \in \mathbb{M}$ **do**
/* Find working path */
wp = Modified-Dijkstra($\mathbb{G}_f$,m);
First-Fit(wp);
foreach *edge* $e \in wp$ **do**
$\mathbb{R}(e) \leftarrow$ set of SRGs containing e
foreach $r \in \mathbb{R}(e)$ **do**
remove from $\mathbb{G}_f$ all edge listed in r;
/* Find backup path */
bp = Modified-Dijkstra($\mathbb{G}_f$,m);
First-Fit(bp);
Insert edges of wp and bp to $\mathbb{E}$; Add back edges of wp and bp to $\mathbb{G}_f$ with weight 0;

the ILP model and thus give us the optimal solution of the problem. However, the ILP model explodes rapidly when the $\mathbb{N}$, $\mathbb{W}$ or the number of SRG $|\mathbb{R}|$ increases therefore, we can only run the ILP for very small number of network nodes, i.e. from 5 to 7 nodes.

We have conducted several tests in order to evaluate the performance of the proposed topology design algorithm. In these tests, we we set the coefficients $\mu_1 = \mu_2 = 1$, that means the cable related cost for an unity of length is made equivalent to an optical interface cost. An input for the proposed heuristic algorithm is characterised by:

- $\mathbb{N}$: the number of nodes of the network.
- $\mathbb{W}$: the number of wavelengths per fiber.
- $\mathbb{D}$: the fiber length matrix. $\mathbb{D} = \{d_{ij}, \forall i, j \in \mathbb{N}\}$ where d_{ij} is the length of path would be taken for running fiber between nodes i and j. These possible lengths of fiber links are generated randomly.
- $\mathbb{M}$: the requested traffic matrix. The requests in $\mathbb{M}$ are generated randomly between nodes with requested bandwidth limited by the number of wavelengths in a fiber $\mathbb{W}$.
- $\mathbb{R}$: the list of all SRGs may exist in paths between nodes in $\mathbb{N}$. Each SRG $r \in \mathbb{R}$ lists the pairs of nodes in $\mathbb{N}$ whose paths for running fiber share the same risk r.

Table 1 shows the gaps between the heuristic solutions and the optimal solutions obtained from ILP in diferent network instances. The columns Opt and Heuristic show the costs of the networks designed respectively by the two algorithms. The cost is computed by (2). The column Gap shows how many times the physical topology designed by the proposed heuristic is more expensive than the optimal topology. For each Dataset, several network instances have been tested and the results are the average values given by all network instances. In Dataset 1, the gap is only 0.11, that means the network designed by the heuristic costs in average only 11% more than the optimal topology. The gaps seem to be bigger then the network sizes increase. In the remaining Datasets, the gaps vary but they are still smaller than 1. In other words, the networks designed by the proposed heuristic are not twice more expensive that the optimal network in the current tests.

We have also tested the proposed heuristic only with larger network instances. Table 2 shows the test results in networks of 10, 20 and 30 nodes. In each network size, the number of SRGs varies from 2 to 6. We can remark that the network cost increases when the number of SRGs increases. This increment is reasonable since the more SRGs there are, the more links need to be excluded while finding a backup path for a connection request. Consequently, more links may need to be added to the topology in order to be able to find a backup path.

Table 1. Comparison of network costs of the proposed heuristic against the optimal solution, $\mathbb{W} = 10$

Dataset	$\lvert\mathbb{N}\rvert$	$\lvert\mathbb{M}\rvert$	$\lvert\mathbb{R}\rvert$	Opt	Heuristic	Gap
1	5	4	2	390.4	439.0	0.12
2	5	5	2	344.2	510.5	0.48
3	6	5	2	422.9	502.9	0.19
4	6	6	2	412.02	647.7	0.57
5	7	4	2	218.7	406.0	0.86
6	7	5	2	345.22	581.7	0.69

Table 2. Network costs of large networks

Dataset	$\lvert\mathbb{N}\rvert$	$\mathbb{W}$	$\lvert\mathbb{M}\rvert$	$\lvert\mathbb{R}\rvert$	Network cost
7				2	1132.6
8	10	8	10	4	1123.4
9				6	1007.7
10				2	1843.6
11	20	16	20	4	1908.2
12				6	1908.2
13				2	2963.5
14	30	16	30	4	3103.7
15				6	3103.7

4 Conclusions

In this paper we study the problem of physical topology design for survivable optical networks with the objective to minimize the network cost given a set of network nodes and the future network load. The main point distinguishes our work from the existing studies is that our physical topology design solution takes into account the fact that fiber cables may be bundled together in the same conduit. As a result, those fiber cables belong to the same SRG and they should not be used in the same time in both working path and backup path of a connection. Since this design problem is NP-hard, we have proposed a simple heuristic for solving the problem. The comparison of the heuristic and the optimal solution in very small size networks show that the heuristic can provides solutions in about 12% different from the optimal ones. Further experiments for analysing the impact of SRGs on topology is reserved for the future.

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