Designing Survivable Networks using Effective Routing and Wavelength Assignment (RWA)

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Abstract: Electronic layers use primary and backup paths for protection. With WDM both may traverse the same physical link and fail simultaneously. We develop RWA strategies that maintain network connectivity in the event of link failures.

I. Introduction

This paper deals with the problem of routing logical links (lightpaths) on a physical network topology in such a way that the logical topology remains connected in the event of single physical link failures (e.g., fiber cut). This is a relatively new view on the Routing and Wavelength Assignment (RWA) problem, that we believe to be critical to the design of WDM-based networks. We call this version of the RWA problem *survivable RWA*. In a WDM network the logical topology is defined by a set of nodes and lightpaths connecting the nodes while the physical topology is defined by the set of nodes and the fiber connecting them. Given the logical and physical topologies of the networks, one important question to ask is how to embed the logical topology onto the physical topology. This leads to a static version of the routing and wavelength assignment (RWA) problem. In this version of the problem, the set of lightpaths, defined by the logical topology, are known in advance. In this context various researchers have developed RWA algorithms with the goal of minimizing network costs, including number of wavelengths required, number of wavelength converters, fiber use, etc. [1]. Since with WDM each physical fiber link can support many lightpaths (as many as there are wavelengths on the fiber), once the lightpaths are routed on the physical topology, it is possible (or in fact, likely) that two or more lightpaths would share the same physical link. Hence, the failure of a single physical link, can lead to the failure of multiple links in the logical topology. Since protected logical topologies are often designed to withstand only a single link failure, it is possible that a single physical link failure could leave the logical topology disconnected. While there has been a great deal of work in the area of optical layer protection [3,4], this survivable routing formulation is a new approach to network protection that has significant implications of the design of future WDM-based networks. In particular, our new approach has application to the design of protected SONET/WDM and IP/WDM networks.

As a simple illustrative example, consider the logical and physical topologies shown in Figure 1. The logical topology is a ring with nodes ordered 1-3-4-5-2-1. Clearly, such a ring topology is 2-connected, and would remain connected if one of its links failed. The 5 logical links of this ring can be routed on the physical topology as shown in Figure 1a, where each physical link is labeled with the logical link that traverses it. For example logical link (1,3) traverses physical links (1,5) and (5,3). As can be seen from the figure, no physical link supports more than one logical link. Hence, the logical ring would remain protected even in the event of a physical link failure.

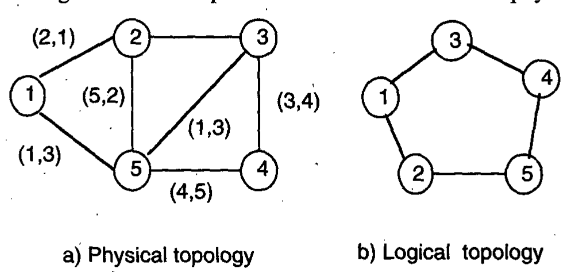

Figure 1. Survivable routing of a logical topology on a physical topology.

Alternatively, had we routed logical link (1,3) on physical links (1,2) and (2,3) the routing would no longer be survivable because physical link (1,2) would have to support both logical links (1,3) and (2,1) hence its failure would leave the logical topology disconnected. Furthermore, for many logical topologies, no survivable routings can be found. For example, if the logical topology was a ring with nodes ordered 1-4-2-3-5-1 then it can be easily seen that no routing exists that can withstand a physical link failure. Hence, it is clear that although the logical topology of the network may be connected, once it is embedded on top of a WDM physical network, it may no longer withstand a physical link failure (e.g., fiber cut).

II. Problem formulation

Using Theorem 1, below, we are able to formulate the problem of survivable routing of a logical topology on a given physical topology as an Integer Linear Program (ILP). Given a physical topology and a corresponding logical topology, we wish to find a way to route the logical topology on the physical topology such that the logical topology remains connected even in the event of a physical link failure. In order to route a logical link (s,t) on the physical topology one must find a corresponding path on the physical topology between nodes s and t. Such a lightpath consists of a set of physical links connecting nodes s and t as well as wavelengths along those links. Let $f_{ij}^{st}=1$ if logical link (s,t) is routed on physical link (i,j) and 0 otherwise. The following theorem gives necessary and sufficient conditions for survivable routing.

Theorem 1: A routing is survivable *if and only if* for every cut-set CS(S,N_L-S) of the logical topology the following holds. Let E(s,t) be the set of physical links used by logical link (s,t), i.e., E(s,t) = {(i,j) ∈ E for which $f_{ij}^{st}=1$}. Then, for every cut-set CS(S,N_L-S),

$$\bigcap_{(s,t)\in CS(S,N_L-S)} E(s,t)=\varnothing.$$

The above condition requires that no single physical link is shared by all logical links belonging to a cut-set of the logical topology. In other words, not all of the logical links belonging to a cut-set can be routed on the same physical link. This condition must hold for all cut-sets of the logical topology. Proof of Theorem 1 is straight forward and relies on the max-flow min-cut theorem for network flows [2]. Using this theorem we can now formulate the survivable routing problem as the following ILP, with the objective of minimizing the total number of links and wavelengths used in the network.

<u>Integer Linear Program for survivable routing:</u>

Minimize $\displaystyle\sum_{\substack{(i,j)\in E\text{ (set of physical links)}\\(s,t)\in E_L\text{ (set of logical links)}}} f_{ij}^{st}$ Subject to:

a) Connectivity constraints: for each pair (s,t) in E_L:

$$\sum_{j\,s.t.(i,j)\in E} f_{ij}^{st} - \sum_{j\,s.t.(j,i)\in E} f_{ji}^{st} = \begin{cases}1 & if \quad s=i\\ -1 & if \quad t=i\\ 0 & otherwise\end{cases}$$

$$\forall i\in N.$$

b) Survivability constraints:

$$\begin{matrix}\forall (i,j)\in E\\ \forall S\subset N_L\end{matrix},\qquad \sum_{(s,t)\in CS(S,N_L-S)} f_{ij}^{st}+f_{ji}^{st} < |CS(S,N_L-S)|$$

c) Capacity constraints

$$\forall (i,j)\in E,\qquad \sum_{(s,t)\in E_L} f_{ij}^{st}\le W$$

d) Integer flow constraints: $f_{ij}^{st}\in\{0,1\}$

III. Results

The above ILP can now be solved using a variety of techniques. We implemented this ILP using the CPLEX software package. To illustrate the utility of this approach, we implemented the ILP for the NSFNET physical topology shown in figure 2. We attempted to embed random logical topologies of degree 3, 4, and 5. For each, we generated 100 random logical topologies and used the ILP to find optimal survivable routing on the NSFNET. Since we are mainly concerned with the survivable routing, in our implementation we ignored the capacity constraint (i.e., we assume no wavelength restriction). Obviously, if needed, the capacity constraints can be easily incorporated into the solution. We also compare our approach to the survivability provided by shortest path routing for the same random logical topologies. In each case we checked to see if the shortest path solution yields a survivable routing. This can be accomplished by individually removing each physical link and checking to see if the remaining topology is connected.

Our results are summarized in Table 1. Shown in the table are results for both the Shortest Paths solution (labeled SP) and the ILP solution (labeled ILP). As can be seen from the table, the ILP was able to find a protected solution for every one of the random logical topologies. In contrast, the shortest path approach resulted in 86 out of 100 of the degree 3 topologies being unprotected. With higher degree logical topologies, shortest path was able to protect more of the topologies, still 38 and 27 of the random degree 4 and 5 topologies, respectively, remained unprotected. However, as expected, the ILP solution on average required both more physical links and more total wavelengths (wavelength*links). This difference in link requirements appears to be small and well justified by the added protection that it provides.

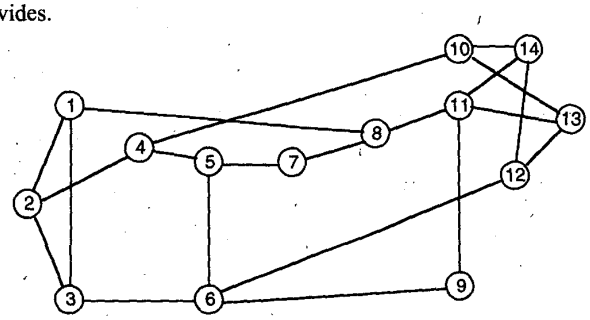

Figure 2. The 14-node, 21 link NSFNET.

Table 1. Embedding random logical topologies on the NSFNET of figure 2.

	Logical Top's	Unprotected solution	Ave. links	Ave. λ*links
Degree 3 -ILP	30	0	19.55	46.07
Degree 3 - SP	30	86	19.31	45.25
Degree 4 -ILP	30	0	20.30	60.64
Degree 4 - SP	30	38	20.17	60.47
Degree 5 - ILP	30	0	20.50	75.40
Degree 5 - SP	30	27	20.48	75.31

IV. Summary

We present a new approach to designing survivable networks that is based on considering the logical topology of the network. Our approach is useful in networks where the electronic layer provides some level of protection (e.g., SONET, IP). Our results show that this new formulation is able to offer a much greater degree of protection when compared to shortest path routing of lightpaths. We will also discuss the applicability of our approach to SONET rings as well as the Internet.

Referencs

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