Load Distribution-Survivable Lightpath Routing for the Optical Virtual Private Network

Chutima Prommak, David Tipper

Department of Information Science and Telecommunications
University of Pittsburgh, Pittsburgh, PA 15260, USA
Email: cprommak@sis.pitt.edu

Abstract

The optical virtual private network (OVPN) services are expected to be one of the major applications in the future optical networks. To establish the OVPN, the lightpaths (virtual connections) are layout through the provider optical network element and finally connected to the client edge devices. Service reliability is one of the major requirements in the OVPN design. In this paper, we propose a mathematical model for an efficient lightpath routing called ***Load Distribution-Survivable Lightpath Routing (LD-SLR)*** which can mitigate the impact of the failure disruption in the OVPN by introducing the load distribution concept to the survivable lightpath routing. Our results show that the LD-SLR produces an efficient lightpath routing for both sparse and dense virtual network design compared to other lightpath routing models in literature.

Keywords: lightpath routing, routing and wavelength assignment, survivability, OVPN

1. Introduction

Dense Wavelength Division Multiplexing (DWDM) technology and the optical transport network are promising solutions to support the tremendous growth of data traffic brought by new Internet and enterprise applications. Several optical services are expected to rollout in the near future [1]. These services include lambda leasing, provisioned bandwidth, bandwidth on demand, and Optical Virtual Private network (OVPN). Among these services OVPN services are expected to be one of the major applications in the future optical network motivated by the recent advance in IP/MPLS-based VPN and the convergence of IP and optical networking [2]. A variety of applications that will be supported by OVPN include ISP edge router networks, content delivery among a network of servers and storage for corporation. OVPN services allow a corporation to communicate in their secure and manageable virtual networks.

To establish the OVPN, the lightpaths (virtual connections) are layout through the provider optical network element and finally connected to the client edge devices[3]. Several service requirements have been raised for the OVPN [3,4]. One of the major requirements from the service providers is that the OVPN design should provide reliable service with minimum disruption to the client virtual networks.

In the optical network capable of wavelength conversion, a lightpath represents concatenation of wavelengths along the path. Lightpath routing is one of the major design issues that have been received lot of attention in the optical network research and industry [5]. There have been several works proposed to address the lightpath routing problem, which usually referred to as a routing and wavelength assignment (RWA) problem. Various RWA algorithms have been developed with different goals. For example, in [6] and [7], the objective is to minimize the blocking probability in the WDM networks while the work in [8] aims to minimize number of wavelengths and fiber cables. With DWDM technology, many wavelengths are carried on a single fiber cable. In the event of a single fiber cable failure, all lightpaths transverse that failed fiber will be corrupted. This could disconnect many client virtual networks and result in information islands. To minimize this impact, one should take into account a survivability issue in the lightpath routing algorithm [9,10]. Recently, lightpath routing techniques proposed in [11] and [12] incorporated survivability aspects in their lightpath routing problems. In [11], Crochat et al. proposed a protection interoperability design technique for the SONET over WDM network where the RWA problem in WDM network layer is integrated with the recovery mechanism provided in the SONET network layer. In the case of fiber cable failure, their lightpath routing assures the connectivity of the virtual network in the WDM network layer which in turn allows the operation of the recovery technique in the SONET network layer. In [12], Modiano et al. proposed the survivable lightpath routing (SLR) algorithm, which guarantees connectivity of the client virtual network. In the case of a single fiber cut, SLR prevents partitioning the client virtual network into islands and allows the recovery mechanism in the higher layer network to restore affected traffic.

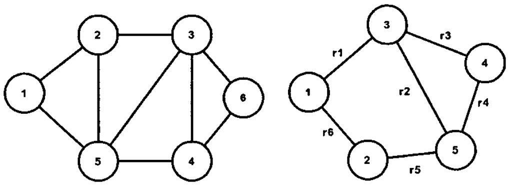
In this paper, we extend the work of [12] to further mitigate the impact of the failure disruption in the OVPN by introducing the load distribution concept to the survivable lightpath routing. The problem is formulated as a minimization problem called the load distribution-survivable lightpath routing (LD-SLR). It aims to minimize the number of wavelengths and fiber cables used to setup the OVPN while guarantee connectivity of the virtual network in the case of a fiber cable failure. Another objective is to minimize the number of interrupted lightpaths to reduce disruption impact. In the event of failure, the LD-SLR further enhances reachability and interworking of IP traffic carried over the OVPN. We point out that the SLR [12] does not work well in the design of a dense virtual network. It yields lightpath routing like that of the shortest path routing (SPR) algorithm. Our results show that the LD-SLR yields an efficient lightpath routing in both sparse and dense virtual network design.

The rest of this paper is organized as follows. Section 2 presents the LD-SLR problem formulation. Section 3 illustrates routing results. We discuss and compare the lightpath routing using SPR vs. SLR vs. LD-SLR. Finally, section 4 concludes the paper.

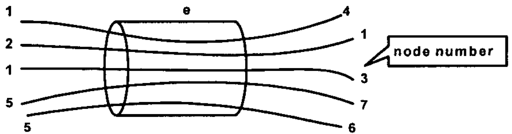
2. Problem Formulation

Let $G(N, E)$ be the optical network graph. It is an undirected graph. N = a set of nodes $\{1, 2, \ldots, N\}$. E = a set of fiber links $\{1, 2, \ldots, E\}$. We define a virtual network is a graph $G(N_v, L)$ where $N_v \subset N$. In this case, L represents a set of all connections in the virtual network. A set of eligible paths P_l is pre-computed for a virtual connection l for $\forall l \in L$. Each path is limited by a hop count between a source and a destination node. Note that one path will be selected from P_l for the virtual connection l.

Considering a virtual network topology, we define virtual connections that are originated or terminated at a particular node as connections significant to that node. We define DP_i as a set of virtual connections that significant to node i. Let DP_i = {connection between node pair (s, d) in the virtual network, where $s = i$ or $d = i$, $i \in N_v$}. For example, from figure 1b, $DP_3 = \{r1, r2, r3\}$. The idea of the load distribution is to minimize service disruption to each node in the virtual network. In other words, it tries to minimize number of simultaneously failed connections significant to each node when the failure occurs.



a. Physical network b. Virtual network



a. Example of penalty function

Figure 1 Example network and penalty cost function

Given a virtual network, we wish to determine how to route lightpaths on the optical network such that the virtual network remains connected when a fiber optic link fails. In addition to maintain connectivity, we aim to reduce failure impact to each node in the virtual network by distributing connections significant to each node over different fiber links. We introduce a penalty function to realize the load distribution objective. A penalty function is developed on a concept of a set DP_i, i.e., consider each fiber cable, the penalty cost is a function of virtual connections in a set DP_i using the same fiber cable. Let $P(e, DP_i)$ be a penalty function. Consider a fiber cable e and a node i where $e \in E$, $i \in N_v$.

$$P(e, DP_i) = x^2$$

where x is the number of virtual connections in DP_i that transverse the fiber cable e.

We use a polynomial function degree two in the penalty cost function because we want to increase degree of penalty with the number of connections in DP_i that use the same physical links. For example, from figure 1b, if only $r1$ passes link e, $P(e, DP_3)$= 1. If $r1$ and $r2$ pass like e, $P(e, DP_3)$ = 4. If $r1$, $r2$ and $r3$ pass link e, $P(e, DP_3)$ = 9. Another example is illustrated in figure 1c. The penalty cost incurs on this link is $3^2 + 2^2$. There are five connections using this link. Three of them are connections significant to node 1 and two of them are significant to node 5, resulting in a penalty cost of 3^2 and 2^2, respectively.

The LD-SLR problem can be formally states as shown in figure 2.

Figure 2 LD-SLR formulation

Indices:

$p = 1, 2, \ldots, \vert P_l \vert$	eligible paths for a virtual connection l
$e = 1, 2, \ldots, \vert E \vert$	physical fiber links
$l = 1, 2, \ldots, \vert L \vert$	virtual connections
$i = 1, 2, \ldots, \vert N \vert$	nodes in the physical network

Variables:

$f^{l,p}$	1 if a virtual connection l uses path p, $p \in P_l$, $l \in L$; 0 otherwise

Constants:

c_e	cost of using a physical link e (for simplicity we assume $c_e = 1$)
$\delta_e^{l,p}$	1 if path p for a virtual connection l passes link e, $p \in P_l$, $e \in E$; 0 otherwise

Objective:

$$Min \quad \sum_{l \in L} \sum_{p \in P_l} \sum_{e \in p} c_e \delta_e^{l,p} f^{l,p} + \sum_{e \in E} \sum_{i \in N_v} P(e, DP_i)$$

Constraints:

$$(1) \quad \sum_{p \in P_l} f^{l,p} = 1, \forall\, l \in L$$

$$(2) \quad \sum_{l \in CS(S, N_v - S)} \sum_{p \in P_l} \delta_e^{l,p} f^{l,p} < \left| CS(S, N_v - S) \right|, \forall e \in E, \forall S \subset N_v$$

$$(3) \quad \sum_{l \in L} \sum_{p \in P_l} \delta_e^{l,p} f^{l,p} \le W_e, \forall e \in E$$

In LD-SLR, the objective is to minimize the cost of the lightpath routing for a specified OVPN. The cost comprises of two components: the use of optical links and the penalty cost for load distribution. Constraint (1) is a fundamental flow conservation constraint in the network flow problem [13]. It assures that only one path from the pre-computed path set is selected for each virtual connection. Constraint (2) is adopted from [12]. It guarantees survivability (connectivity) of the virtual network in the event of a single fiber cut. It assures that all connections in a cutset of the virtual network do not transverse the same physical link. Note that a terminology $CS(S, N_v\text{-}S)$ in the constraint (2) represents a cutset which contains a set of virtual connections whose one endpoint is in a set of nodes S and the other endpoint is in a set of nodes $N_v\text{-}S$. [12]. $|CS(S, N_v\text{-}S)|$ equal the number of connections in the cutset. Finally, constraint (3) limits the fiber optic capacity. It specifies the number of wavelengths, W_e, available in the fiber cable.

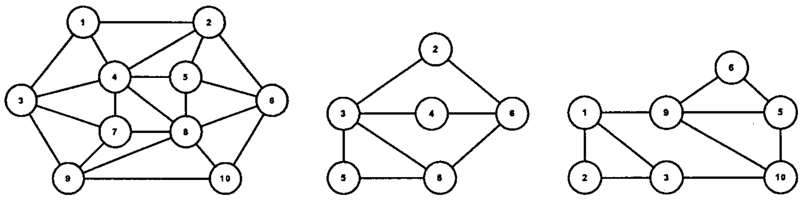
The LD-SLR problem is coded in AMPL and solved with CPLEX software package. In order to use penalty cost, which is a nonlinear function, we transform the nonlinear term into piecewise linear function. The routing results are illustrated in the next section.

3. Experimental Results

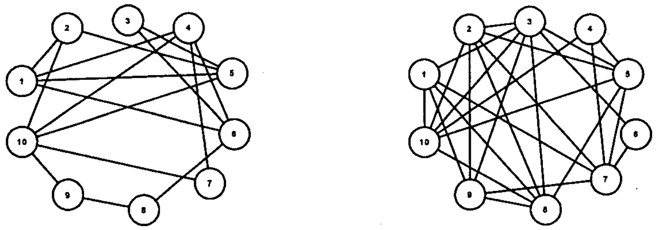
We conduct design experiments on various virtual network topologies ranging from sparse to dense networks. A physical network topology is depicted in figure 3a. The virtual network topologies are randomly generated. The sparse virtual network (figure 3b) is established across six nodes using eight lightpaths (virtual connections). Another sparse virtual network (figure 3c) is built across seven nodes using ten lightpaths. The rather dense virtual network (figure 3d) is built over ten nodes with 16 lightpaths. Finally, the denser virtual network (figure 3e) is built over ten nodes with 26 lightpaths.

We compare the lightpath routing results using LD-SLR against the results using SPR and SLR. Figure 4 illustrates the lightpath routing for the sparse virtual network in figure 3b. SPR yields the lightpath routing as depicted in figure 4a where the connectivity of the virtual network will not maintain if the fiber cable 3-4 fails. Figure 4b and 4c show the routing results using SLR and LD-SLR, respectively. The later two routing models yield the routing that will remain connectivity of the virtual network for any case of a single physical link failure. In addition to maintain connectivity, the LD-SLR further mitigates the impact from the failure by distributing lightpath through different fiber cables as shown in figure 4c where the routing of the connection 3-2 transverses path 3-1-2 instead of path 3-4-2. As a result, when the fiber cable 3-4 fails, the number of simultaneously failed connections would be less compared to those results using SLR.

The lightpath routing for another sparse virtual network (figure 3c) is presented in table 1. SPR yields the lightpath routing, which does not maintain connectivity of the virtual network when the fiber cable 1-2 or 1-3 fails. However, SLR and LD-SLR yield the routing of the virtual network that will remain connected in any case of a single physical link failure. Again, the LD-SLR further enhances survivability of the OVPN by diverting the lightpath through different routes. Consider the dense virtual networks in figure 3d and 3e. SLR and SPR yield the same routing results. The reason is that when the virtual network is dense, the lightpaths tend to spread widely across the physical network. This reduces a chance that the virtual network will be disconnected in case of a single physical fiber cut. However it might happen that many lightpaths concentrate on the same fiber cable where the failure of this cable would severely impact the communication services of the virtual network. The LD-SLR mitigates this impact by spreading lightpaths onto different fiber links. Table 2 presents the lightpath routing by SLR compared to those results from LD-SLR.

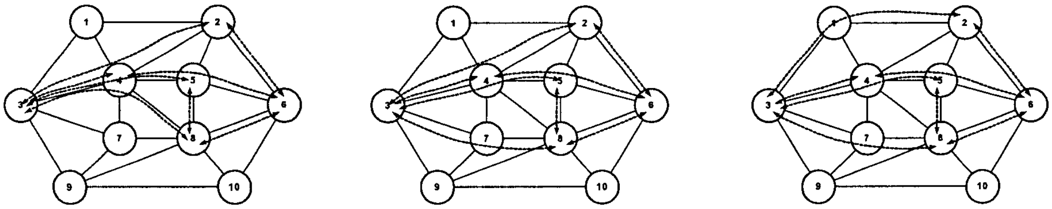


a. Physical network of 10 nodes, 21 links
b. Virtual network of 6 nodes, 8 connections
c. Virtual network of 7 nodes, 10 connections



d. Virtual network of 10 nodes, 16 connections
e. Virtual network of 10 nodes, 26 connections

Figure 3 A physical network and different virtual networks used in the experimental design



a. Lightpath routing using SPR
b. Lightpath routing using SLR
c. Lightpath routing using LD-SLR

Figure 4 Example of the lightpath layout for a sparse virtual network in figure 3b

Table 1 Lightpath routing for the sparse virtual network (Figure 3c)

Virtual connection Between node pair (i, j)	SPR design	SLR design	LD-SLR design
(1,2)	1-2	1-2	1-2
(1,3)	1-3	1-3	1-3
(1,9)	1-3-9	**1-4-7-9**	**1-4-7-9**
(2,3)	2-1-3	**2-4-3**	**2-4-3**
(3,10)	3-9-10	3-9-10	3-9-10
(5,6)	5-6	5-6	5-6
(5,9)	5-8-9	5-8-9	**5-4-3-9**
(5,10)	5-6-10	5-6-10	**5-8-10**
(6,9)	6-8-9	6-8-9	6-8-9
(9,10)	9-10	9-10	9-10

Table 2 Lightpath routing for the dense virtual networks

Virtual network	Virtual connection Between node pair (i, j)	SPR and SLR design	LD-SLR design
Rather dense virtual network (Figure 3d)	(1,5)	1-2-5	1-4-5
	(3,6)	3-1-2-6	3-9-10-6
	(4,6)	4-2-6	4-5-6
	(7,10)	7-8-10	7-9-10
Dense virtual network (Figure 3e)	(2,8)	2-4-8	2-6-8
	(2,9)	2-1-3-9	2-6-10-9
	(3,8)	3-4-8	3-7-8
	(5,7)	5-4-7	5-8-7

4. Conclusion

Service reliability is one of the important requirements in the OVPN services. In this paper, we consider the survivable lightpath routing problem for the OVPN design. We propose a mathematical formulation for an efficient lightpath routing called ***Load Distribution-Survivable Lightpath Routing (LD-SLR)***. We incorporate survivability concern in our routing model to further mitigate impact of a single fiber failure. The experimental results show that our routing formulation offers higher survivable degree to the OVPN services compared to other lightpath routing in literature. In addition, our results illustrate that the LD-SLR can effectively design various virtual networks ranging from sparse to dense virtual network topologies.

5. References

[1] Benjamin, D., Trudel, R., and Shew, S., "Optical services over the intelligent optical network," *IEEE Communication Magazine*, vol. 39, no. 9, pp. 73-78, Sept.2001.

[2] *http://optical-networks.com* 2001.

[3] Ould-Brahim, H. and Rekhter, Y., "BGP/ GMPLS optical VPNs," *PPVPN Working Group Internet Draft, work in progress*, July2001.

[4] Ould-Brahim, H. and Rekhter, Y., "Service requirements for Optical Virtual Private Networks," *PPVPN Working Group Internet Draft, work in progress*, July2001.

[5] Zang, H., Jue, J. P., and Mukherjee, B., "A review of routing and wavelength assignment approaches fro wavelength-routed optical WDM network," *Optical Networks Magazine*, vol. 1, no. 1, pp. 47-60, Jan.2000.

[6] Lee, K. C. and Li, V. O. K., "A wavelength rerouting algorithm in wide-area-all-optical networks," *Journal of Lightwave Technology*, vol. 14 pp. 1218-1229, 1996.

[7] Mohan, G. and Murthy, C. S. R., "A time optimal wavelength rerouting algorithm for dynamic traffic in WDM networks," *Journal of Lightwave Technology*, vol. 17 pp. 406-417, 1999.

[8] Banerjee, A. and Mukherjee, B., "A practical approach for routing and wavelength assignment in large wavelength routed optical networks," *IEEE Journal on Seclected Areas of Communications*, vol. 14, no. 5, pp. 903-908, June1996.

[9] Zhang, Z., Fu, J., Guo, D., and Zhang, L., "Lightpath routing for intelligent optical networks," *IEEE Network*, vol. 15, no. 4, pp. 28-35, Aug.2001.

[10] Gerstel, O. and Ramaswami, R., "Optical layer survivability: A services perspective," *IEEE Communication Magazine*, vol. 38, no. 3, pp. 104-113, Mar.2000.

[11] Crochat, O., Le Boudec, J. Y., and Gerstel, O. N., "Protection interoperability for WDM optical networks," *Ieee-Acm Transactions on Networking*, vol. 8, no. 3, pp. 384-395, June2000.

[12] Modiano, E. and Narula-Tam, A., "Survivable routing of logical topologies in WDM networks," *INFOCOM 2001, IEEE Proceeding*, vol. 1 pp. 348-357, 2001.

[13] Ahuja, R. K., Magnanti, T. L., and Orlin, J. B., *Network flows: Theory, algorithms, and applications* Upper Saddle River, New Jersey: Prentice-Hall, 1993.