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Role of Edge Connectivity and Centrality Factors in Survivable Optical Network Design

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Abstract: Survivability in optical networks is the ability to maintain the connections intact against failures. Protecting an optical link is critical since a link failure may lead to huge amount of data loss. The network can be represented as a graph and the edge connectivity is an important parameter in measuring the fault tolerance capability of the network. The node centrality factor represents the significance of the node in a network. This paper combines both the link metric and node metric to investigate the impact of edge connectivity and node centrality factors on the survivability of optical networks. A heuristic approach has been developed in which these factors are incorporated in optical network protection with an objective to improve the recovery performance with minimum network cost incurred. Single link failures are attempted based on shared path protection. Three irregular meshed networks are compared in terms of loss of traffic and cost aspects. The cost factor includes the number of wavelengths used along with the node cost and link cost. The wavelength requirements for varying the number of shared paths are also evaluated. Simulation results demonstrate that the performance of the proposed approach provides better solutions than the existing methods on optical network protection.

Key words: Optical networks, network protection, topology, network cost, expected loss of traffic

INTRODUCTION

The optical networking technology has become a promising solution for high-data-rate communication over long distances. To transmit huge amounts of data in a quick and reliable way over long distances, optical networks are emerging as potential solution as standard TCP does not perform well in high-bandwidth environment (Wang *et al*., 2010). The transmission and routing/switching capabilities of optical networks will need to keep pace with the steadily growing Internet traffic (Saleh and Simmons, 2011). The design process of optical networks is critical to meet the design requirements while controlling the cost involved (Katrinis and Tzanakaki, 2011). In optical networks, the lightpaths have long duration and the cost to set up a lightpath is high when compared with the non-optical networks. It is quite unlikely for the service provider to reject a lightpath request due to the higher revenue it offers. Instead, it would be more appropriate to upgrade the network by the addition of more capacity on existing links to honor the new lightpath demands. Redirecting or preempting connections become undesirable as data loss per unit time is proportional to the network bandwidth. Therefore the dimensioning process should focus on assigning additional resources to the existing network without disturbing the existing framework.

In optical networks, the network topology has a significant impact on the resource requirements to accommodate the traffic demands. There is an extensive study made in the literature on the influence of topological parameters on resource requirements. The key topological parameters are node degree, its sub classes such as minimum and maximum node degree, average node degree, connectivity of the network and the mean intermodal distance. Another important measure of a topology is the centrality measures which describe a node's relative importance to the entire network. Any type of network architecture a network planner chooses to adapt, still it is an open question on where to locate the links and how to assign the capacity to the links. The right selection of the choices will greatly influence the cost of the network both in terms of capital and operational expenditures. Therefore, it is very important to analyze the association that relates these topological parameters with the resource requirements of the network.

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Since the dimensioning process involves with resource assignment at lower cost, the role of topological parameters in building an effective dimensioning process is to be investigated. A single link failure in optical networks will result in huge amount of data loss and hence, the survivability is of prime concern in optical networks. The foremost challenge in survivable optical networks is to efficiently allocate the network resources aiming at lessening the cost combined with improved survivability against failures. It is necessary to characterize networks and identify network topologies that minimize wavelength usage by relying on simple metrics. An important measure of the quality of a topology is the number of wavelengths required to establish the connection demands. The wavelength reuse factor of a network is measured in terms of the above mentioned factor (Marsan *et al*., 1993).

Extensive studies on topology of communication networks have been made in the literature (Hu, 1993; Albert *et al*., 1999). Other than the resource needs, even the effect of crosstalk in Ring and Mesh Topologies are investigated by the authors (Tan *et al*., 2007).

The factors that relate the physical connectivity of a network and wavelength usage are provided by Baroni and Bayvel (1997). It is shown by Fenger *et al*. (2002) that accuracy in the estimation of number of wavelengths is improved by using node degree variance and the number of spanning trees in the network. Chatelain *et al*. (2009) have shown that the algebraic connectivity provides the very accurate wavelength usage estimation. All these research work focused on the effect of topology on resource requirements in unprotected networks. The study on the effect of topologies on cost aspects in protected optical networks is still a nascent topic of research. The topology of a network can play a significant role in network survivability (Grover, 2003). As the information reliability is a becoming more and more important, the protection of fiber based networks becomes a crucial factor which is currently achieved by adopting redundant network equipments (Zhou *et al*., 2011). Early failure detection is very important to avoid huge loss of information in the event of damage on active optical links (Ab-Rahman *et al*., 2011a-c). Therefore, future optical networks need to be resilient (To and Neusy, 1994). Hence there is a need to explore the various metrics of network topologies further in network protection to yield a cost efficient solution. This paper proposes an approach in which the edge connectivity and node centrality parameters are considered in network protection to arrive at a cost effective result. This paper considers both the node and link metrics for protection of optical network and explores their impact on resource requirements.

PROBLEM FORMULATION

G = (N,L) is a graph that represents a network physical topology, where N is a set of nodes in the network and L is a set of fiber links (s, d) from node s to node d. Each fiber carries W wavelengths. The traffic matrix that specifies the connection demands between node pairs is Ts,d. The degree of a node is denoted as Δ. Fw represents the fiber pair F that carries W wavelengths. All connection demands are to be established and spare capacity has to be provisioned based on shared path protection scheme for single link failures. Two light paths in a same fiber must use distinct wavelengths. The wavelength continuity constraint is not considered here since the nodes are assumed to have full wavelength conversion capabilities.

Objective function: Let C_{NW} is the total network cost associated with both the node and link cost such as number of used wavelengths, ports, fiber pairs, regenerators and amplifiers. Then the objective is to minimize the total network cost C needed to honor the given number of connection demands.

$$C = \sum_{n \in N} Cn + \sum_{l \in L} Cl \quad (1)$$

PROTECTION BASED ON EDGE CONNECTIVITY AND CENTRALITY

In recent years, considerable attention has been given on the design of survivable optical networks (Zhang and Mukherjee, 2004). The protection strategies in optical networks can be broadly classified as 1+1 protection and shared path protection. Under 1+1 protection, the data is transmitted on both the working and protection paths. At the receiver side, the receiver can make a decision to accept a specific copy of data based on the quality of the signal. In shared path protection the protection path is shared by more than one working path and in the event of failure, the traffic is switched to the protection path. The capacity required of protection path can be reused to protect other connections resulting in better capacity utilization. The protection and restoration mechanisms may be link-based or path based (Ramamurthy and Mukherjee, 2003) and (Iraschko and Grover, 2000). In link-based schemes, upon a link failure, the affected connections are rerouted around the failed link. In path based schemes, each affected connection is reallocated to a backup route. The path-based schemes achieve higher capacity efficiency with easier implementations, while link-based schemes achieve shorter recovery time. The protection issues in optical

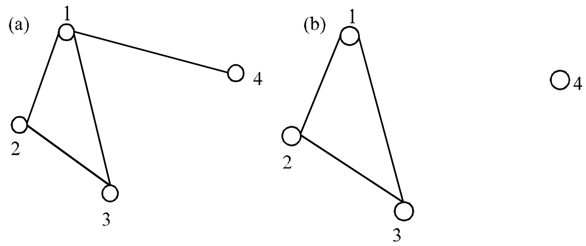

Fig. 1(a-b): Edge Connectivity, (a)Connected Graph and (b) Disconnected graph

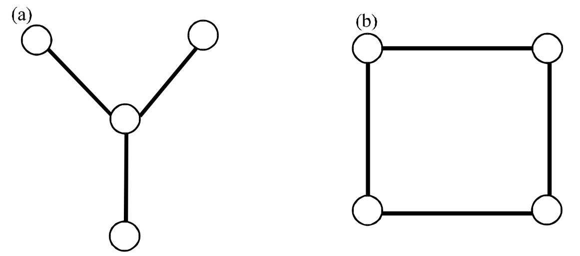

Fig. 2(a-b): Basic concept of centrality, (a) Centralization =1 and (b) Centralization =0

networks are analyzed in a wider perspective in the literature. The reliability and security enhancement issues are addressed in user controlled optical networks to address the network management challenges (Wu *et al*., 2007). Ab-Rahman *et al*. (2011a-c) introduced a hybrid restoration technique that enabled linear and ring configurations to be integrated in single optical network which can be activated according to the type and degree of failures. The authors have implemented a protection mechanism capable of diverting the signal onto protection line according to the failure conditions and fault locations in access network (Ab-Rahman *et al*., 2011a). A framework is presented by Qureshi *et al*. (2011) to construct shortest path tree with embedded backups for single link failure on any location in shortest path from source to destination.

Edge connectivity: The specific properties of networks can be analyzed by computing and comparing the local or global network parameters. The connectivity of a network is defined as:

$$\alpha = 2L/ [N (N-1)] \quad (2)$$

L is the set of links (edges) and N is the set of nodes. Another factor on connectivity is the edge connectivity which is the significant reliability criterion of the graph underlying a network (Weichenberg *et al*., 2004). The edge connectivity of a graph is the minimum number of edges whose removal disconnects the network. Fig. 1a shows a connected graph and when link 1-4 is removed the network is disconnected (Fig. 1b). Therefore the edge connectivity of this network is one.

The following bounds relate edge connectivity β and node connectivity β to the basic parameters of a graph (Harary, 1969). The relevance of these parameters in the reliability of the networks is examined in circulant family of graphs (Boesch and Wang, 1985) and Moore graphs, (Wilkov, 1972).

$$\chi \leq \beta \leq \delta \leq \eta = 2L/N \quad (3)$$

The mean node degree η is defined by the Eq. 4.

$$\eta = 1/N \sum_{i=1}^{N} \Delta i \quad (4)$$

The term Δ is the minimum degree of the graph and Δ is the degree of node. Since the edge connectivity is very much related to minimum and mean node degree, the node degree factor should also be considered with a note that the nodal degree influences the fiber length and capacity utilization of optical routed mesh networks (Hjebne, 1999). It is shown that the networks with average nodal degree varying between 3 and 4.5 are of particular interest (Coelho *et al*., 2002).

Centrality: In a network, the significance of a node is often associated with its degree or with centrality metrics which relate to its reachability and shortest paths passing through it. The centrality is a measure of a node's significance relative to the network functionality. Raaf and Messabih (2010) presented an approach to compute the betweenness centrality index on to predict the most influential event in elementary net systems. In general, centrality is 1 if the network has a star topology and 0 if all nodes have the same connectivity as illustrated by Fig. 2.While the term centrality can be classified based on degree, closeness and so on, this paper considers residue centrality which is calculated using the changes of the mean inter nodal distance under removal of node k with its links.

$$RD_K = |D\text{-}Drem, k| \quad (5)$$

$$D = \sum_i \sum_j Dij / N (N-1) \quad (6)$$

where, D is the mean inter nodal distance, with $D_{rem,k}$ represents the mean inter nodal distance after the removal of node k and corresponding links from the network.

The practical topologies usually have a minimum node degree $\delta \leq 2$ and the edge connectivity is bounded by this value. It is highly unlikely for all the edges incident to the node with minimum degree δ, fail simultaneously. Hence, the survivability factor can be improved by assigning additional capacity to the link that adjoins the node with minimum degree **δ** and one of the neighbor nodes of some significance. This neighbor node is selected based on its residue centrality, because it is the deciding factor on intermodal distance based on which the number of wavelengths, fiber pairs, ports and other equipments (terminal multiplexers, regenerators, optical amplifiers etc.,) are decided upon. Once this node (N_{DXmax}) is selected, it has to act as a sort of bridge that connects the node with minimum degree **δ** to the rest of the network. Therefore among the neighbor nodes of N_{DXmax}, the node with highest residue centrality (N_{DYmax}) with degree greater than the average node degree η is selected.

Additional fibers are assigned to two sets of links, (1) the link that adjoins the node with minimum degree **δ** and N_{DXmax} (2) the other that adjoins the node N_{DXmax} and the node N_{DYmax}. By doing this the availability of resources on these significant links is increased thereby providing more flexibility in calculating the protection paths. This concept is a form of hardware redundancy, so that the desired network performance can be maintained in the event of link failures. By assigning additional fibers only to the very significant links, the redundancy cost is reduced and at the same time, availability of shortest paths is also increased.

In the pseudocode, step 6 assigns the neighbor node of N_Δ with highest value of RD as N_{DXmax}. The step 8 considers the neighbor nodes Ny of N_{DXmax} except the node of origin N_Δ. Among Ny neighbor nodes, the node with highest residue centrality with degree greater than the average node degree is designated as N_{DYmax}. In step 16, the links that adjoin the nodes N_Δ, NX_{max} and N_{DYmax} are assigned with additional fibers compared to other links.

The Pseudo code of the Algorithm

```
G = (N, L)
j = Links j³L;
RD = Residue Centrality;
NΔ= Nodes with Minimum degree δ;
K = Number of Nodes with Minimum degree δ;
Fw = Number of Fibers with w wavelengths;
1.  for (NΔ = 1; NΔ = K; NΔ ++)
2.  {
3.        for ( all neighbors Nx of NΔ)
4.        {
5.                calculate RD;
6.                N_DXmax = N_X having RD [max];
7.        }
8.        for ( all neighbors Ny of N_DXmax , Ny≠NΔ)
9.        {
10.               if (ΔNy>η)
11.               {
12.                   calculate RD;
13.                 N_DYmax= N_Y having RD [max];
14.                   L_ΔD = Links that adjoin NΔ,
                      N_DXmax and N_DXmax , N_DYmax ;
15.                   if (j ª L_ΔD)
16.                   Fw = 2;
17.                   else
18.                   Fw = 1;
19.               }
20.       }
21. }
```

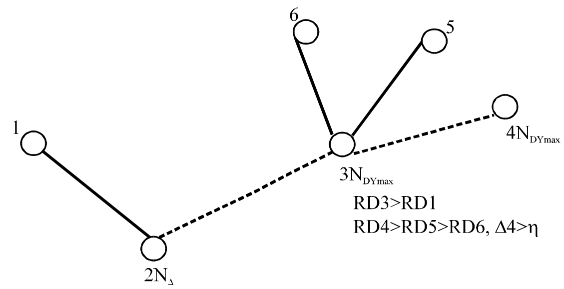

Fig. 3: Illustration of the proposed approach

Table 1: Topology information of networks

Network	Nodes	Links	Min. degree	Max. degree	Average node degree	α
NSFNET	14	21	2	4	3	0.23
NJLATA	11	23	2	8	4.18	0.42
Test NW	19	28	2	4	2.95	0.16

In the Fig. 3, the proposed method is explained briefly. The node 2 is N_Δ i.e., the node with minimum degree **δ**. Among the neighbor nodes 1 and 3, node 3 has higher residue centrality RD compared to node 1. Hence, node 3 is N_{DXmax}. Among the neighbor nodes of N_{DXmax}, the node 4 has the maximum residue centrality and the node degree greater than the average node degree η. Therefore the additional fibers are added to the links that adjoin the nodes 2-3 and nodes 3-4 as marked by the dotted lines. The links with additional fibers are identified based on their relative importance to the network since they greatly affect the performance of the network both in terms of survivability and handling the traffic demand growth. The possibility of all neighbor nodes of N_Δ to be the nodes with minimum node degree is highly unlikely in mesh networks and is not considered in this study.

PERFORMANCE EVALUATION

Two well known practical networks NSFNET, NJLATA and a TEST network specified (Ramaswami and Sivarajan, 2004) are taken for simulation purposes (Fig. 4). These networks are selected as their key topological parameters are distinctly different from each other. The connection requests are created randomly. The topology specifications of the networks are displayed in Table 1. Full wavelength conversion is assumed for each node in the network. Each fiber carries 40 wavelengths. Routing is done based on the inverse value of number of free wavelengths available on a link. In order to have a fair comparison, all the three networks are tested for the same

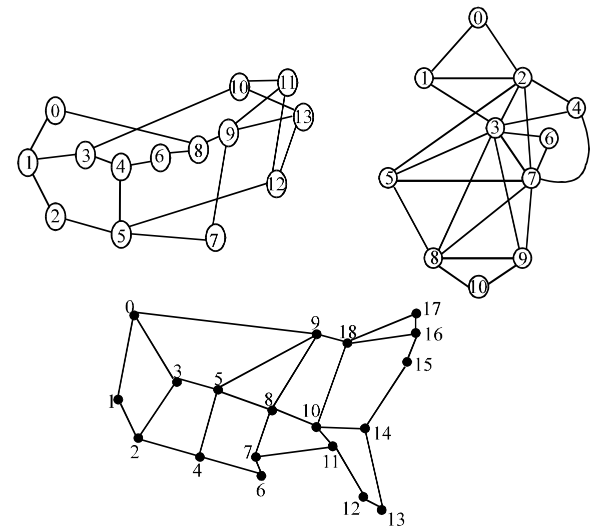

Fig. 4: Networks under study

number of connection demands which is set to 500. Traffic grooming is not considered as each demand is assumed for full wavelength. The connections honored remain active and new connection requests are accommodated by dimensioning the wavelength capacity. The shared path protection is used with 1:10 ratio carried out on link disjoint basis. This paper explores the impact of individual link failure on network performance. Instead of generating random failures, defined failures are generated i.e., the impact of all possible single link failures on network performance is studied and the average value is considered. A single link is failed at a time. The network is returned to pre-failure state before the next link failure is attempted. The expected loss of traffic in Gb/Year is calculated as:

$$E_{XL}=[(1-A)OC\text{-}N\times 24(hr/day)\times 365(days/yr)]\times [N\times 0.05184(Gb/OC\text{-}48)\times 3600(sec/h)] \quad (7)$$

A is availability and OC-N represents optical carrier with N data rate. The capacity of an OC-1 frame is equal to 51.84 Mbps. The value of N considered in this paper is OC-48 which accounts to 2.488 Gb sec^{-1}.

The average expected loss of traffic for single link failures for the three networks is shown in Fig. 5. This value is calculated as:

$$Loss = \frac{\Sigma E_{XL}}{(L\times T)} \quad (8)$$

Where:
T = Total No. of connection demands
L = No. of links in the network

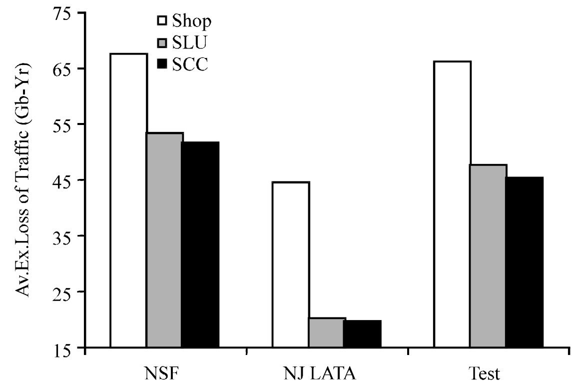

Fig. 5: Average expected loss of traffic for the three networks

Table 2: Average availability for link failures

	SHOP	SLU	SCC
NSF	0.9999818226	0.9999856019	0.9999861018
NJLATA	0.9999869376	0.9999939560	0.9999940208
Test	0.9999762686	0.9999827469	0.9999836466

The SHOP denotes the shared path protection with hop count as cost metric .The inverse of free wavelengths on a fiber is used as a cost metric for SLU (shared path protection-least Used). The proposed approach is denoted as SCC-shared path protection based on edge connectivity and centrality. In all the three networks SCC approach outperforms the other methods with least value of average expected loss of traffic. The increased capacity over the significant links improves the flexibility for finding link disjoint paths in the event of link failure. The value of loss of traffic is minimum in NJLATA due to its higher connectivity factor (α) and higher average node degree. Table 2 displays the average availability in the event of link failures for the three networks. The average availability is calculated as follows:

$$\text{The availability } A = 1-\frac{MTTR}{MTBF} \quad (9)$$

Where:
MTTR = Mean time to repair
MTBF = Mean time to fail

The average availability can be calculated by dividing the value over total number of connection demands. Since the flexibility of finding a backup path is increased in SCC method, its average availability value is high compared to other methods. The detailed view of link wise information of expected loss of traffic for NSFNET network is shown in Table 3. For instance in Table 3, the net value of expected loss of traffic for SHOP method is

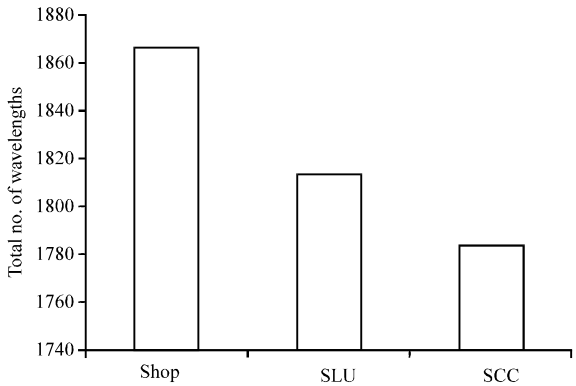

Fig. 6: Total No. of wavelengths used-NSFNET

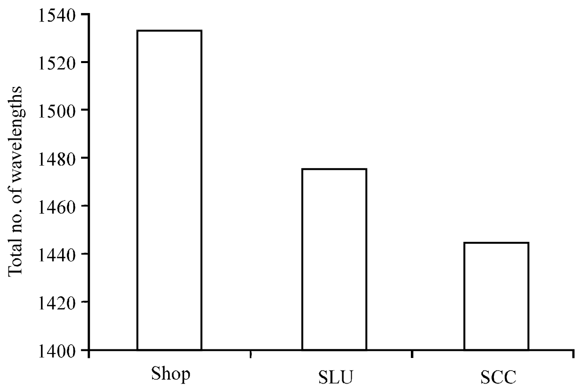

Fig. 7: Total number of wavelengths used-NJLATA

Table 3: Link wise Expected loss of traffic (Gb year^{-1}) -NSFNET

Links	SHOP	SLU	SCC
node 0 <> node 1	64.34	59.49	56.49
node 1 <> node 2	32.95	25.11	23.54
node 0 <> node 2	28.25	45.51	43.94
node 1 <> node 3	87.88	72.18	56.49
node 3 <> node 4	80.03	61.20	39.23
node 4 <> node 6	95.72	73.75	76.89
node 6 <> node 8	37.66	4.71	29.82
node 8 <> node 9	117.69	72.18	67.48
node 0 <> node 8	78.46	69.05	73.75
node 3 <> node 10	95.72	81.60	69.05
node 10 <> node 11	67.48	25.11	25.11
node 2 <> node 5	109.85	136.52	134.95
node 5 <> node 7	64.34	73.75	73.75
node 5 <> node 12	116.32	114.55	114.55
node 4 <> node 5	87.88	86.31	81.60
node 9 <> node 13	53.35	1.57	3.14
node 11 <> node 12	26.68	26.68	17.26
node 11 <> node 9	64.34	36.09	37.66
node 9 <> node 7	47.08	25.11	25.11
node 13 <> node 12	59.63	29.82	29.82
node 10 <> node 13	9.42	10.98	9.42
$\sum E_{XL}/T$	1425.07	1131.27	1089.05

1425.07. When this value is divided by the number of links, i.e., 21 in NSFNET, the average value is 67.86 as shown in Fig. 5.

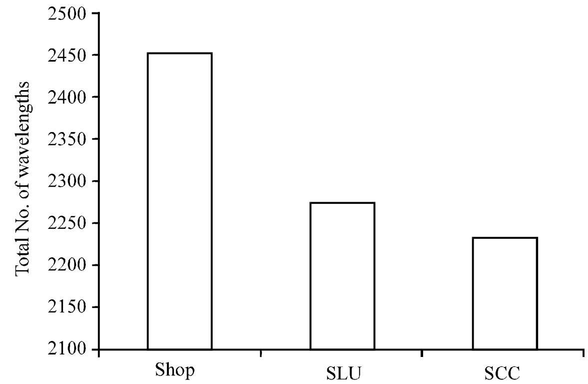

Fig. 8: Total No. of wavelengths used-test network

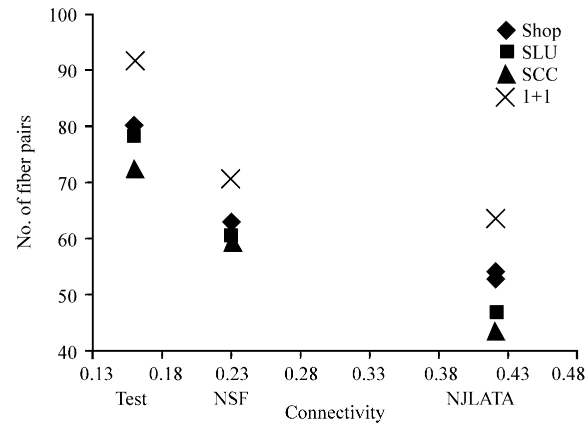

Fig. 9: Number of fiber pairs used

Figure 6-8 show the total number of wavelengths used to accommodate 500 light path demands. The proposed method SCC results in smaller number of wavelengths used than the other methods for all the three networks. In evaluating the network cost the number of wavelengths used is of prime importance since the cost of most of the network elements is related to this value. The TEST network required highest number of wavelengths to accommodate same number of connection demands due to it poor connectivity.

The number of fiber pairs used to accommodate 500 demands for the three networks is shown in Fig. 9. The comparison includes the number of fiber pairs required for 1+1 protection. The SCC approach results in least number of fiber pairs compared to other three schemes for all the three networks. Again the number is minimum in NJLATA. This is attributed to the fact that for the network with higher connectivity, the destination nodes can be reached with lesser number of hops. Figure 10 shows the reduction in port count relative to the port count needed for 1+1 protection. The probability to find

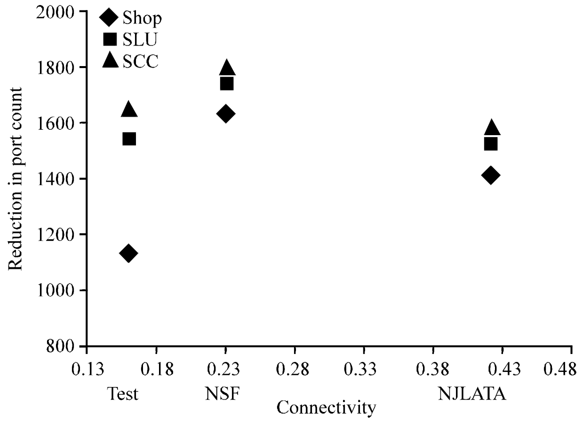

Fig. 10: Reduction in port count relative to 1+1 protection

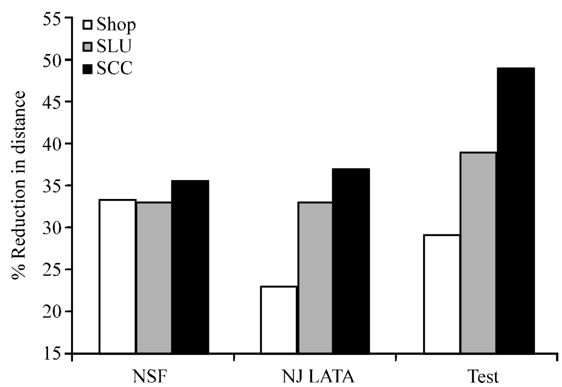

Fig. 11: Reduction in distance relative to 1+1 protection

free wavelengths to accommodate the traffic in SCC is high compared to the other methods. The lesser number of wavelengths used and reduced number of fiber pairs in SCC result in smaller port count. This contributes to further reduction in network cost, since the number of ports dominates the node cost in a network. The relative reduction in distance traversed by the light paths with respect to 1+1 protection is shown in Fig. 11. The cost associated with regenerators, amplifiers and regenerator cards are directly related to the distance of the light paths. It is evident from the graph that the maximum reduction in distance offered by SCC relates to lessening the cost.

Figure 12-14 show the wavelength requirements for various 1: N ratios in shared path protection for the three networks. Since the essence of shared path protection lies in more number of paths being shared effectively, the ratio starts with 1:3.

The wavelength requirements remain same for N ranging from 3 to 10 for SHOP scheme. In SLU method, the wavelength requirements decreases initially but remain flat for subsequent values of N. The SCC scheme

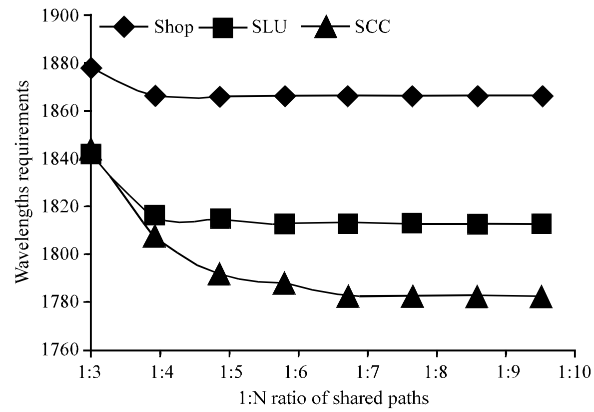

Fig. 12: Wavelength requirements for varying ratios of shared path protection-NSFNET

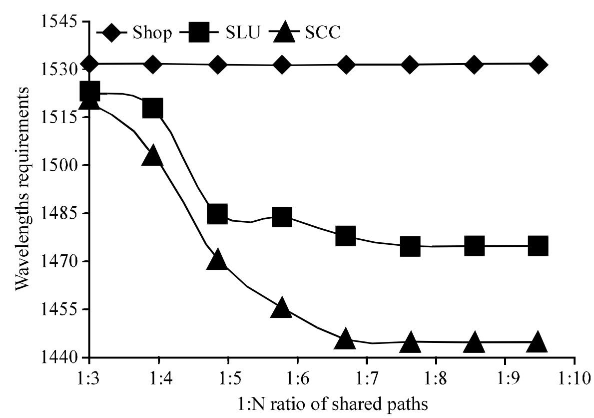

Fig. 13: Wavelength requirements for varying ratios of shared path protection-NJLATA

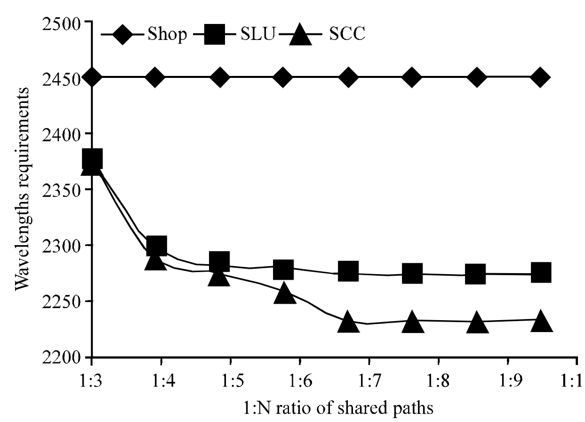

Fig. 14: Wavelength requirements for varying ratios of shared path protection-test network

results in smaller number of wavelengths and shows a gradual decline in wavelength requirements for most part

Table 4: Spare capacity information

Network	SHOP	SLU	SCC
NSF	776	723	693
NJLATA	664	607	577
TEST	1023	845	804

Table 5: Link wise spare capacity distribution-test NW

Links	SHOP	SLU	SCC
node0 < > node1	37	22	23
node0 < > node3	24	23	18
node0 < > node9	46	38	7
node1 < > node2	30	25	37
node10 < > node11	27	15	13
node10 < > node14	49	67	2
node10 < > node18	31	19	15
node11 < > node12	46	27	76
node12 < > node13	23	27	59
node13 < > node14	47	27	50
node14 < > node15	39	38	58
node15 < > node16	37	16	38
node16 < > node17	8	36	27
node17 < > node18	32	11	28
node18 < > node16	44	32	8
node2 < > node3	38	12	21
node2 < > node4	30	34	40
node3 < > node5	45	25	19
node4 < > node5	28	18	20
node4 < > node6	41	43	73
node5 < > node8	40	30	3
node5 < > node9	20	32	9
node6 < > node7	43	42	67
node7 < > node11	37	44	65
node7 < > node8	43	22	9
node8 < > node10	48	38	4
node8 < > node9	43	26	2
node9 < > node18	47	56	13
Total	1023	845	804

Table 6: Link wise fiber pair distribution-NJLATA

Links	SHOP	SLU	SCC
node 0 < > node 5	2	1	1
node 0 < > node 7	2	1	1
node 1 < > node 0	3	3	3
node 1 < > node 2	2	2	2
node 2 < > node 0	2	2	2
node 2 < > node 4	3	3	3
node 3 < > node 0	2	3	2
node 3 < > node 4	2	1	1
node 3 < > node 7	2	1	1
node 3 < > node 8	2	2	2
node 4 < > node 10	4	3	3
node 4 < > node 5	2	2	2
node 4 < > node 6	2	3	2
node 4 < > node 7	2	1	1
node 4 < > node 8	2	3	3
node 5 < > node 7	2	2	1
node 7 < > node 10	3	1	2
node 8 < > node 10	2	1	1
node 8 < > node 9	2	4	4
node 9 < > node 10	4	2	1
node 2 < > node 3	3	3	2
node 6 < > node 7	2	2	2
node 8 < > node 7	2	1	2
Total	54	47	44

of the curve for increased value of N. The additional fibers are added initially to the links concerned with node centrality, availability of shortest paths through these links is increased. Therefore, the potential for choosing a path with more number of hops is reduced and henceforth the connection demands can be honored with lesser number of wavelengths. The spare capacity used for three methods in the three candidate networks is given in Table 4. The spare capacity assignment is minimum in SCC than the other two methods for all the networks due to higher sharing of spare capacity for the recovery process. For fair representation of each network behavior on various aspects, the detailed link wise information on spare capacity distribution is shown for the TEST network in Table 5 and 6 shows the link wise distribution of fiber pairs for the three methods in NJLATA.

The link wise expected loss of traffic is already given for NSFNET network in Table 3.

CONCLUSION

This study studied and investigated the role of topological metrics in survivable optical network design to achieve a cost efficient solution. A method was proposed in which the significant links in the network were identified based on edge connectivity and residue centrality of the nodes on either side of the links. These links were assigned with additional capacity and the performance was evaluated in three mesh networks in terms of average expected loss of traffic and total network cost. The network cost included the total number of wavelengths used, spare capacity, number of fiber pairs and the port count. The nodes were assumed to have full wavelength conversion capabilities. The network was simulated for single link failures using shared path protection. The wavelength requirements for changing values of 1:N ratio of the shared path protection was evaluated with SCC yielded the minimum value. The number of fiber pairs and reduction in port count were estimated with respect to 1+1 protection and the results were represented for various network connectivity values. The results showed that the proposed method outperformed the other standard protection schemes both in terms of loss of traffic and the associated network cost.

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