Restoration in IP over WDM Optical Networks

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Abstract

An important requirement in any high speed network is to ensure the network's survivability, i.e., the ability to provide reroutes of ongoing connections after the failure of network components. We consider the problem of embedding an IP layer topology in the WDM transport network layer with the objective of achieving the network's survivability in the IP layer. Specifically, we consider the problem of embedding an arbitrary IP layer topology in a WDM wavelength-routing ring network such that the IP topology remains connected under the presence of the failure of any link in the WDM layer.

Keywords: Network survivability, Restoration, IP layer, WDM optical layer, IP over WDM optical network.

1 Introduction

Fiber optic networks hold out the promise of achieving terabit-per-second throughputs by employing Wavelength Division Multiplexing (WDM) on an optical fiber. There is a widespread consensus that a wavelength-routing WDM optical network with service overlays is the best model to satisfy the diverse requirements of today's traffic. Several optical internetworking overlay models are considered for data networks to access an underlying optical transport network [3, 8]. In particular, IP over WDM (an IP network, made of IP routers, built on top of a WDM infrastructure) is considered as the most promising internetworking structure.

Our focus in this paper is on finding an embedding of an IP layer topology in the wavelength-routing WDM ring network with the objective of achieving the network's survivability in the IP layer. Using this embedding, the IP topology remains connected under the presence of any single link failure in the ring. Our study of rings as the underlying WDM topology is motivated by the fact that they are popular topologies in electro-optic SONET networks and have continued to receive attention as possible all-optical WDM network topologies.

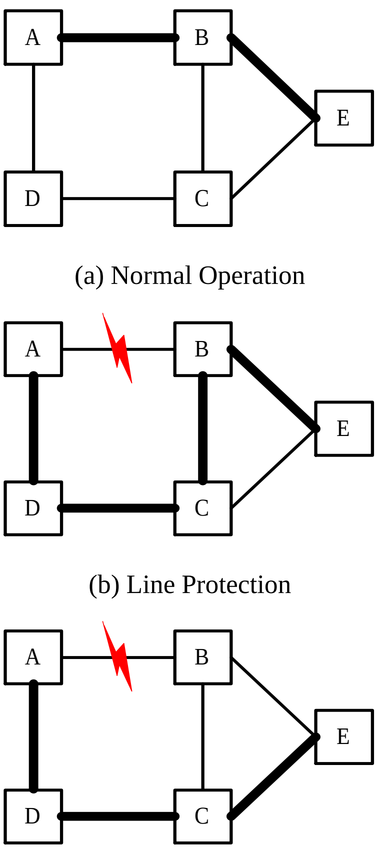
The rest of this paper is organized as follows. A brief overview of protection and restoration techniques in different network' layers (i.e., IP and WDM layers) is given next. In Section 2, a formal description of our problem and the network model are presented. Our results are presented in Section 3. We conclude the paper in Section 4 with discussions of future research directions.

1.1 Protection and Restoration

In order to guarantee the resilience of the networks' service against a fault, two possible approaches are considered to find a reroute of the compromised path: a preplanned *protection* path and a dynamically computed *restoration* path. Protection techniques depend on redundant capacity within the network. Since a protection route for each working route is preplanned, reroute using this is faster (less than 50 ms in SONET/SDH network) [4, 5, 10] and simpler than a restoration [5] which is usually performed in a distributed way.

Based on the criterion of a dedicated protection versus a shared protection, there are three types of protection techniques known as 1+1 protection, 1:1 protection, and 1:N protection. The 1+1 protection transfers the identical data through both working and protection routes and makes the receiver choose a proper signal. In the case of 1:1 protection, the protection routes are used only when the working routes do not operate normally. Under the 1:N protection scheme, upto N working routes share one protection route [5, 10].

Protection techniques are also classified by whether it is a line protection or a path protection. The difference between these two schemes are depicted in Figure 1. Figure 1 (a) shows that the traffic stream A-E uses a path A-B-E. If there is a fault on link A-B, a line protection detours A-B link by using the pre-designed path A-D-C-B and the rest of the path is used, which is shown in Figure 1 (b). On the



(a) Normal Operation

(b) Line Protection

(c) Path Protection

Figure 1: Line and Path Protections.

contrary, a path protection does not use the path including the faulty link at all and takes another path completely disjoint from the original path. The example in Figure 1 (c) uses the path A-D-C-E, instead of A-B-E.

Different protection schemes are developed and implemented for ring and mesh topologies. As ring based protection schemes, two-fiber unidirectional path-switched rings (UPSR), four-fiber bidirectional link-switched rings (BLSR/4), two-fiber bidirectional line-switched rings (BLSR/2), and Dual Homing are widely accepted. The details of each scheme can be found in [10]. As a mesh based protection scheme, a protection cycle is available [10].

Restoration can be used to provide either more efficient routes after the protection is completed, or additional resilience against further faults before the first fault is fixed [5]. Usually, restoration mechanism is quite slow (seconds to minutes) [5] and can be computed on the fly by a centralized management system [5]. Under the current technology, a restoration of a ring based optical network takes about 50 msec [4, 1, 7] and that of an end-to-end path-disjoint mesh based optical network needs a few hundreds of msec.

1.2 Three Models of Protection and Restoration in IP over WDM Networks

Depending on the scope of the control and signaling functions of WDM layer, the protection and the restoration in IP over WDM network can be classified into three models [6].

The first model is employing an autonomous and smart optical connectivity management. More precisely, an optical layer has most of the control and signaling functions such as configuration and capacity management, routing, topology discovery, exception handling and restoration using its own complete control and signaling functions. The major disadvantage of this model is the redundancy of control and signaling functions since those network management functions are already available in the IP layer. Under the current technology, a restoration of a ring based optical network takes about 50 msec [4, 1, 7] and that of an end-to-end path-disjoint mesh based optical network needs a few hundreds of msec while, for IP protection, 1+1 protection requires a few tens of msec and 1:1 protection takes at least a few secs [4, 1]. Based on a type of IP protection scheme, it might take many seconds or even minutes [7].

As the second model, "big fat router (BFR)" can be considered. Each IP router is connected using an optical fiber and WDM. Thus, there is no lightpath concept on this model. All the control and signaling depend on IP layer.

The third model is "Smart Router - Simple Optics", which is an intermediate version between the first and the second models. Currently, IETF (Internet Engineering Task Force) and OIF (Optical Internetworking Forum) are working on this model using GMPLS (General Multi-Protocol Label Switching), which intergrates MPLS (Multi-Protocol Label Switching) and MPLambdaS (Multi-Protocol Lambda Switching).

As a key issue of the third model, the problem of embedding IP topology in WDM topology discussed in this paper plays a key role in IP over WDM protection, especially when WDM layer does not support a lightpath protection or link protection, or the protection path is not working normally due to multiple faults.

1.3 Motivation

A major issue on the survivability of IP over WDM network is *fault propagation*. That is, single link faults in WDM layer may cause more than one link faults in IP layer. In some cases, the propagation of a single link fault on WDM layer makes all the possible paths on IP layer disable. Therefore, by carefully designed mapping of each node and link of IP network to WDM network, the IP over WDM network should be prohibited from encountering this problem. This is the motivation of our work in this paper.

2 Network Model and Problem Formulation

Graph-theoretic arguments are used throughout the paper. To start, we introduce some notations. For the rest of the paper, link and edge (similarly, node and vertex) are interchangeably used. Readers can refer to [2] for further notation and related results stated here.

A graph G on n vertices is called *complete* or *completely connected* if every pair of vertices in G is connected by an edge, and such a graph is denoted by K_n. The *edge-connectivity*, $\lambda(G)$, of a graph G is defined as the least cardinality $|S|$ of a subset $S \subset E(G)$ such that $G - S$ is *disconnected*. Connectivities are among the most extensively studied graph invariants, partly due to their many applications. The well-known theorem by Menger [2] states that G is k-edge-connected if and only if there exist k edge disjoint paths for every pair of vertices.

The problem of our interest is then formulated as follows.

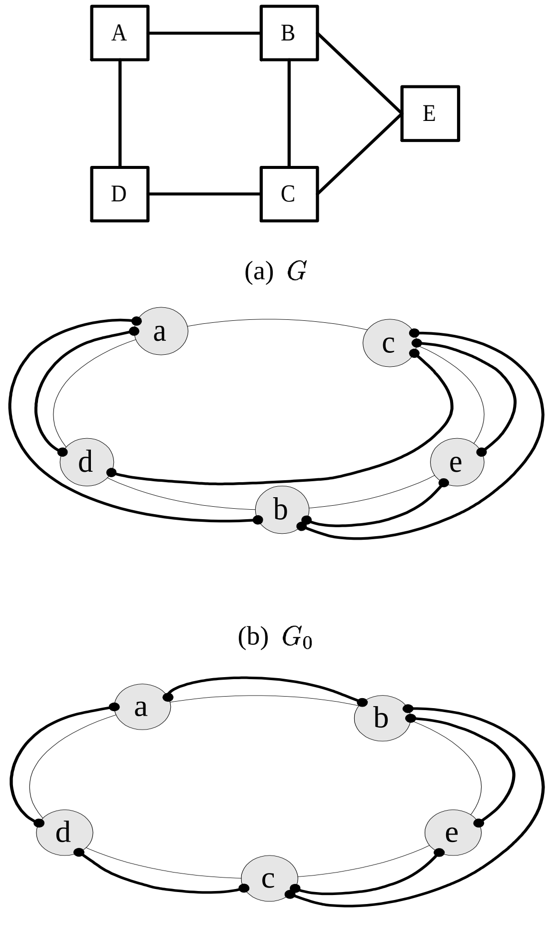
Node and Link Embedding Problem (*NLEP*):

Given: a k-edge connected ($k \geq 2$) IP layer topology G and a k_0-edge connected ($k_0 \geq 2$) WDM topology G_0 such that $|V(G_0)| \geq |V(G)|$.

Objective: to find mapping functions $f : V(G) \to V(G_0)$ and $h : E(G) \to P(G_0)$ such that (i) $P(G_0)$ is the set of lightpaths established in G_0 and (ii) for any edge-cut $C \subseteq E(G)$ and any link $e_0 \in E(G_0)$, there exists a t least one edge $e \in C$ with $e_0 \notin h(e)$.

Without loss of generality, we assume that, for any nodes $u \neq v \in V(G)$, $f(u) \neq f(v)$ in any mapping f. Any feasible solution satisfying the above condition ensures that there exists a re-routed path in G (i.e., G remains to be connected) after any single link failure (e.g, a fiber cut) of G_0. Therefore, G is tolerant to the failure of any single link in G_0.

Consider an IP topology shown in Figure 2 (a). Suppose the WDM optical network topology is a ring, and two different embeddings of G in G_0 are shown in Figure 2 (b) and (c). (Note that node labeled with the lower case letter corresponds the node mapped from the corresponding capital letter. For example, a in G_0 corresponds to A in G.) Consider the failure of an arbitrary link in (b), say link (a, d). The failure of link (a, d) then results in failures of two lightpaths connecting $A - D$ and $A - B$, which causes IP node A completely isolated from the network. Hence, re-routing of any traffic from node A is impossible. On the other hand, any single-link failure in (c) does not cause any IP node isolated from the network. Note that both G and G_0 are 2-edge connected, and the embedding shown in (c) clearly satisfy the conditions in the problem formulation; hence, it is a desired solution.



(a) G

(b) G_0

(c) G_0

Figure 2.

3 Embedding of IP in WDM

In this section, we approach the problem by considering the ring network as the underlying WDM transport network's topology. In the following lemma, we first characterize the mapping condition for a feasible solution which will be used in developing our algorithm later.

Lemma 1 *Suppose G is 2-edge connected and G_0 is a ring. Let $f : V(G) \to V(G_0)$, and $h : E(G) \to P(G_0)$ be map-*

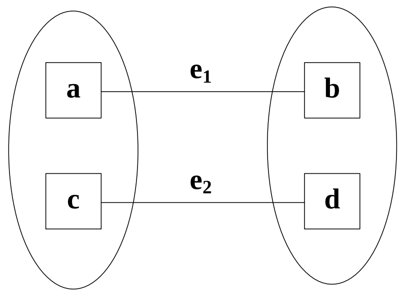
pings. If G is tolerant to the failure of any single link in G_0, then for any edge cut of size two $\{e_i = (a,b), e_j = (c,d)\} \subseteq E(G)$ where a and c (b and d, respectively) belong to the same component of $G - \{e_i, e_j\}$, vertices $f(a), f(c), f(b), f(d)$, in this order, may not be lay out in G_0 in the clockwise or counterclockwise direction.

Proof: Let $\{e_i = (a,b), e_j = (c,d)\} \subseteq E(G)$ be an edge-cut of G. Let $f : V(G) \to V(G_0)$ be a mapping function such that vertices $f(a), f(c), f(b), f(d)$, in this order, are lay out in G_0 in the clockwise direction. There then exists a link in G_0 that is used in both lightpaths connecting $f(a) - f(b)$ and $f(c) - f(d)$. (See Figure 3 for example.) If a failure occurs in a link in G_0 used by the two lightpaths, no restoration of on-going traffic from one side (the side including a and c in Figure 3 (a)) of the network G to the other side (the side including b and d) is possible since IP links (a,b) and (c,d) both become failed. When vertices $f(a), f(c), f(b), f(d)$, in this order, are lay out in G_0 in the counter-clockwise direction, a similar argument can be applied. This completes the proof of the lemma. □

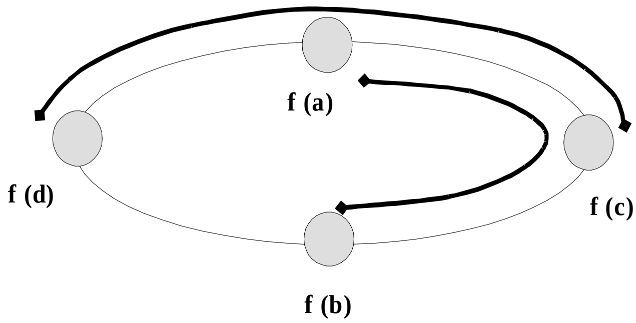
The result of Lemma 1 implies that if the mapping function f maps vertices a, b, c, d in G_0 in the order of $f(a)$, $f(c)$, $f(b)$, $f(d)$ in the clockwise or counter-clockwise direction, then f cannot lead to a feasible solution. This implies that any feasible mapping f should be designed not to allow such mappings. Based on the result in Lemma 1, we next proceed to show that there exists an algorithm to find a feasible solution to the NLEP for a 2-edge connected graph G and a ring network G_0.

3.1 Algorithm NLEA

Our algorithm is called *Node and Link Embedding Algorithm (NLEA)* which solves the NLEP in a recursive way using the divide-and-conquer technique. Let G be a 2-edge connected graph, i.e., the edge-connectivity of G is at least two. If the size of the minimum edge-cut is larger than two, delete edges from G, one at a time, until the size of the minimum edge-cut of the new graph G' becomes two. Those deleted edges (i.e., links) will not be considered in our link-to-path mapping since the survivability of G' clearly suffices the survivability of G, i.e., if G' is survivable, then G is also survivable. Let $C = \{e_i = (a,b), e_j = (c,d)\} \in E(G)$ be an edge-cut of size two in G. Deleting edges e_i and e_j divides the remaining graph into two connected components, say G'_{left} and G'_{right} where $a, c \in G'_{left}$ and $b, d \in G'_{right}$. From G'_{left} and G'_{right}, we define G_{left} and G_{right} such that (i) $G_{left} = G'_{left}$ if $(a,c) \in E(G'_{left})$ or G'_{left} is 2-edge connected, and (ii) $G_{left} = G'_{left} \cup \{(a,c)\}$, otherwise. G_{right} is similarly defined from G'_{right} with a possible addition of link (b,d). We then observe that G_{left} and G_{right} are both 2-edge connected.



(a) G

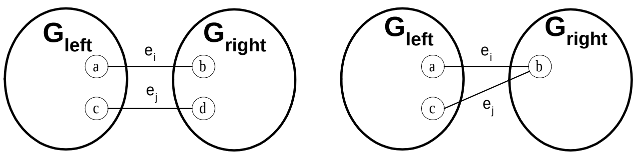


(b) G_0

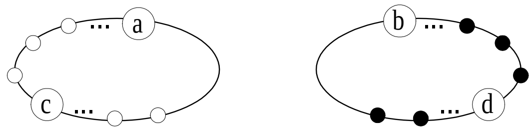
Figure 3.

Suppose G_{left} and G_{right} are independently embedded in two rings G_0^{left} and G_0^{right} satisfying the conditions in the NLEP, i.e., the survivability of G_{left} and G_{right} is guaranteed in the presence of a single link failure of G_0^{left} and G_0^{right}, respectively. Our job is then to combine the two rings into a single ring G_0 and to complete the mapping of the remaining links (i.e., e_i and e_j) in G while keeping the survivability of G. The combining step of our algorithm is discussed next using the figures in Figure 4.

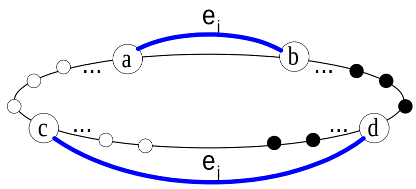
Let $C = \{e_i = (a,b), e_j = (c,d)\} \in E(G)$ be an edge-cut of size two in G. There are two cases to be considered as shown in Figure 4 (a): (i) a, b, c, d are all distinct and (ii) b and d are the same vertex (or, a and c are the same vertex). We first consider the case (i). We assume that G_{left} and G_{right} are independently mapped in G_0^{left} and G_0^{right} preserving the survivabilities. Figure 4 (b) shows G_0^{left} and G_0^{right} where vertices in G_0^{left} are lay out in the order of $\langle a, \cdots, c, \cdots \rangle$ in the counter-clockwise direction, and vertices in G_0^{right} are lay out in the order of $\langle b, \cdots, d, \cdots \rangle$ in the clockwise direction. Combining G_0^{left} and G_0^{right} is done in such a way that all vertices $\langle b, \cdots, d, \cdots \rangle$ in G_0^{right} are mapped in the same order, in G_0, right after a as shown in (c) and (d), where (c) shows the case (i) and (d) shows the case (ii). Mapping of links (a,b) and (c,d) for case (i) is done as in (c), and mapping of links (a,b) and (c,b)



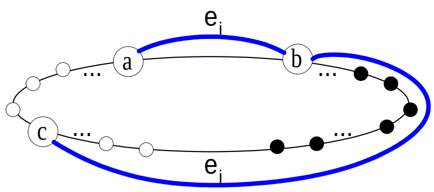
(a) G



(b) G_{left} and G_{right}

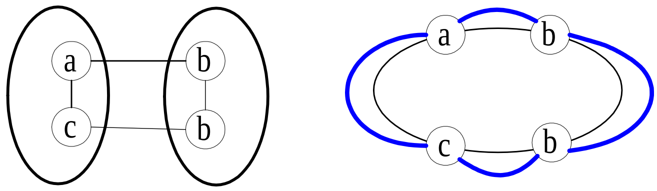


(c) G_0

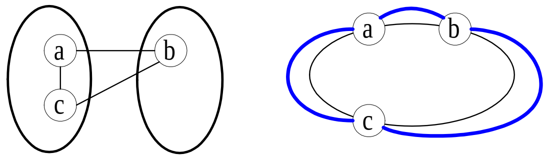


(d) G_0

Figure 4 (Contd.)



(e)



(f)

Figure 4.

for case (ii) is done as in (d). To complete the mapping of links in the combined ring, we do the following. iLet q be a lightpath connecting from a node u to a node v in G_{left} in the clockwise (or counter-clockwise) direction. We then connect a lightpath in G_0 from u and v in the clockwise (or counter-clockwise, respectively) direction. Lightpaths in G_0^{right} are similarly defined in G_0. One should observe that the combining step of our algorithm does not create any infeasibility if G_0^{left} and G_0^{right} both are feasible solutions. That is, if G_{left} (and G_{right}) remains connected after the failure of a single link of G_0^{left} (and G_0^{right}, respectively), G also remains connected after the failure of any single link of G_0.

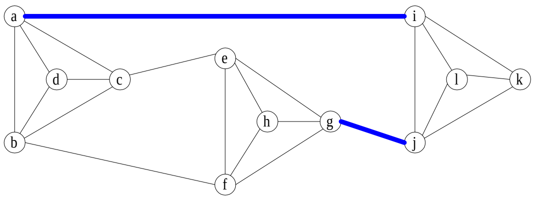
To consider the basis of our recursive steps, let G be a smallest 2-edge connected graph. Then, G must be a simple cycle of length four or a simple cycle of length three. In each case, the ring can be embedded in G_0 following the same structure. See (e) and (f). If G is a single node, then mapping becomes trivial.

Figure 5 shows an example of complete mappings following our algorithm discussed above. Consider a graph G in Figure 5(a), and let $C_1 = \{(a,i),(g,j)\}$ be an edge-cut of size two. G is then divided into two parts, G_{left} and G_{right} as shown in (b). Let $C_2 = \{(c,e),(b,f)\}$ be an edge-cut of G_{left}. When considering G_{left} as G in (c), $C_3 = \{(d,c),(b,c)\}$ is reported as an edge-cut of size two after deleting edge (a,c). The graph is then divided again into two parts as shown in (d). At this point, each of G_{left} and G_{right} in (d) can be easily embedded into rings as shown in (e). Combining the two rings in (d) is shown in (f). Embedding of the subgraph G^r_{left} in (b) following our algorithm is shown in (g), and (h) shows a ring after combining two rings in (f) and (g). Finally, (i) shows a complete embedding of the original graph G in (a).

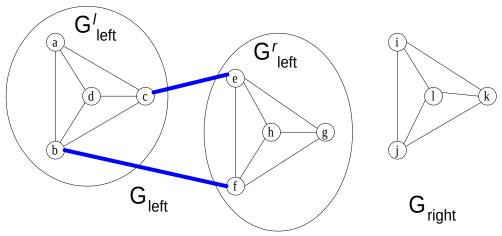
3.2 Main Result

The following main result is now established.

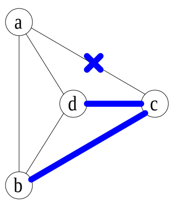
Theorem 1 *Given a 2-edge connected IP topology G and a WDM ring network G_0, there exists an embedding of G in G_0 such that iin the presence of any single link failure in G_0, G remains to be connected.*



(a) G



(b)



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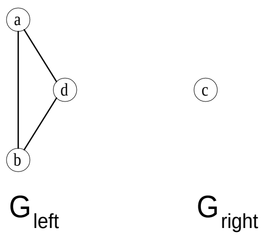
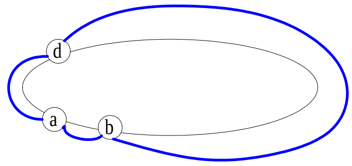
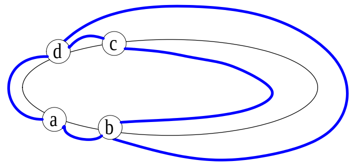


(d)

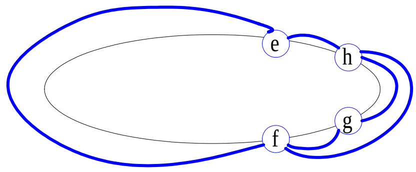
Figure 5 (Contd.)



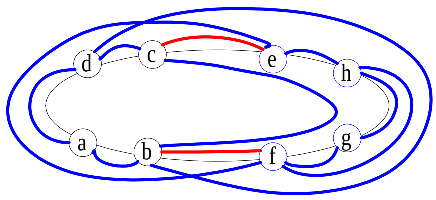
(e)



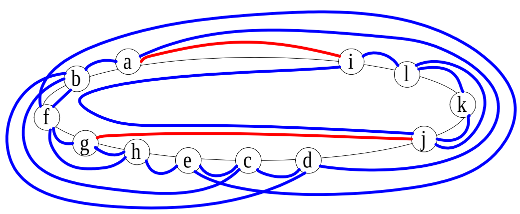
(f)



(g)



(h)



(i)

Figure 5.

4 Conclusion

In this paper, we have considered IP over WDM network's survivability by formulating the problem of embedding IP layer's topology into WDM topology with the objective of providing the IP layer's survivability. Our results show that by carefully designing embedding of IP layer topology into a ring based WDM network, a restoration scheme in the IP layer can always find available re-routed paths dynamically in the presence of the failure of any single link in the WDM network.

There are many interesting directions for future works. An extension of this paper is to consider mesh structured WDM networks, and characterize the condition for the existence of an embedding providing the IP layer's survivability and develop such an embedding. One important parameter to be considered in finding such an embedding is the capacity utilization, i.e., the amount of IP traffic to be rerouted when a WDM link fails. One possible approach is to design an embedding by considering the traffic load carried on each fiber.

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