An Online Distributed Protocol for the Restoration of Connectivity in the Virtual topology after Link failure in IP over WDM networks

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Abstract

Recently, there has been growing interest in IP-over-WDM networks. A set of lightpaths that are established a priori defines the virtual topology of a Wavelength Division Multiplexing (WDM) optical network. Internet Protocol (IP) makes use of virtual topology to route its traffic in the optical form. If a physical link fails, then all lightpaths that are using the failed link also fail and may leave the virtual topology partitioned into a number of sets of nodes. Thus, a node belonging to one set of nodes cannot communicate with nodes in other sets. In such a case, the restoration of connectivity in the virtual topology may be indispensable. Hence, it may be necessary to alter the existing virtual topology in order to restore the connectivity. In this paper, we propose a distributed protocol for the restoration of connectivity in the virtual topology in the event of a link failure. The proposed protocol for connectivity establishment tries to minimize the number of changes committed to the virtual topology and assures all-to-all communication path (either using single hop or multi-hop path) in the virtual topology. The performance of our algorithm is studied based on the results obtained from extensive simulations.

Key Words: WDM Optical Network, Link Failures, Reconfiguration of Virtual topology, On-line protocol, Distributed protocol.

1 Introduction

With the Internet Protocol (IP) playing a dominant role in wide area networking technology and advancements in wavelength-routed wavelength division multiplexing (WDM) technology to provide huge bandwidth, the IP-over-WDM technology becomes the right choice for next generation Internet networks [1]. In these networks, messages are carried from one node to another node using lightpaths. A *lightpath* is an all-optical path established between two nodes in the network by the allocation of same wavelength on all links of the path. In IP-over-WDM networks, lightpaths are established between IP routers. If a lightpath exists between two nodes, data exchange between them requires no buffering or electro-optical conversion at intermediate nodes. The problem of establishing lightpaths statically (a priori) is referred to as *static lightpath establishment (SLE)* problem. IP-over-WDM networks make use of these lightpaths to transfer data. This set of pre-established lightpaths is called as *virtual topology.* Virtual topology is a graph with nodes as the routers in physical network (IP-over-WDM network) and edges corresponding to the lightpaths between them. A node pair may not have a lightpath due to non-availability of wavelengths between them or transmitters at the source or receivers at the destination. Traffic between a node pair sans a lightpath, is routed using multiple lightpaths (logical hops).

A virtual topology (which is a graph) is said to be *connected,* if every node in the virtual topology can communicate either using single lightpath (single hop) or using multiple lightpaths (multihop) to every other node. A virtual topology is designed by assuming the number of wavelengths available on a fiber and the traffic demand between node pairs as given in [2]. A virtual topology may be designed with an objective of minimizing certain metric (objective function) such as maximum congestion on a lightpath [3], average packet delay [4], or average weighted hop count [5].

Virtual topology needs to be altered in various situations. This procedure is referred to as *reconfiguration.* The first situation, which calls for reconfiguration, is when the traffic demand changes at higher layers. Here, a set of lightpaths needs to be changed to reflect the new traffic. The second situation for altering the virtual topology arises when the network elements such as links and nodes fail. Due to a link failure, even though the physical topology is connected, the

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virtual topology may become disconnected. It means that physically the network may be connected, but the virtual topology may be partitioned into a number of components. In such a case, the virtual topology may be altered to provide connectivity among the nodes in the network. This process could succeed only if the number of transceivers at every node is greater than one. Hence in our work, we assume that more than one transceiver exists in every node. Also we consider a 2-Connected physical topology which remains connected even after the failure of a physical link. In [6] the authors have proposed ILP formulations for survivable routing of virtual topology. In this the virtual topology is designed in such a way that the removal of a link does not disconnect the virtual topology. However, for a given physical topology, it is possible to find survivable routing only for a restricted set of logical topologies. Also, the added survivability comes only at the expense of additional network resources.

In [7, 8] centralized algorithms for virtual topology reconfiguration due to link and node failures were proposed. These algorithms try to establish the connectivity of the virtual topology after a link and node failure respectively. Though the centralized algorithms are well suited for a country-wide network, they may not be suitable for world-wide networks such as IP networks. This is because of huge control traffic to and from centralized node. Also the centralized node in these algorithms is a single point of failure. We propose a distributed reactive solution to the problem of connectivity establishment in the virtual topology after link failure.

The rest of the paper is organized as follows. Section 2 describes the problem. Section 3 explains the distributed connectivity establishment methodology. Section 4 discusses performance study of our method. Section 5 concludes the paper.

2 Problem Description

We assume the physical topology is 2-connected and hence it will remain connected even after a link failure. However, the virtual topology may not be 2-connected and hence a link failure may result in partitioning the virtual topology into more than one component. Since there is no connectivity exist between the divided components, a node in one component cannot communicate with a node in other components. We also assume that every node has T tunable transmitters and T tunable receivers and a fiber carries W wavelengths. A physical link between two nodes is assumed to be bi-directional, in the sense that if the link between a node pair (s,d) fails then the link between node pair (d,s) also fail. In our work we deal with a situation where failure of a link causes the partition of virtual topology into more than one component but the connectivity of the physical topology remains undisturbed.

We can state that, *though the number of elements in the cut-set of physical topology is greater than one, the number of elements in the corresponding cut-set of virtual topology may be one.* It can be explained as follows. Assume that failure of a physical link between nodes $a \in A$ and $b \in B$ causes the virtual topology partitioned into three components. We assume (Figure 1) that these components are A, B, and C. Assume that lp1 is a lightpath passing from a node $a \in A$ to a node $b \in B$. Similarly, lp2 is a lightpath passing from a node $a \in A$ to a node $d \in C$ via nodes $b \in B$ and $c \in B$ and lp3 is a lightpath passing from a node $e \in A$ to a node $i \in A$ via nodes $f \in B$, $g \in C$ and $h \in C$. Hence, although the cut-set of physical topology contains more than one link (in between nodes a and b, and in between nodes e and f), the cut-set of virtual topology may contain only one lightpath lp1 as shown in Figure 1.

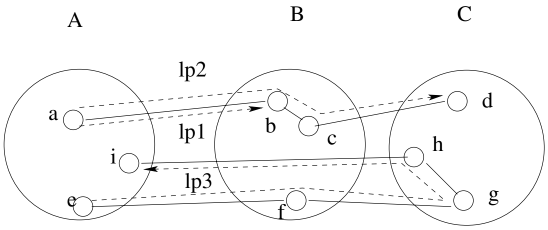

Figure 1. Example 1

We can also state that, *though the failure of a physical link 'cuts' the physical network into only two components, failure of a physical link may 'cut' the virtual topology into more than two components.* This is because, the failed physical link may carry more than one lightpath and these lightpaths may be the only members of different cut-sets.

Lemma 1: *If a virtual topology is disconnected due to failure of a physical link, then it can always be made connected by altering the virtual topology if the number of elements in the physical cut-set for which the failed link belongs to is greater than one.*

Proof: From the second part of above Lemma, let us assume that the physical cut-set consists of more than one link (as shown in the Figure 1). This assures that the physical network does not get disconnected when a link fails. Lightpath lp1 starts at a node $a \in A$ and ends at a node $b \in B$. Similarly, lp2 starts at $a \in A$ and ends at a node $d \in C$. If the physical link between nodes a and b fails then the lightpaths lp1 and lp2 also fail. This divides the virtual topology into three components A, B, and C. If lp3 is disturbed and altered in such a way that it starts at a node $e \in A$ and ends at a node $f \in B$ then the nodes in components A and B can communicate in the virtual topology. Thus the connectivity can be achieved between components A and B. This can be supported by the results that all nodes belonging to a component can communicate either using single hop or multiple hops among them. In the above Lemma it is assumed that *all lightpaths belonging to a cut-set of a virtual topology should make use of the failed physical link.* This is a necessary condition to get the disconnected logical topology whenever a physical link fails.

Lemma 2: *The maximum number of one-way disconnected components formed due to the failure of a directed physical link is W, where W is the number of wavelengths carried by the physical link.*

Proof: If a directed physical link carries W wavelengths, then these W wavelengths may carry W lightpaths (virtual links) each of which may constitute a cut-set of virtual topology. Thus the failure of this link causes the failure of W cut-sets of virtual topology thereby dividing the entire virtual topology into W one-way disconnected components. As a corollary to this we can state that the maximum number of one-way disconnected components due to the failure of an undirected physical link is 2W and the maximum number of two-way disconnected components due to the failure of an undirected physical link is W.

3 Connectivity restoration methodology

The various control messages used by our protocol are sent through the control channel. The control channel is established by duplicating the physical topology on the virtual topology using the wavelength W_0. Since physical topology is 2-connected and the control channel is a duplication of the physical topology, it remains connected even after the link failure. Every node is assumed to know the following details: All lightpaths emerging from it, all lightpaths incident on it, load on each lightpath associated with that node and route of each lightpath. Our protocol deletes a lightpath only when deletion of a lightpath does not affect the connectivity of the network. That is, even after the deletion of link there exists a path between two end nodes of the deleted lightpath on the virtual topology. Such lightpaths are referred to as *non-critical lightpaths.* The lightpaths whose deletion disconnects the virtual topology are referred to as *critical lightpaths.* Criticality of a lightpath is verified by flooding a control packet on the virtual topology. If the source of the lightpath receives an acknowledgment then it can conclude that the particular link is non-critical. The sequence of events that take place during the connectivity restoration after the link failure are discussed below:

3.1 Identifying the link failure

The failure of a physical link say xy is first identified by the nodes x and y. If W is the number of wavelengths carried by each of the directed links xy and yx. Then all these 2W lightpaths are affected due to the failure. Once the failure is detected, nodes x and y prepare a message containing the set of sources and destinations of the affected lightpaths and send it to the source and destination of each affected lightpath using the control channel.

3.2 Formation of components

Assume {s1,s2,...sn} be the various sources and {d1,d2,....dn} be the various destinations of the failed lightpaths. As mentioned in Lemma 2, in the worst case, the virtual topology will be partitioned into 2W one-way disconnected components with each component containing a source say si or a destination say di where W is the number of wavelengths in the directed link xy. Upon receiving the set of sources and destinations of the affected lightpaths from x or y through the control channel, a node say t (can be a source or destination of the affected lightpaths) sends a message to every other source and destination of the affected lightpaths on the virtual topology. If a node r receives this message, it sends an acknowledgment back on the control channel. From this acknowledgment node t comes to know that there exists one-way connectivity from the component containing node t to the component containing node r. Node t also understands that node r is present in its own component as node r is reachable from node t. Thus every node in the set {s1,s2,...sn} U {d1,d2,....dn} finds all the nodes that it can communicate.

3.3 Election of the coordinators

It is necessary to have a coordinator for every component to establish the connectivity with other components. In a component, one node is elected as the coordinator. Our protocol elects the node that is having the least (IP) address as the coordinator. If there is only one node in a component then it is considered as the coordinator.

3.4 Finding the coordinators of other components

The coordinator node in each component sends a control message using the control channel to all the nodes in the set {s1,s2,...sn} U {d1,d2,....dn} for which it does not have connectivity. The nodes on receiving this message reply with the IP address of their coordinator node. Thus the coordinator in every component is informed about the coordinators of other components and hence the total number of logically divided components. Every coordinator prepares the list of coordinators to which connectivity does not exist.

3.5 Broadcasting the request for new lightpaths

The coordinator of each component broadcasts a Req_Estab_lp message on the virtual topology for establishing connectivity to every non-reachable component. This message requests the establishment of a set of new lightpaths that provide the connectivity to the set of non-reachable components. Every Req_Estab_lp message consists of the list of coordinators to which the establishment of connectivity is requested.

3.6 Bidding for the requested lightpaths

A node (say k) on receiving the Req_Establ_lp message looks for a physical link connecting k and a node say q which is belonging to a component whose coordinator is mentioned in the received Req_Estab_lp message. If such a link exists then node k checks for the availability of a transmitter with it. If it is not available, it checks whether the transmitter can be made free by deleting some other non-critical lightpaths. If so, it sends Req_Bid_Resource message to node q using the control channel. Node q checks for the availability of receiver in a similar way as node k did. Similarly availability of wavelength on link kq is also verified. Once the information regarding the availability of resources is available then node k computes the weight of the lightpath that it wants to establish. The weight field gives a measure of the disturbance that will be caused to the network due to deleting some other lightpaths for providing required resources. Here, lightpaths carrying less traffic or lightpaths whose hop count on the physical topology is less will be given less weight. A weight value of infinity indicates that the resource cannot be granted. Once the weight of the lightpath is computed the same may be informed to the coordinator using Bid_estab_lp message sent on the control channel.

3.7 Establishing the new lightpaths

The coordinator after getting the Bid_Estab_lp messages from various nodes finds the node which sent the lowest weight in its Bid_Estab_lp. The co-ordinator then sends a Estab_lp message to the node which sent the least weight in its Bid_Estab_lp message. This node establishes the connectivity by deleting the least weighted lightpaths whose resources are necessary for the establishment of the new lightpath. After the establishment of the new lightpath this node sends an Estab_lp_Ack to acknowledge the establishment of the new lightpath.

3.8 Coalescing of the coordinators

If a co-ordinator c1 has established connectivity with another component whose coordinator is c2, then c1 informs that it has established connectivity to c2 to all the other coordinators through the control channel. The other coordinators on receiving this message will try to establish connectivity to either of the component containing c1 and the component containing c2 because there is connectivity from c1 to c2. Thus all the coordinators view the component containing c1 and the component containing c2 as a single component containing $\{$c1,c2$\}$. This process continues till all the divided components become connected and all the components are viewed as a single component containing all the coordinators. This ensures that the connectivity between the various components is restored.

4 Performance Study

In this section, the performance of the proposed protocol is studied. Extensive simulation experiments are conducted on NSFNET T1 backbone network. To design a virtual topology, wavelength continuity constraint is enforced, and it is assumed that only one lightpath may exist between a node pair, and the lightpath is chosen on the shortest path between source-destination pairs. We use the model given in [5] to simulate the values of traffic matrix. Traffic is measured between all pairs of nodes and is given as an N x N matrix, say *Traffic,* where $Traffic_{i,j}$ represents the average traffic from node i to node j. It is to be noted that $Traffic_{i,j}$ may not be the same as $Traffic_{j,i}$. The objective of the connectivity restoration process is to provide connectivity with minimum number of changes N_{ch} and minimum message overhead.

The parameters with respect to which these metrics can be studied are, the number of transceivers T and the number of wavelengths W. In our experiments, we observed the values for performance metrics such as Number of messages sent and number of changes made to the virtual topology(N_{ch}). These observations are made while fixing one of the parameters. The failures of all the twenty one links of NSFNET are observed by varying the above specified parameters. It is observed that the increase in number of resources causes the increase in the number of messages that are to be sent. It is because of the existence of more number of lightpaths in the topology designed with more resources. Also the number of messages is less for connected topologies than that of disconnected topologies. (The virtual topology which is remained connected after the failure of a physical link is termed as the *connected topology*, whereas the virtual topology which is disconnected and divided into a set of components is termed as *disconnected topology*.) It is evident in Figure 2 through Figure 4.

Figure 2 shows the variation in number of messages sent with respect to the network resources. Here by resources we mean transceivers T and wavelengths W. Number of transceivers is taken to be equal to the number of wavelengths. Figure 3 shows the variation in number of messages sent with respect to the number of transceivers (transmitters and receivers) used. Number of wavelengths W is taken as 5. Figure 4 shows the variation in the number of messages sent with respect to the number of wavelengths carried by each fiber. The number of transceivers T is taken as 2. Table 1 indicates the number of disconnected topologies, average number of components formed and the number of changes that are to be carried out under various resource conditions.

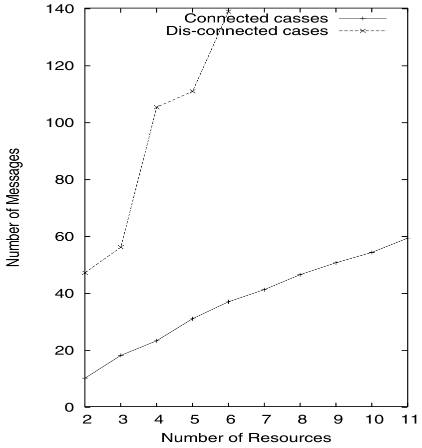

Figure 2. Effect of Resources on number of messages

Table 1. Connectivity restoration results at T=W

W=T	Disconn. cases	Components	Changes
2	14	2	3.8
3	1	2	2
4	6	2.166	2.33
5	4	2.25	2.5
6	1	2	2
7	0	0	0
8	0	0	0

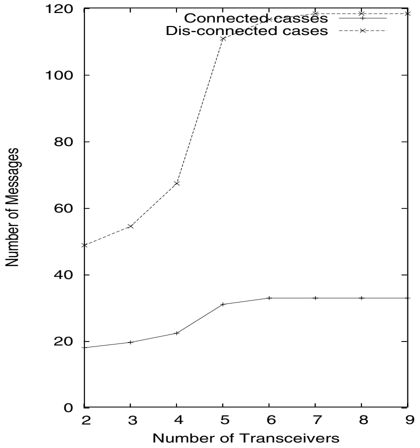

Figure 3. Effect of Number of Transceivers on number of messages

5 Conclusions and Future Work

In IP-over-WDM networks, the IP traffic may make use of a set of lightpaths that are already established (virtual topology). A virtual topology is said to be connected, if every node in the virtual topology can communicate either using single lightpath (single hop) or using multiple lightpaths (multihop) with every other node. Failure of a link may cause disconnection of the virtual topology, even though the physical network is connected. In such a case, some lightpaths may be established to achieve a connected virtual topology. This is possible only if every node has at least two transceivers. In this paper, we made an attempt to device distributed protocols that provide connectivity in the event of a link failure. Extensive simulations are performed on NSFNET to support our results empirically. The effect of link failure on the objective function value can be studied in future.

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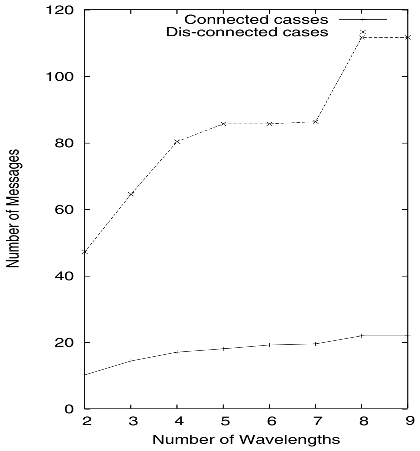

Figure 4. Effect of Number of Wavelengths on number of messages

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