Reconfiguration of Survivable Logical Topologies in WDM Ring Networks

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Abstract — **We consider the design of reconfiguring logical topologies over physical WDM ring networks. The logical topology consists of the same set of nodes as the physical topology, and the links of the logical topology are lightpaths established (or embedded) over the physical topology. The logical topology is said survivable if the failure of any single physical link does not disconnect the logical topology. In this paper, we consider the following problem. Given a logical topology with its survivable embedding over a physical ring network and a new logical topology to be reconfigured, find a sequence of lightpaths additions and deletions satisfying the given wavelengths and ports constraints such that the logical topology remains survivable throughout the reconfiguration.**

I. Introduction

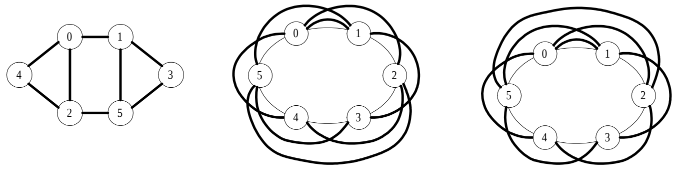
Optical networks employing Wavelength Division Multiplexing (WDM) and wavelength-routing are capable of providing lightpaths to higher service layers. Lightpaths are optical circuit-switched paths that have transmission rates of a few Gb/s. By the use of WDM, multiple lightpaths may traverse the same optical fiber link, each one using a different wavelength.

Survivability is a very important requirement for high-speed optical networks. There has been a large amount of work that focuses on pre-allocating backup capacity so that any failed lightpaths may be restored rapidly as soon as normal operation is disrupted in the event of link break. The proposed techniques are classified as either link protection or path protection, depending on whether the rerouting of lightpaths is done around the failed link, or on an end-to-end basis. Protection at the optical layer is considered to be fast, partly because of the proximity of the optical layer to the physical layer at which the failure is first detected, and partly because of the coarse granularity at which restoration is done (at the lightpath or fiber level).

When an electronic service layer is embedded over a WDM optical network, then it may be the case that the electronic layer incorporates its own survivability functions, thereby making the optical layer recovery redundant, and in the worst case, perhaps conflicting. Furthermore, when a physical link fails, it may not be necessary for all the affected lightpath traffic to be restored. Thus, there is a case to be made for recovery to be done solely at the electronic layer. If the electronic layer were the IP layer, then the only requirement for the layer to be survivable is that it be connected.

Motivated by the above, we have considered in [2] the embedding of an electronic layer on a physical WDM network such that the electronic layer network is connected when a single link fails. The connectivity at the electronic layer is represented by the *logical topology*. The logical topology is a topology which has as its nodes the set of electronic nodes. The edges of the logical topology correspond to the set of lightpaths that are established over the physical topology. As mentioned above, multiple lightpaths may be routed over the same physical link, and therefore, it is possible for a single physical link failure to break more than one edge on the logical topology. Since survivability at the logical topology depends on the availability of multiple routes between nodes at the logical layer, it is clear that there must be some amount of coordination between the two layers if survivability has to be achieved at the logical layer. In [2], we focussed on the design of logical topologies that are *survivable*. We defined a logical topology to be survivable if the failure of any single physical link does not disconnect the logical topology. Survivable logical topology design not only involves the determination of the logical edges but on the embedding of those edges on the physical topology, i.e., the routing of the lightpaths.

Consider a logical topology shown in Figure 1 (a) corresponding to a connection request set $C = \{(0,2),(2,4),(4,0),(1,3),(3,5),(5,1),(0,1),(2,5)\}$ to be embedded over a WDM ring network with six nodes. Figure 1 (b-c) show the physical ring topology and two different lightpaths assignments, in which the logical topology maintains its connectivity in the presence of any single physical link failure when the lightpath setup is done using the routes shown in (b), and it does not when the setup is done using the routes in (c) and when link $(0,1)$ fails.



(a) (b) (c)

Figure 1: (a) A logical topology, (b) a survivable embedding, and (c) a non-survivable embedding.

There has been other recent research in the survivable design of logical topologies. In [1], the problem of embedding lightpaths such that the minimum number of source-destination pairs are disconnected at the logical layer was considered, and some optimization heuristics were presented. In [3], a similar problem was considered and some conditions for the survivability of a logical topology were presented. In both of these papers, the physical topology was assumed to be an arbitrary mesh.

In this paper, we address the problem of reconfiguring the network from logical topology G_1 to logical topology G_2 in such a way that the logical topology remains connected in the presence of any single physical link failure (i.e., survivable) throughout the reconfiguration process. Our goal is to find a sequence of lightpaths additions (i.e., finding routes and wavelength assignments) and deletions such that the logical topology's survivability is maintained during the entire period of reconfiguration. We consider in this paper a physical ring network. Ring networks are important because the prevalent topology for SONET is the ring. As these networks are upgraded to WDM, it is likely that the topology will be maintained for some time before growing into a mesh network. Secondly, the simplicity of the topology enables us to take a deeper look into the complexity of the problem.

In the next section, we formally state the problem we attempt to solve in this paper. Some insight into the complexity of the problem is presented in Section III. We present a simple algorithm in Section IV, and a limitation on implementing this simple algorithm is discussed in Section V. Concluding remarks in Section VI complete the paper.

II. Network Model and Problem Formulation

Let R denote a ring network with n nodes. Each link is bidirectional supporting W wavelengths channels. Each node is assumed to have p ports that can be used as a source or a sink of up to p lightpaths.

Let G_1 and G_2 be logical topologies for R such that G_1 and G_2 both are survivable, i.e., G_1 and G_2 both have survivable embeddings in R. Given a survivable embbeding of G_1 in R corresponding to the current set of lightpaths established over R and a logical topology G_2 corresponding to a new set of lightpaths to be reconfigured from G_1, a reconfiguration process is called *survivable* if during the entire period of reconfiguration,

(i) the logical topology remains survivable (i.e., connected under the failure of any single physical link), and

(ii) the port and wavelengths constraints are satisfied.

Our problem is to find a survivable reconfiguration of the network from G_1 to G_2 by establishing a sequence of lightpaths additions and deletions.

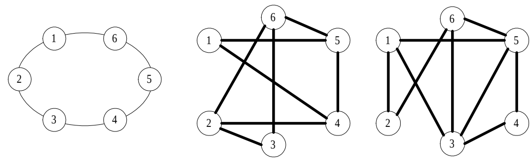
III. Problem Complexity

If there is no constraint on the number of lightpaths that can be established at each node or the number of wavelengths that can be used in each link, one can simply add all lightpaths in $G_2 \setminus G_1$ to G_1 and form $G_1 \cup G_2$, and then delete all lightpaths in $G_1 \setminus G_2$. (Assume that survivable embeddings of G_1 and G_2 are used in the setup of lightpaths.) This will ensure the survivability of the logical topology throughout the reconfiguration process. On the other hand, if the logical topology (including all nodes in R) corresponding to the set of existing lightpaths in $G_1 \cap G_2$ is connected, a survivable reconfiguration can be easily done first by deleting all lightpaths in $G_1 - (G_1 \setminus G_2)$, and then by adding lightpaths in $G_2 \setminus G_1$.

The above observations suggest that reconfiguration steps for adding and deleting lightpaths must be designed carefully to find a feasible solution. In what follows, we illustrate the complication of the problem even further by examining three different cases.

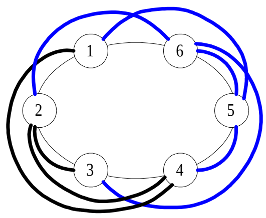
CASE 1 : A feasible solution that modifies the current embedding of some lightpaths in $G_1 \cap G_2$.

Consider a ring network R with $W = 4$ and $p = 4$, and two logical topologies G_1 and G_2 to be embedded over R as shown in Figure 2, where $G_1 \setminus G_2 = \{(1,4),(2,3),(2,4)\}$, $G_1 \cap G_2 = \{(1,5),(2,6),(3,6),(4,5),(5,6)\}$, and $G_2 \setminus G_1 = \{(1,2),(1,3),(3,4),(3,5)\}$. Survivable embeddings of G_1 and G_2 are shown in Figure 3.

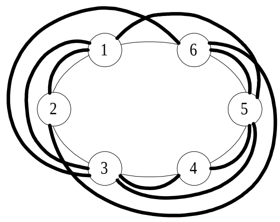


(a) R (b) G_1 (c) G_2

Figure 2: Physical and Logical Topologies



(a) G_1 over R



(b) G_2 over R

Figure 3: Survivable Embeddings

Now, we are going to reconfigure the logical topology from G_1 whose current embedding is shown in Figure 2 (a) to G_2 as shown in Figure 2 (c). Suppose there exists a survivable embedding of G_2 without changing any of the current lightpaths in $G_1 \cap G_2$. (The current lightpaths in $G_1 \cap G_2$ are shown in Figure 4.) Consider the two lightpaths (corresponding to logical links (2,1) and (2,6) in G_2) to be established at node 2. If the lightpath connecting 2 and 6 is kept as it is in Figure 3 (a), the lightpath connecting 2 and 1 has to be established in the counter-clockwise direction from 2 to 1 since otherwise the failure of physical link $(1, 2)$ will isolate node 2 from the remaining network. However, in such an embedding, if the physical link $(1, 6)$ fails, both lightpaths corresponding to logical links $(2, 1)$ and $(2, 6)$ will fail and the failure of these two lightpaths will make again node 2 isolated from the rest of the network. Therefore, any feasible solution must modify the current embedding of the lightpath between 2 and 6 (i.e., a lightpath between 2 and 6 must be re-established in the counter-clockwise direction from 2 to 6). The embedding shown in Figure 3 (b) is such an embedding.

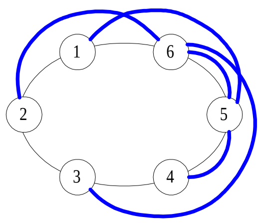


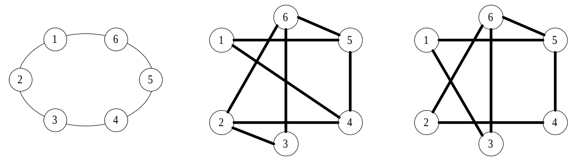
Figure 4: $G_1 \cap G_2$

<u>*CASE 2 :*</u> *A feasible solution that temporarily deletes and reestablishes some lightpaths in $G_1 \cap G_2$ due to the wavelength constraint.*

Consider a ring network R of 6 nodes with $W = 3$ and $p = 4$ and two logical topologies G_1 and G_2 to be embedded over R as shown in Figure 5, where $G_1 \setminus G_2 = \{(1, 4), (2, 3)\}$, $G_1 \cap G_2 = \{(1, 5), (2, 4), (2, 6), (3, 6), (4, 5), (5, 6)\}$, and $G_2 \setminus G_1 = \{(1, 3)\}$. Survivable embeddings of G_1 and G_2 are shown in Figure 6.

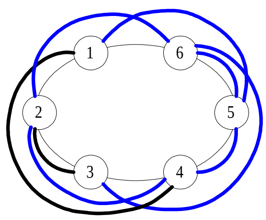
Note that during the reconfiguration, lightpaths corresponding to logical links $(1, 4)$ and $(2, 3)$ must be deleted and a new lightpath corresponding to logical link $(1, 3)$ must be established. Suppose there is a feasible solution that only adds lightpaths in $G_2 \setminus G_1$ and delete lightpaths in $G_1 \setminus G_2$ during the entire reconfiguration process. If lightpath $(1, 4)$ or $(2, 3)$ is deleted before adding lightpath $(1, 3)$, the failure of physical link $(1, 6)$ or $(3, 4)$, respectively, will make node 1 or 3 isolated. Hence, any feasible solution in this case must add lightpath $(1, 3)$ before deleting lightpath $(1, 4)$ or $(2, 3)$. So we consider two cases for the setup of lightpath between 1 and 3: clockwise from 1 to 3 and counter-clockwise from 1 to 3.

If lightpath between 1 and 3 is added in the counter-clockwise direction from 1 to 3, then the existing lightpath $(2, 4) \in G_1 \cap G_2$ must be deleted beforehand since otherwise four lightpaths will use physical link $(2, 3)$, violating the wavelength constraint. Now assume that lightpath between 1 and 3 is added in the clockwise direction from 1 to 3. Similarly, one of the existing lightpaths $(2, 4), (3, 6) \in G_1 \cap G_2$ must be deleted before adding lightpath $(1, 3)$ since otherwise the wavelength constraint will be violated on the physical link $(3, 4)$. In either case, at least one existing lightpath in $G_1 \cap G_2$ must be temporarily deleted and reestablished later.

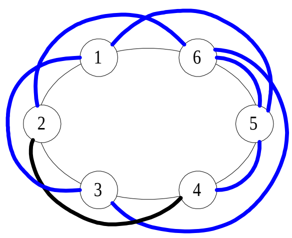


(a) R (b) G_1 (c) G_2

Figure 5: Physical and Logical Topologies



(a) G_1 over R



(b) G_2 over R

Figure 6: Survivable Embeddings

CASE 3 : A feasible solution that temporarily adds some lightpaths not in $G_1 \cup G_2$ to guarantee the survivability during the reconfiguration period.

Consider the same example for the physical and logical topologies discussed for CASE 2 (see Figures 5 and 6). As discussed in CASE 2, any feasible solution cannot delete lightpath $(1,4)$ or $(2,3)$ without adding new lightpaths. In what follows, we present a feasible solution by temporarily adding a lightpath that is not in $G_1 \cup G_2$ and deleting it later.

Initially, the lightapths are as shown in Figure 6 (a). A lightpath between 1 and 2 is temporarily added in the counter-clockwise direction from 1 to 2. We then safely delete the existing lightpath $(1,4)$, and add a new lightpath between 1 and 3 in the counter-clockwise direction from 1 to 3. The existing lightpath $(2,3)$ is now deleted, and then the temporary lightpath $(1,2)$ is finally deleted.

IV. Reconfiguration Algorithm

As discussed in the previous section, maintaining logical topology's survivability during the entire reconfiguration period requires a careful design of lightpaths additions and deletions. But, if the current setup of lightpaths only uses up to $W-1$ wavelengths in each of the physical link and upto $p-2$ ports at each node, one can easily find a feasible solution using the following steps: (i) add a lightpath between each pair of adjacent nodes, (ii) delete all lightpaths in G_1, and (iii) establish all lightpaths in G_2 based on its survivable embedding.

This procedure is simple and may be further improved by considering cost parameters related with lightpaths establishment and deletion if wavelengths and ports are still available. (Heuristic algorithms to optimize certain cost parameters will be discussed in a full paper.)

V. Implementation of Reconfiguration Algorithm

Intuitively, the implementation of our simple algorithm presented in the previous section would be always feasible if the number of wavelengths W and the number of ports p are large and the current logical topology G_1 has only a small number of lightpaths established at each node (except possibly for a few nodes). In this section, we argue that the choice of a survivable embedding of any given logical topology is important when considering a survivable reconfiguration. The following discussion exhibits a construction of a *bad* (yet survivable) embedding of a logical topology that would make its reconfiguration to other logical topology difficult.

Let n denote the number of nodes in a ring physical network R, and $W = n-k+1$ (where W is an arbitrary integer in $1 \leq W \leq n$) denote the number of wavelengths supported by each link in R. It is assumed that the number of ports p available at each node is equal to $2W$. Hence, the wavelength (not the port) availability is a major constraint to be considered in the establishment of a new lightpath. Figure 7 shows a survivable embedding of a logical topology G over a ring. The set of logical links in G is given as $\{(n,i),(i,n-k) \mid 1 \leq i \leq n-k-1\} \cup \{(j,j+1) \mid n-k \leq j \leq n-1\}$, and the route of each lightpath corresponding to each logical link is as shown in Figure 7. Note that the number of lightpaths established in each node, except for nodes n and $n-k$, is only 2. However, each link between n and $n-k$ in the counter-clockwise direction has fully utilized its available wavelengths (i.e., $n-k+1$). Therefore, implementing our simple algorithm discussed in Section IV would be impossible.

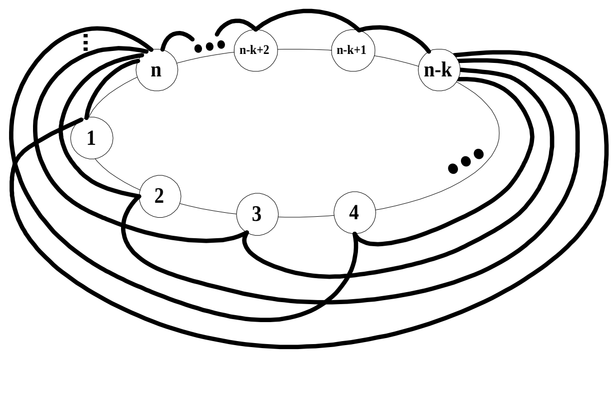


Figure 7: $W = n-k+1$.

VI. Conclusion

In this paper, we addressed the issue of reconfiguring logical topologies in WDM optical rings. Specifically, we consider the problem of finding a sequence of lightpaths additions and deletions such that the logical topology remains connected in the presence of any single physical link failure throughout the reconfiguration.

We first discussed the complexity of the problem by exhibiting examples that require complicated designs of reconfigurations. We then presented a simple algorithm that can be implemented if a certain condition is satisfied. A limitation on implementing this simple algorithm is also discussed.

Further work may concentrate on developing heuristic algorithms to minimize reconfiguration costs such as minimizing the reconfiguration time or minimizing the restoration time if a physical link failure occurs during the reconfiguration.

Acknowledgments

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