Paper

Guaranteed Protection in Survivable WDM Mesh Networks – New ILP Formulations for Link Protection and Path Protection

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Abstract—In this paper we propose new simple integer linear programs (ILPs) formulations for minimizing capacity (in wavelength link) utilization in survivable WDM network. The study examines the performance of shared based protection schemes, such as path protection scheme and link protection scheme under single fiber failure. The numerical results obtained show a reduction in capacity utilization using random traffic compared to the reported ILP formulation. We also present the results using Poisson's traffic to identify the frequently used links for the widely used NSF network. The proposed work not only reduces the wavelength consumption in different traffic scenarios but also efficient in terms of simulation time.

Keywords—Lightpath, Protection, RWA, Survivability, WDM network.

1. Introduction

Wavelength-division-multiplexing (WDM) is a well established technology used in optical network that allows to support high bandwidth application such as HDTV, video conferencing etc. A connection is realized by a lightpath in WDM networks. Efficient routing and wavelength assignment (RWA) algorithms are needed in such networks to enhance the network throughput [1]–[3]. Integer programming solves the above sub-problems (routing and wavelength assignment) simultaneously irrespective of the traffic patterns, such as static or dynamic. In case of static traffic, connections are known in advance and the objective is to minimize the usage of network resources such as, wavelength utilization for a certain number of connections. Whereas in the case of dynamic traffic, connection request comes in random fashion one after another. Since enormous amount of data flows through the optical networks, it is desirable that the network has to provide service in the course of network failure, particularly fiber cut. In order to continue service in the event of failure, protection and restoration techniques are used while designing survivable WDM networks. To ensure network survivability, several techniques are realized by providing some additional capacity within the network. In protection scheme, backup resources (route and wavelength) are reserved during connection setup. On the other hand, in restoration scheme backup resources are computed dynamically for each interrupted connection. Restoration schemes are more efficient in terms of wavelength consumption as they do not reserve wavelengths in advance. Network resources can be dedicated (1+1) protection or shared based (1:N) protection. Shared based schemes offer better capacity utilization at the same time, dedicated based schemes offered better switching time [4], [5].

Survivable WDM optical networks have been exploring new design and optimization techniques. A variety of solutions have been proposed by researchers and the methods are broadly classified into two groups: heuristic method and exact methods (such as ILPs). Heuristic methods provide sub-optimal solutions and require low computational effort. On the other hand exact methods are much more computationally intensive and do not scale well with the network size. However, since the exact methods are able to provide absolute optimal solution it can be used as a direct planning tool or as a standard to validate and test the heuristic methods. The proposed work concerns exact methods to plan and optimize wavelength utilization in survivable WDM networks. In particular we focus on ILP, a widespread technique to solve exact optimization problem.

Previous work. In WDM networks, flow of different commodities corresponds to different lightpaths to be established between the nodes in the network. ILP formulations are presented in [2] for maximizing network throughput hence minimizing blocking probability. The author proposed RWA algorithms and evaluate the performance of the algorithms using uniform and non-uniform traffic patterns. A review on fault management in WDM mesh networks is presented in [6]. The author reviewed various fault management techniques involved in deploying a survivable optical mesh network. Integer linear program formulations are presented in [7] to allocate working and spare capacity in a WDM survivable network. The author considered symmetrical arc-capacity and presented ILP formulations for capacity allocation. Both node-arc and arc-path version of capacity allocation models are presented. In [8] ILP based survivable algorithms are investigated for WDM mesh networks. The author focuses on protection and restoration schemes to calculate capacity utilization and switching time for survivable schemes such as, dedicated-path, shared-path, and shared-link protection. Restorable survivable network design with static traffic demands is also reported in [4], [9], [10]. Survivable network design is reported in [11], the author propose new routing strategies under single fiber cut scenario so that the virtual topology remains connected. Link restoration in distributed real-time environment, is reported in [12]. The objective is to find spare-capacity consumption, with restricted hop-limits on restoration routes, which are still efficient in terms of utilization of spare resources. The ILP formulation is solved both for mesh and ring topologies. Interesting routing algorithms, network flow problems with optimization techniques are available in [13], [14]. A different version of this work appeared in [15]. Earlier we have reported protection switching time for shared path and shared link protection schemes [16].

Traditional WDM transmission system consists of two fibers and two transceivers, one for forward traffic and other for backward traffic. This is called simplex transmission system. Significant cost savings is possible with so called bi-directional transmission using WDM technology where individual wavelengths used for each direction. In such case linking two nodes will involve only one fiber and this is called full-duplex transmission system. Keeping this thing in mind we have formulated ILPs to realize full-duplex survivable WDM transmission system.

In this study we examine different approaches to protect a mesh-based WDM optical network from single fiber failures. These approaches are based on two basic survivability paradigms: 1) path protection and 2) link protection. The summary of the work is as follows:

- New ILP formulations are developed which can provide optimal solution with less simulation time.
- The ILP formulations are developed for realizing shared path protection (SPP) and shared link protection (SLP) schemes against single fiber failure.
- Joint optimization technique is also developed (minimizing primary and backup capacity altogether) to minimize wavelength utilization for SPP scheme.
- To identify the links often used (frequently used/critical links) in the network by applying multiple traffic matrices as data inputs.

The proposed formulations for minimizing the wavelength utilization for a given number of connections request similar to [7], in addition to the wavelength continuity constraint. We have calculated the number of wavelength links utilized assuming random traffic demand. The results obtained are compared with the results obtained using the reported ILP formulations in [8]. Simulations are also carried out by using several traffic patterns to identify the frequently used links in NSF network. The reported ILPs and the proposed ILPs have been simulated in same environment. The rest of the paper is organized as follows. Section 2 presents mathematical models for the working capacity and the spare capacity utilization models for SLP and SPP schemes. In Section 3 we have discussed the simulation setup and the numerical results obtained and the conclusion of the work is given in Section 4.

2. Mathematical Model for Capacity Allocation

In this section, we present the ILP formulation of shared-path protection and shared-link protection scheme to protect WDM network against single fiber failure. In particular we need to calculate number of wavelength links utilized in the above two schemes in survivable WDM networks. Simulations are carried out by using two different kinds of traffic scenario, i.e., random traffic and Poison's distributed multiple traffic matrices. Multiple traffic matrices are used to find the average link utilization. The results obtained using the above schemes are compared to evaluate the performance of the ILPs. Wavelength utilization for a given connection is the sum of the wavelength channels required to establish the primary lightpath and the backup lightpath. The proposed ILP models are solved using CPLEX.

Sets and parameters:

N – set of nodes,
L – set of links,
WP – number of wavelengths used for primary paths,
WB – number of wavelengths used for backup paths,
W – number of wavelengths on each fiber link, $W = (WP + WB)$,
d_{ij} – number of requested connections between node pair i and j, where i and $j \in N$,
D – set of demand pairs $(i, j) \in D$ implies that $d_{ij} > 0$,
P_{ij} – set of paths between node pair i and j, $\forall (i, j) \in D$,
R – set of all paths,
w_p – index of wavelengths used for primary paths,
w_b – index of wavelengths used for backup paths,
A_{ij} – set of paths used link (i, j) directed from i to j,
Z_{st} – set of all paths from 's' to 't' except the direct link (s,t),
V_{ij}^{st} – set of directed paths accessible for restoration from i to j when (s,t) fail,
$\widetilde{V}_{ij}^{st}$ – set of directed paths not accessible for restoration from i to j when (s,t) fail.

Variables:

w_{ij} – working capacity on link (i, j),
s_{ij} – spare capacity on link (i, j),
x_{pw_p} – 1 if lightpath p exists with wavelength w_p , 0 otherwise,
$y_{pw_p}^{st}$ – 1 if lightpath exists on path p with wavelength w_b, when link (s,t) fail, 0 otherwise.

2.1. Working Capacity Allocation Model

The ILP model for allocating working capacity or establishing primary path and assigning a wavelength without survivable provision is presented below. In our model, we consider communication can be made in both directions. Link (i,j) in our model means a fiber link between node i and node j. If a lightpath use link (i,j) and another lightpath use link (j,i) we consider, capacity consumption on link (i,j) is 2, of course with different wavelengths. Instead of considering all possible paths between a pair of nodes, we have restricted the number of hops so as to provide three to four paths between every pair of nodes.

Minimize $\sum\limits_{(i,j)\in L} w_{ij}$.

Wavelength continuity: $\forall(i,j)\in L,\ 1\leq w_p\leq WP$

$$\sum_{p\in A_{ij}} x_{pw_p}+\sum_{p\in A_{ji}} x_{pw_p}\leq 1\,. \tag{1}$$

Demand between node pair: $\forall(i,j)\in D$

$$\sum_{p\in P_{ij}}\sum_{w_p=1}^{WP} x_{pw_p}=d_{ij}\,. \tag{2}$$

Working link capacity: $\forall(i,j)\in L$

$$\sum_{p\in A_{ij}}\sum_{w_p=1}^{WP} x_{pw_p}+\sum_{p\in A_{ji}}\sum_{w_p=1}^{WP} x_{pw_p}\leq w_{ij}\,, \tag{3}$$

$$w_{ij}\geq 0 (i,j)\in L\,, \tag{4}$$

$$x_{pw_p}=\{1,0\}\quad p\in R,\ \ 1\leq w_p\leq WP\,. \tag{5}$$

Equation (1) ensure that no two lightpaths passes through the link (i,j) has same wavelength. Equation (2) ensure that the number of connection between node pair (i,j) must be equal to the sum of lightpaths within P_{ij} with different wavelengths. Equation (3) says about the number of lightpaths passes through link (i,j) or (j,i). Equations (4) and (5) ensures non negative and binary variables respectively.

2.2. Spare Capacity Allocation Model

WDM networks are meant for high bandwidth applications; hence, fiber cut leads to loss of huge data as well as revenue. To provide a certain quality of service (QoS) to users, we need to guarantee the service in the event of fiber failure. Here we present mathematical models to calculate spare network resources such as, spare wavelengths need to reserve in the event of fiber failure. Since probability of multiple fiber failure is rare, we assume single link failure in our models. Out of the number of protection strategies available [1], [6], we consider shared based protection schemes as a counter part to dedicated based protection schemes. Though the later strategies provide better switching time [8], [16], it consumes high network resources. Shared protection schemes can be implemented in three ways [6]: link protection, path protection and subpath protection. In link protection backup route is discovered around the failed link, whereas, in path protection backup path is discovered from source to destination for any failed link on the primary lightpath. In subpath protection, when a link failure occurred, the upstream nodes of the failed link detect the failure and discover a backup route from itself to the corresponding destination node for each disrupted connection. Link protection and path protection schemes are discussed below.

2.2.1. Shared Link Protection (SLP)

In link based protection, we assumed that each node is capable to detect a link failure and run a rerouting algorithm around the failed link. The traffic is rerouted only around the failed link. In this strategy for calculating backup capacity we should have knowledge about the working capacity or the number of primary lightpaths passes through any link. This is being calculated from the method described before from working capacity allocation model. When any link (i,j) fails, node i looks for searching restoration path for each lightpaths that passes through link (i,j) around (i,j). The ILP model can be written mathematically as follows.

Minimize $\sum\limits_{(i,j)\in L}(w_{ij}+s_{ij})$.

Wavelength continuity for the backup lightpaths: $\forall(i,j)\in L$, $1\leq w_b\leq WB$

$$\sum_{p\in A_{ij}} x_{pw_b}+\sum_{p\in A_{ji}} x_{pw_b}\leq 1. \tag{6}$$

Lost link capacity: $\forall(s,t)\in L$

$$\sum_{p\in Z_{st}}\sum_{w_b=1}^{WB} y^{st}_{sw_b}=w_{st}\,. \tag{7}$$

Spare link capacity: $\forall(s,t)\in L$, $(i,j)\in L\backslash(s,t)$

$$\sum_{p\in A_{ij}}\sum_{w_b=1}^{WB} y^{st}_{pw_b}+\sum_{p\in A_{ij}}\sum_{w_b=1}^{WB} y^{st}_{pw_b}=s_{ij}\,. \tag{8}$$

Fiber capacity limit: $\forall(i,j)\in L$

$$w_{ij}+s_{ij}\leq W\,, \tag{9}$$

$$s_{ij}\geq 0 (i,j)\in L\,, \tag{10}$$

$$y^{st}_{pw_b}=\{1,0\}\ \forall(s,t)\in L,\ \forall_p\in R,\ \ 1\leq w_b\leq WB\,. \tag{11}$$

Where w_{ij} may be calculated from the working capacity model. Equation (6) ensures that no two backup lightpaths can have same wavelength traversing in a link. Equation (7) ensure that the number of lightpaths affected due to failure of fiber link (s,t) where $\forall(s,t)\in L$. The affected lightpaths must be rerouted through all the paths from s to t except the failed link (s,t) with the available backup wavelengths. Equation (8) ensure that the sum of backup lightpaths passes through link (i,j) and (j,i) must be less than the total number of backup lightpaths. Equation (9) ensures that the sum of the primary lightpaths and the backup lightpaths on any link is limited to the number of wavelengths available on the fiber link. In our work we have considered homogeneous network, i.e., all the fiber links have the same number of wavelengths. Equations (10) and (11) ensure non-negative and binary variables.

2.2.2. Shared Path Protection (SPP)

Failure of a link affects all the primary lightpaths that passes through it. Upon link failure the nodes adjacent to the failed link sends a link fail message to source and destination nodes of all the lightpaths that traverse through it. The wavelengths occupied by the primary lightpaths that traverse through the failed link may be freed. Therefore, path protection scheme consume less spare resources compared to link protection scheme and is verified from Fig. 1 and 2. The ILP model for path protection may be written mathematically as follows.

Minimize $\sum_{(i,j)\in L} (w_{ij} + s_{ij})$.

Wavelength continuity for the backup lightpaths: $\forall (i,j) \in L$, $1 \le w_b \le WB$

$$\sum_{p\in A_{ij}} x_{pw_b} + \sum_{p\in A_{ji}} x_{pw_b} \le 1\,. \qquad (12)$$

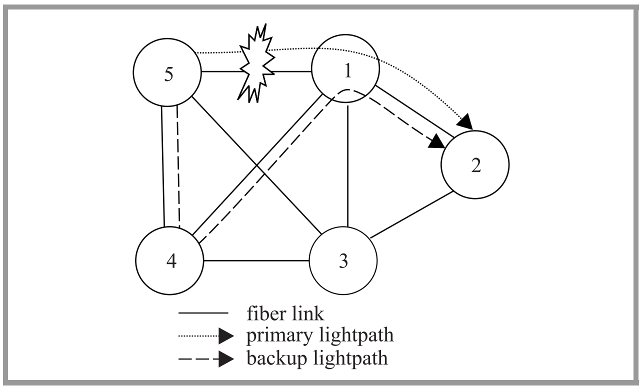

Fig. 1. Link restorration.

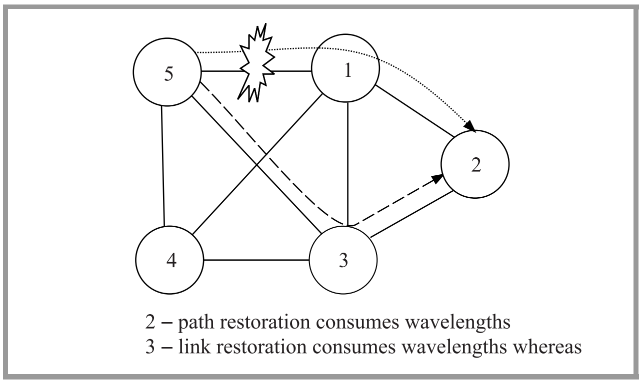

Fig. 2. Path restoration.

Spare link capacity: $\forall (s,t) \in L$, $(i,j) \in L \backslash (s,t)$

$$\sum_{p\in A_{ij}} \sum_{w_b=1}^{WB} y^{st}_{pw_b} + \sum_{p\in A_{ij}} \sum_{w_b=1}^{WB} y^{st}_{pw_b} \le s_{ij}\,. \qquad (13)$$

Lost capacity in forward direction: $\forall (s,t) \in L$, $\forall (i,j) \in D$

$$\sum_{p\in v^{st}_{ij}} y^{st}_{pw_b} \sum_{p\in \widetilde{v}^{st}_{ij}} x_{pw_p} \;\; 1 \le w_p \le WP, \;\; 1 \le w_b \le WB\,. \qquad (14)$$

Lost capacity in reverse direction: $\forall (s,t) \in L$, $\forall (i,j) \in D$

$$\sum_{p\in v^{st}_{ji}} y^{st}_{pw_b} \sum_{p\in \widetilde{v}^{st}_{ji}} x_{pw_p} \;\; 1 \le w_p \le WP, \;\; 1 \le w_b \le WB\,. \qquad (15)$$

Fiber capacity limit: $\forall (i,j) \in L$

$$w_{ij} + s_{ij} \le W\,, \qquad (16)$$

$$s_{ij} \ge 0\,(i,j) \in L\,, \qquad (17)$$

$$y^{st}_{pw_b} = \{1,0\}\; \forall (s,t) \in L, \;\; \forall p \in R, \;\; 1 \le w_b \le WB\,. \qquad (18)$$

Where w_{ij} may be calculated from working capacity model explained before. Equation (12) ensures that no two backup lightpaths can have same wavelength traversing in a link. Equation (13) ensure that the sum of backup lightpaths passes through link (i,j) and (j,i) must be less than the total number of backup lightpaths. Equation (14) and (15) ensures that the number of lightpaths affected from (i,j) and (j,i) respectively when link (s,t) fails. Equation (16) ensures that the sum of primary lightpaths and backup lightpaths on any link is limited to the number of wavelengths available on that fiber link. Equations (17) and (18) ensure non negative and binary variables.

2.2.3. Joint Model for Shared Path Protection

In joint mode instead of calculating working and spare capacity separately the combined working and backup capacity is minimized jointly.

Minimize $\sum_{(i,j)\in L} (w_{ij} + s_{ij})$.

Equations (1)–(5) and Eqs. (12)–(18).

3. Results and Discussion

In this section, we present the details of our proposed models implemented in AMPL language with CPLEX 10.2 to solve the ILPs for simulation. Primary and backup lightpaths are established for link protection and path protection schemes. We focus our work on single fiber cut, which is the predominant form of failures in WDM networks. Backup lightpaths are derived for the above schemes under single link failure assumption. Models presented in this paper runs for 500 different traffic matrixes, which are generated, using Poissons process, then percentage link utilization is presented for different links in the entire network in graphical manner. We assume that, wavelength converters are not available at the network nodes; hence the connection between the source and the destination is established with a single wavelength throughout the path it traverses. *k*-shortest path algorithm is implemented using C language to generate three successive shortest paths between origin-destination pairs. Simulations are carried out assuming 32 wavelengths in each link in both directions on NSF Net [5] having 14 nodes, shown in Fig. 3. First number in the brackets adjacent to the links represents kth link and second number represents the corresponding link weight. The results are obtained by taking 276 paths in the network among the node pairs and the number of connections varies from 64 to 118 connections in the entire networks.

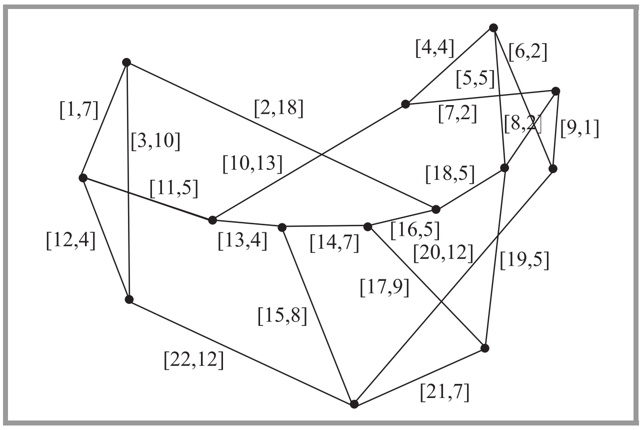

Fig. 3. NSF Net (14 Node).

Table 1

Wavelength utilization using SLP scheme for random demand/connections for NSF Net with 32 wavelengths

Demand/ connections	Wavelengths utilization reported SLP scheme	Wavelengths utilization proposed SLP scheme
40	213	149
45	243	181
50	266	193
55	309	211
60	339	230
65	353	249

Table 2

Wavelength utilization using SPP scheme for random demand/connections for NSF Net with 32 wavelengths

Demand/ connections	Wavelengths utilization reported SLP scheme	Wavelengths utilization proposed SLP scheme
40	142	130
45	162	150
50	177	159
55	218	180
60	214	196
65	229	211

We have tabulated the results obtained for the proposed ILPs for SLP and SPP model in Table 1 and 2 respectively. The first column represents the number of connections for the random demand matrix. The second column represents the wavelength links consumption for the existing ILPs [8] and the third column represents the wavelength links consumption for the proposed ILPs. The results for the existing ILPs presented here are obtained in 12 hrs where as our method gives results less than 2 min of simulation times. The significant reduction in simulation time is achieved because in the existing ILP formulations, the wavelength of the primary lightpaths and the backup lightpaths is unchanged. On the other hand they are different in the proposed models. Though it is required to be same in before and failure, we believe that, when it is required to calculate the wavelength/capacity consumption for certain number of connections then the proposed model is much better than the available ILPs. A comparative result for wavelength links consumption is also presented in Table 3 among the proposed SLP, SPP and joint formulation for SPP schemes. It has been observed from the Table 3 that the total capacity requirement is still reduced in case of joint formulation at the cost of higher working capacity and simulation time.

Table 3

Wavelength utilization among SLP, SPP and JMSPP schemes with random demand/connections for NSF Net with 32 wavelengths

Connections	SLP scheme	SPP scheme	Joint model for SPP
40	149	130	125
45	181	150	146
50	193	159	158
55	211	180	177
60	230	196	190
65	249	211	206

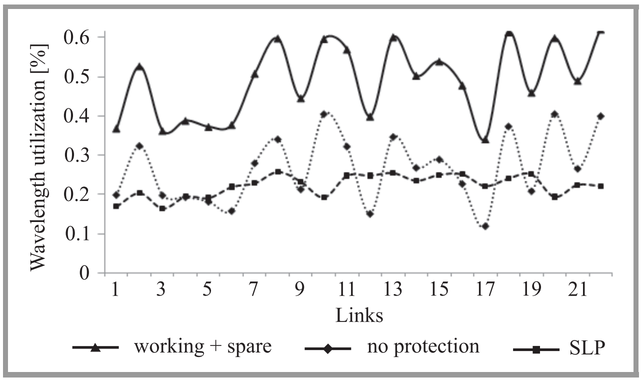

Fig. 4. Percentage of wavelength utilization in different links without and with protection (SLP).

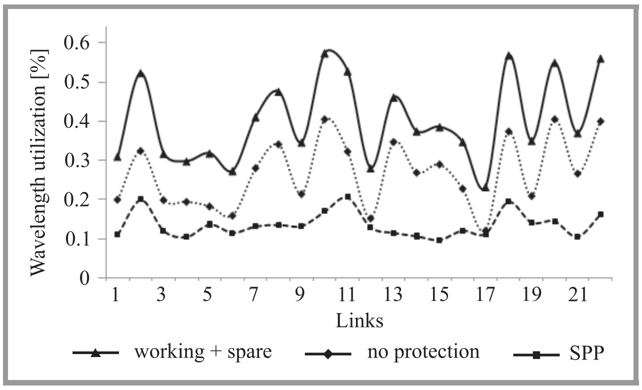

Fig. 5. Percentage of wavelength utilization in different links without and with protection (SPP) scheme.

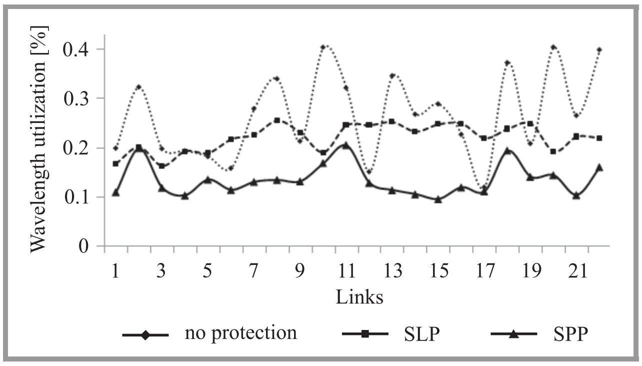

Fig. 6. Percentage of wavelength utilization in different links without and with protection (SLP and SPP) schemes.

For the second set of results, we present the percentage of wavelength link utilization in the existing infrastructure. Instead of random traffic (tabulated in Table 1, 2, and 3) we apply multiple traffic matrices (500) and then averaged to detect the fiber links which are used frequently for routing the lightpaths. SLP and SPP protection schemes comparison are presented in graphical manner in Figs. 4, 5 and 6. From the figures it is found that links numbered 10, 18, 20 and 22 are mostly used for lightpath routing. From Figs. 4 and 5 it is confirm that links numbered 8, 18, 20 and 22 are the links often used so as to provide guaranteed protection. From Fig. 6 indicates that the SPP scheme requires smaller amount of backup capacity (wavelength links) compared to SLP scheme.

4. Conclusions

Survivability is an essential and challenging issue in high speed networks. This work examine the wavelength requirement for guaranteed protection by taking path based and link based protection strategies in WDM networks. Wavelength utilization is considered in this paper which is an important network resource in such networks. The proposed models not only reduce the wavelength consumption in different traffic scenario but also efficient in terms of simulation time. The works also identify the crucial links in the network which is widely used. Further our investigations are in progress to develop efficient algorithms to reduce network capacity utilization at the same time network congestion, for survivable WDM mesh networks.

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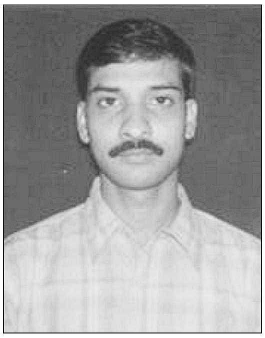

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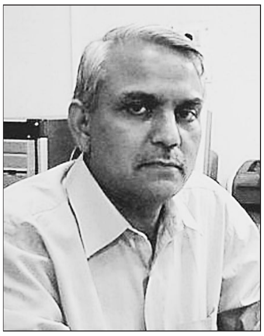

Sudarshan Tiwari received the B.Tech. degree in Electronics Engineering from I.T.BHU, Varanasi, India in 1976, the M.Tech. degree in Communication Engineering from the same institution in 1978 and Ph.D. degree in Electronics and Computer Engineering from IIT Roorkee, India in 1993. Presently, he is Professor and Head of Department of Electronics and Communication Engineering. Motilal Nehru National Institute of Technology (MNNIT), Allahabad, India. He has also worked as Dean Research and Consultancy of the institute from June 2006 till June 2008. He has more than 28 years of teaching and research experience in the area of communication engineering and networking. He has supervised a number of M.Tech. and Ph.D. thesis. He has served on the program committee of several seminars, workshops and conferences. He has worked as a reviewer for several conferences and journals both nationally and internationally. He has published over 78 research papers in different journals and conferences. He has served as a visiting professor at Liverpool John Moore's University, Liverpool, UK. He has completed several research projects sponsored by government of India. He is a life member of Institution of Engineers (India) and Indian society of Technical Education (India), he is a member of Institution of Electrical and Electronics Engineers (USA). His current research interest include, in the area of WDM optical networks, wireless ad hoc and sensor networks and next generation networks.

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