Sub-Graph Routing : A Novel Fault-Tolerant Architecture for Shared-Risk Link Group failures in WDM Optical Networks

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Abstract— **Failure resilience is one the desired features of the Internet. Multiple link failure models, in the form of Shared-Risk Link Group (SRLG) failures, are becoming critical in survivable optical network design. Most of the traditional restoration schemes are based on the single-failure assumption which is unrealistic.**

In our research, we propose a novel survivability approach that can tolerate multiple failures arising out of SRLG situations. Each network has a set of sub-graphs that can be created by removing each of the links in the network and, in addition, removing all of the links of a SRLG. Connections in the newly proposed strategy are accepted if they can be routed in all the sub-graphs, and are protected against all single link and SRLG failures.

We also study how restorability can be achieved for node failures and analyze the performance of our approaches for different network topologies. Our proposed restoration architecture requires the storage of network state information corresponding to each of the possible failure scenarios defined by the sub-graphs. This restoration model is novel and can be implemented in current WDM backbone networks.

I. INTRODUCTION

The explosive growth of the Internet in the past few years has created significant shifts in traffic patterns. Optical communication employing wavelength division multiplexing (WDM) has emerged as a viable solution for satisfying the ever increasing demand for bandwidth due to emerging applications. WDM divides the available fiber bandwidth into multiple wavelengths each of which operates at peak electronic speeds. With the current technology, each wavelength is capable of supporting a capacity of upto 10 Gbps(OC-192). As the trend continues, networks in the near future are expected to have transmission capacities of the order of 40 Gbps(OC-768) per wavelength. Thus any single failure results in a significant loss of data. It is therefore imperative to design survivable networks to avoid catastrophic loss of revenue.

Most research to date in survivable optical network design and operation focusses on single link failures. However the occurrence of multiple-link failures is not uncommon in a practical network. It might happen in nature that two or more distinct physical links may be routed via the same common *duct* or physical channel. Such commonality might be only for a few hundred meters, but if any damage happens to this physical duct, it will cause simultaneous logical failures in two or more distinctly different links. Such instances where seperate fiber optic links share a common failure structure is often referred to as an SRLG (Shared-Risk Link Group) [1].

It has been shown in [2] that a fiber optic link fault can be detected, isolated and recovered from with a high degree of reliability. While detection and isolation must be performed to protect the rest of the network, the network must be able to temporarily restore service to compromised connections while the fault is being repaired. The single link failure model is unrealistic because it implies a dependency among link failures: if one link fails, no other link in the system can fail at the same time. In this paper we are interested in designing a network which can tolerate a single or a group of SRLG failures. This model is more realistic and occurs more often in practise.

Different double link failure models in which any two links in the network may fail at an arbitrary order have been proposed in literature. The basic idea of these approaches are to pre-compute two backup paths for each link in the primary paths and reserve resources on these paths [3]. A significant finding is that such a design for complete dual-failure restorability requires almost triple the amount of spare capacity [4]. In this paper we design the network so that it can provide 100% restoration guarantee against a single or a group of pre-defined SRLG's in the network.

L+1 sub-graph routing [5] is a strategy for routing dependable connections in optical networks. In this approach each network is mapped into *L* distinct sub-graphs resulting from the removal of one link from the original network. A connection in this scheme becomes accepted only if it is accepted in all the sub-graphs. That way in the event of a single link failure, the network state can be restored to the corresponding sub-graph where all connections are guaranteed restoration for that single fault scenario. The *L+1* strategy has been shown to peform significantly better than the traditional backup-multiplexing schemes for routing dependable connections in terms of the blocking probability, network utilization and redundancy.

In our design model, we propose a sub-graph routing scheme which can achieve restorability against all failures caused by a single or a group of SRLG's. In a given network if there are *S* groups of SRLG's, then each network is mapped onto *S* + *E* distinct sub-graphs where *E* comprises the set of edges in the network. Each of these sub-graphs are formed by removal of links in an SRLG or a link $e_i \in E$. A connection in the above scheme becomes accepted only if it is accepted in all the sub-graphs. Hence in the event of a SRLG failure or any independent link failure the network state can be restored to the corresponding sub-graph where all connections are guaranteed restoration in the target sub-graph.

Node failures represent a special case of shared risk link groups where links are placed in groups based on whether or not they share a common node. Furthermore, link faults are also a special case of shared risk link groups where *L* groups are formed, each containing only one link. In this paper we also study the effects of *N+1* sub-graph routing. The *N+1* sub-graph routing represents a upper bound on the number of links effected by a single SRLG failure and hence can be used as a lower bound result for illustrating the routing performance.

Restoration schemes can be classified as either *link restoration* and *path restoration* based on the initialization locations of the rerouting process. Path based restoration has been found to be the more capacity-efficient approach for mesh based networks as compared to link based rerouting schemes [6][7]. Hence the restoration model assumed in our work is *path restoration*.

In the event of a link failure, the network takes on the state of the corresponding subgraph, potentially rerouting some of the connections in the base network to accommodate the fault. This paper also illustrates that sub-graph fault tolerance can be improved by placing constraints on the path a connection can establish in a given sub-graph.

A. Motivation

In traditional networks the importance of considering SRLG's (Shared Risk Link Groups) is increasing, thus motivating us to study the robustness of a fault tolerant scheme under the scenario of multi-link failures. An SRLG is a group of links which share a common component whose failure causes the failure of all the links in that group. One such common components are ducts, or conduits through which multiple independent logical links are routed in the ground. Any physical failure of one of these ducts can invoke a logical failure of multiple links as illustrated in Fig. 1.

SRLG's that involve links incident on a common node, are considered to be more common in practise and are often referred to as *co-incident SRLG's* [1]. Another class of SRLG's which involves multiple links not incident on the same node are referred to as *non co-incident SRLG's*.

B. Outline of the paper

The remainder of the paper is organized as follows: Section II describes the routing in sub-graphs for a given set of SRLG's in a network. Section III discusses the *N+1* routing strategy. Section IV describes constrained sub-graph routing. Section V presents the numerical results, Section VI presents a discussion of the results and Section VII concludes the paper.

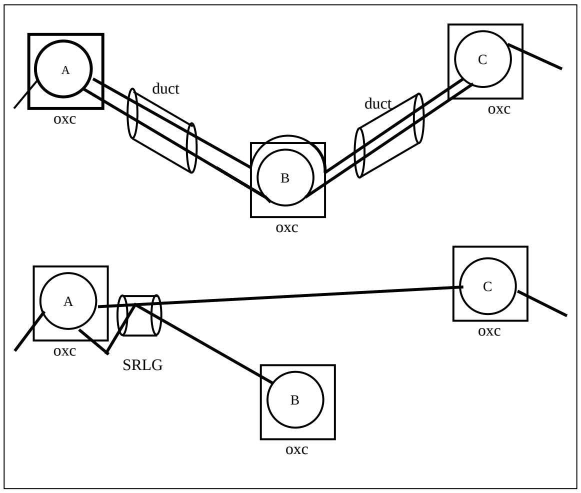

Fig. 1. The difference between nodal bypass and a co-incident SRLG.[1]

II. SUB-GRAPH ROUTING FOR TOLERATING SRLG FAILURES

Sub-graph fault tolerant routing is implemented by maintaining the state of a set of network sub-graphs such that, in the event of a link(s) failure, the network state can be changed to that of the sub-graph corresponding to the fault. All requests are accepted or rejected based on their ability to be routed on all sub-graphs. Networks consist of a set of nodes and links that correspond to the various servers, routers and cables that make up its physical implementation. These nodes and links can be viewed as a set of vertices and edges in a graph. Each graph, *G*, is hence defined by a set of *V* vertices and *E* edges or, in mathematical terms, *G = (V, E)*. Let there be *S* groups of SRLG's in the network. The cardinality of each SRLG given by $|S|$. We can construct $(|S|+E)$ sub-graphs from the original network, $|S|$ of which are generated by removing the edges belonging to each SRLG i.e. $G_i = G - \{e_i \in S_i\}$, The other *E* sub-graphs are generated by removing each edge e_i from the base network, treating each edge, whether unidirectional or bidirectional, as an SRLG of size 1 or 2, respectively.

Let us consider the network as shown in Fig. 2. There are 3 shared-risk link groups, each of cardinality $|S| = 2$. Each link in the network is assumed to be a unidirectional link of total capacity one unit. The corresponding sub-graphs are generated through the removal of individual links, as well as links belonging to each SRLG, and are shown in the same figure. Let there be three requests in the network $R_1 : 1 \rightarrow 2$, $R_2 : 4 \rightarrow 5$ and $R_3 : 3 \rightarrow 4$. The request $R_1 : 1 \rightarrow 2$ can be routed in all the sub-graphs and hence it is accepted for routing in the base network. Similarly the request $R_2 : 4 \rightarrow 5$ finds a route in all the sub-graphs except G_3 and hence is accepted in the base network. We accept a request on a sub-graph which has any node with a degree of zero, i.e. a free

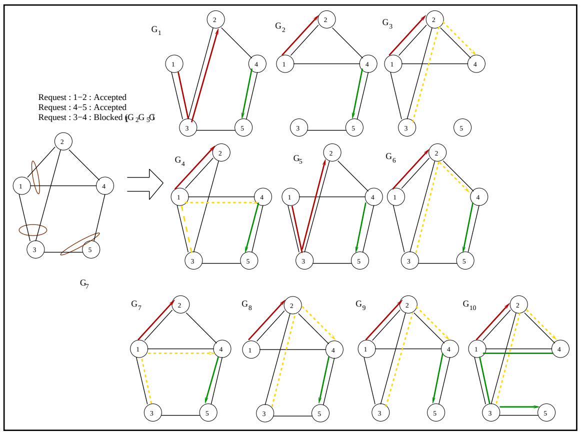

Fig. 2. Sub-graph Routing for tolerating SRLG failures

node, and that node is either the source or destination of the request. We however reject a request on a sub-graph if such a free node appears as an intermediate node in the path of the request. Similarly, the request R_3 attempts to find a route on all the sub-graphs, but cannot be accepted on sub-graphs G_1, G_2 and G_5 because of insufficient capacity. Hence R_3 cannot be routed on the base network.

III. NODE DISJOINT (N +1) SUB-GRAPH ROUTING

Node-disjoint sub-graph routing is similar to *L +1* sub-graph routing except that in this case, the sub-graphs are generated by the removal of each node, $n_i \in N$, one at a time, from the base network. Let us consider the network as shown in Fig. 3. Each link in the network is assumed to be a unidirectional link of total capacity one unit. The corresponding sub-graphs generated by the removal of each node are shown in the same figure. Let there be three requests in the network $R_1 : 1 \rightarrow 2$, $R_2 : 4 \rightarrow 5$ and $R_3 : 1 \rightarrow 4$. The request $R_1 : 1 \rightarrow 2$ can be routed in all the sub-graphs and hence it is accepted for routing in the base network. Similarly the request $R_2 : 4 \rightarrow 5$ finds a route in all the sub-graphs except G_4 but still it is accepted in the base network. We accept a request on a sub-graph which has any node with a degree of zero, i.e. a free node, if that node is either the source or destination of the request. The request R_3 is accepted for routing in each sub-graph except in G_1 where it cannot be routed because node 1 has a nodal degree of zero, however, since node 1 is the source node of the request, it is accepted in the base network.

The node-disjoint sub-graph routing gives a lower bound on the routing performance that can be achieved because it is much more constrained than the sub-graph routing for tolerating SRLG failures. The sub-graphs for tolerating node failures are a special case of the *S +1* routing, since it deals with SRLG groups consisting of links that share a common node.

IV. CONSTRAINED SUB-GRAPH ROUTING

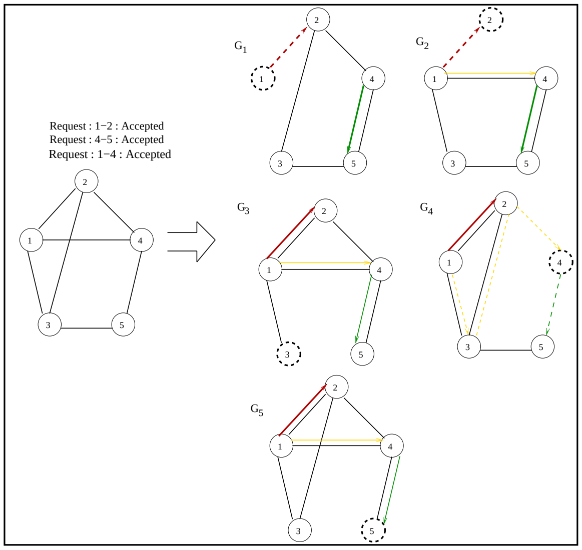

Fig. 3. Node-disjoint (N +1) Sub-graph Routing

One of the potential drawbacks of incorporating the sub-graph routing scheme as a means of tolerating SRLG failures is the issue of connection re-establishment. The above proposed scheme depends on the network state's ability to change to the state of a sub-graph during fault recovery. This potentially requires many connections in the network to be reassigned to different path/trunk combinations as defined a sub-graph. A path is the set of *l* links that connect the source and destination nodes. A trunk is the specific fiber, wavelength and timeslot that the connection is established on within the path. Similar issues have been discussed in the context of *L+1* sub-graph routing in [5].

To overcome this limitation we introduce the concept of *constrained sub-graph routing* in this paper. The constrained sub-graph routing minimizes the probability of reassignment during transition from the base network to the final sub-graph. There are two levels of constrained sub-graph routing. They are:

- **Constraint 1:** A connection is contrained to be routed on the same path as in the base network in all the sub-graphs which contains all the *l* links of the path.
- **Constraint 2:** If constraint 1 is fulfilled, then the connection can be further constrained to be routed along the same trunk in the sub-graph as in the base network.

In the case of link based sub-graphs there are *L* sub-graphs. Constraint 1 requires that the connection be routed on *L-l* sub-graphs with the identical path as in the base network. Constraint 2 requires that a sub-graph connection not only take the same link path, but also the same trunk along that path as in the base netowrk. In this manner, any connection not directly affected by the failed link will not be interrupted in *L-l* sub-graphs. This is an attempt to avoid as much node reconfiguration as possible by minimizing the probability of reassignment. In our results, we will show that path constrained routing can actually improve the blocking performance over the unconstrained case. However, trunk constrained routing significantly degrades network performance in terms of increasing blocking probability, but realizes a very low probability of reassignment for sub-graph routing architectures.

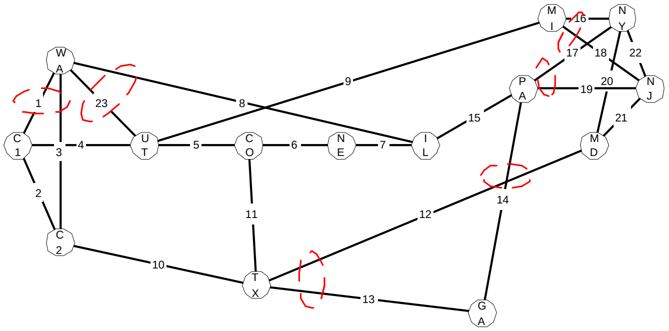

Fig. 4. 14 node, 23 link NSFNET network with SRLG's

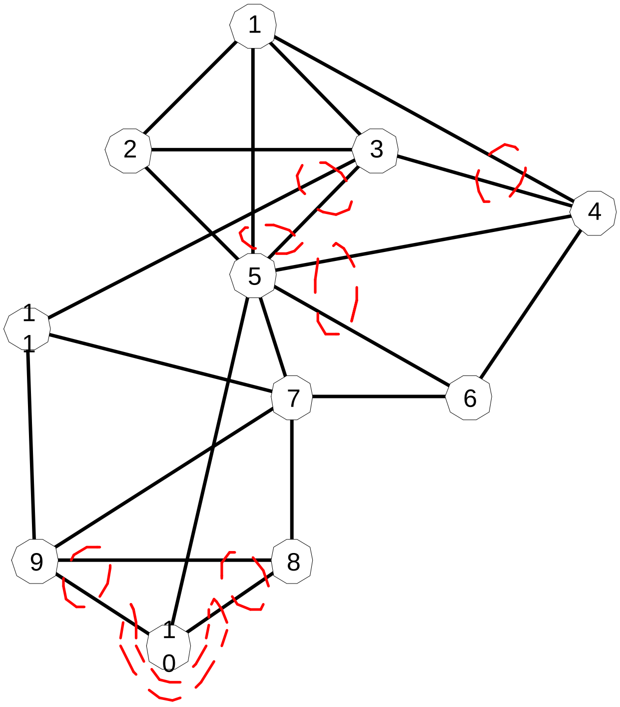

Fig. 5. 11 node, 22 link NJLATA network with SRLG's

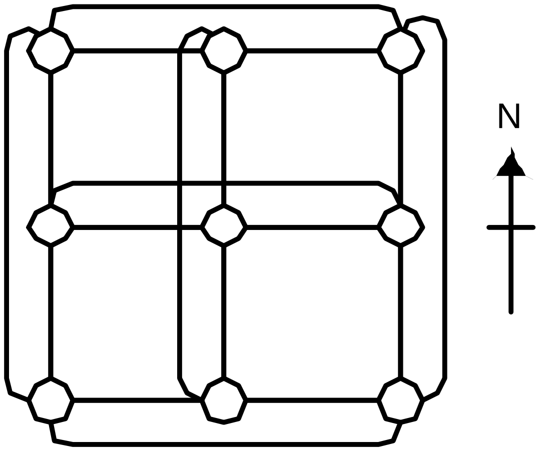

Fig. 6. 9 node, 18 link Mesh Torus network

V. RESULTS

Three different network topologies, shown in Fig. 4, Fig. 5 and Fig. 6 were simulated to assess the performance of sub-graph routing for tolerating SRLG failures. Each of the three topologies consists of links with 1 fiber per link, 16 wavelengths per fiber, and 1 timeslot per wavelength. Each link also consists of 2 unidirectional links that are assumed to be part of the same shared risk link group, meaning that if the link in one direction fails, the link in the opposite direction also fails because they would presumably physically routed together. No nodes offer any wavelength switching capabilities, thus the *wavelength continuity constraint* is obeyed. The arrival of the requests at a node follow a Poisson process with rate λ, and are equally likely to be destined to any other node. The holding time of the requests follow an exponential distribution with unit mean. The capacity requirements of each request is a unit wavelength.

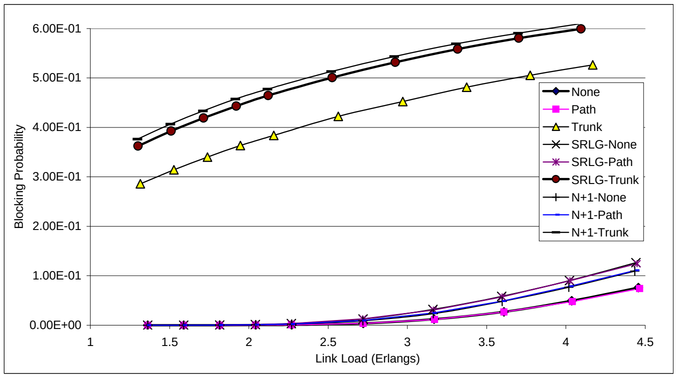

Fig. 7. NSFNET Blocking Probability vs Link Load

Three subgraph formation techniques have been assessed-subgraphs based on all physical link failures (*L+1* sub-graph routing), subgraphs based on arbitrarily chosen shared risk link groups(*S+1* subgraph routing),as shown in Fig. 4, Fig. 5 and Fig. 6, and subgraphs based on all single-node failures (*N+1* sub-graph routing).

For the 3x3 mesh torus, SRLGs were formed as the north and east links leaving a node and the south and west links leaving a node. The number of sub-graphs created for each base network is equivalent to the sum of the number of physical link faults and the number of SRLGs. If a request's source or destination node is a stranded node (one with degree of 0) in a subgraph, a conditional acceptance on that subgraph is granted as discussed in Section III (source or destination nodes can be free, intermediate nodes cannot).

Conditional acceptance is allowed, because any connection formed between two nodes automatically incurs the risk of either the source or destination node failing. The intent of

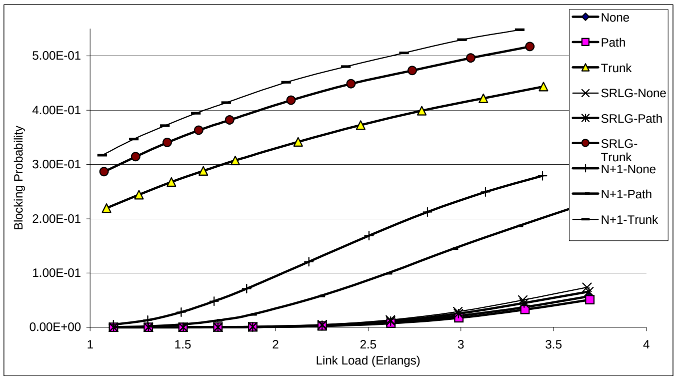

Fig. 8. NJLATA Blocking Probability vs Link Load

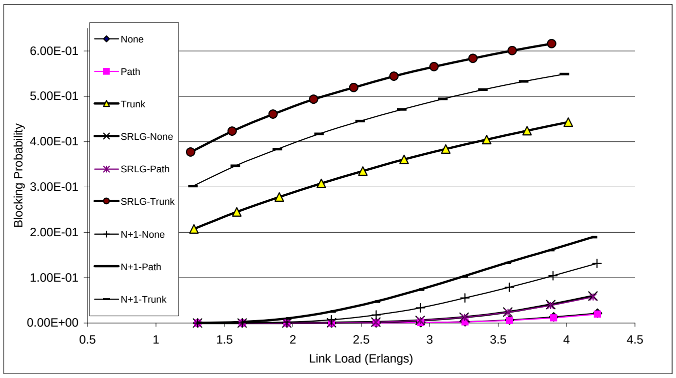

Fig. 9. MESH 3x3 Blocking Probability vs Link Load

providing coverage for all single node faults is to protect against faults occurring at the intermediate nodes in the path of the connection request.

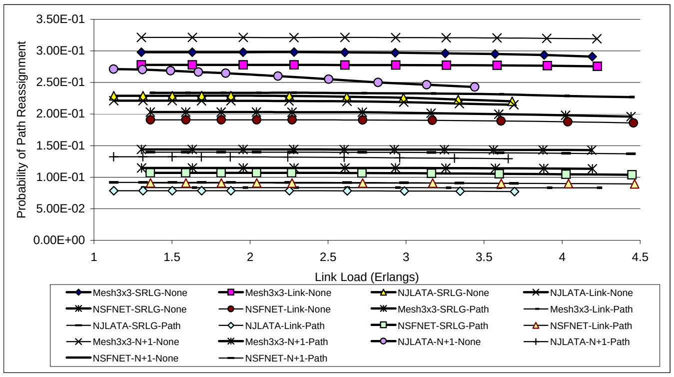

Fig. 10. Probability of Path Re-assignment vs Link Load

Using the 14 node, 23 link NSFNET as an example, the previously described sub-graph formation techniques will be clarified. In the case of link sub-graph generation, an NSFNET base network creates 23 sub-graphs, each missing a pair of uni-directional links physically routed together. For SRLG sub-graph generation, an NSFNET base network creates 6 SRLG sub-graphs in addition to the 23 sub-graphs based on physical links, for a total of 29 sub-graphs. Finally, for node sub-graph generation, an NSFNET base network creates 14 node sub-graphs and 23 link sub-graphs for a total of 37 sub-graphs. Physical link failures are always considered in each sub-graph generation because a physical link can fail in a location where it does not affect the other members of its SRLG.

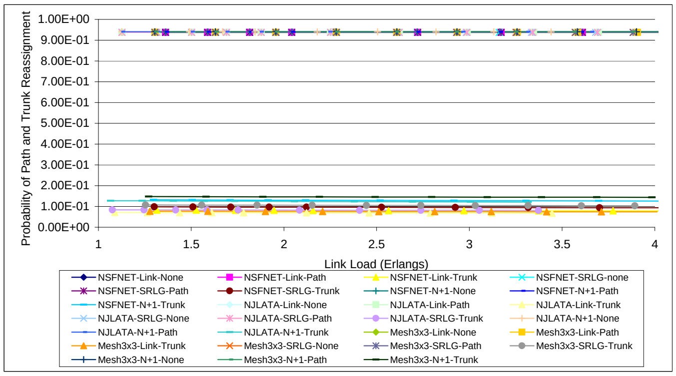

Fig. 11. Probability of Path and Trunk Re-assignment vs Link Load

In all sub-graph cases, all single-link faults are 100% guaranteed, and in the case of sub-graphs based on shared risk link groups, there is a 100% guarantee for all connections in the event of a shared risk link group fault. In the *N+1* sub-graph case, 100% restoration is guarenteed for all intermediate node and single-link failures. The blocking probability results for all three topologies are shown in Fig. 7, Fig. 8 and Fig. 9.

To assess the performance of constrained routing, the probabilities of reassignment to a different path and to a different path/trunk combination are shown in Fig. 10 and Fig. 11. In Fig. 10 the probability of reassignment for unconstrained routing runs between 18-33%. This is in sharp contrast to the probability of reassignment for path constrained routing which ranges from 8-15%. In all cases, path constrained sub-graph routing offers lower probability of reassignment. According to [5], the calculated probability of path reassignment for backup multiplexing ranges between 8-15%, thus making constrained sub-graph routing roughly equivalent to backup multiplexing.

In Fig. 11, the probability of path/trunk combination reassignment is about 93% for path and unconstrained sub-graph routing. This is significantly higher than the probability of path and trunk reassignment for path/trunk combination constrained sub-graph routing, which ranges from 8-15%. This is an expected result because connections are more likely to choose same paths, in similar sub-graphs on any capacity available. In summary, in a recovery situation, a connection will more likely than not have to change its trunk if path/trunk combination constrained routing is not imposed.

In Fig. 12 we observe that the blocking probability for path constrained sub-graph routing is less than the blocking probability for unconstrained sub-graph routing in all but two cases: NSFNET and mesh torus 3x3 node-based sub-graphs. In each topology, the blocking probability for node-based sub-graphs is higher than that for the SRLG, which in turn is higher than that for link-based sub-graphs. The only exception is observed in the results for NSFNET where node-based sub-

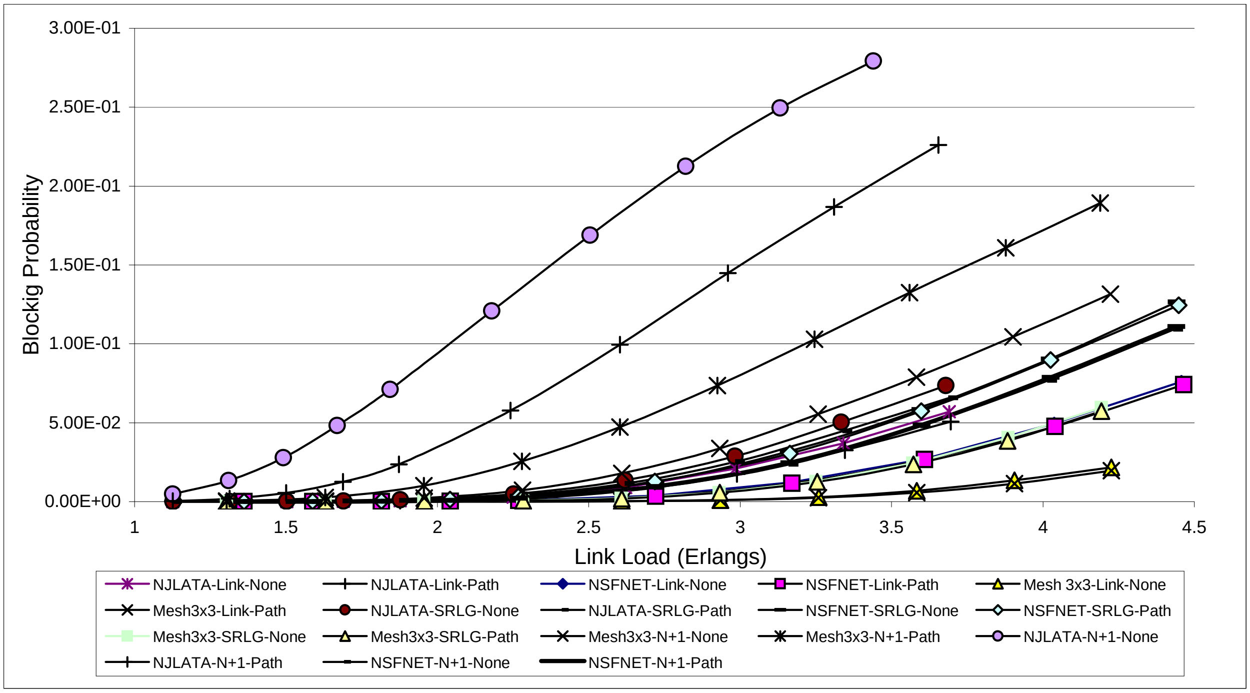

Fig. 12. Blocking Probability vs Link Load for no Contraint and Path constraint

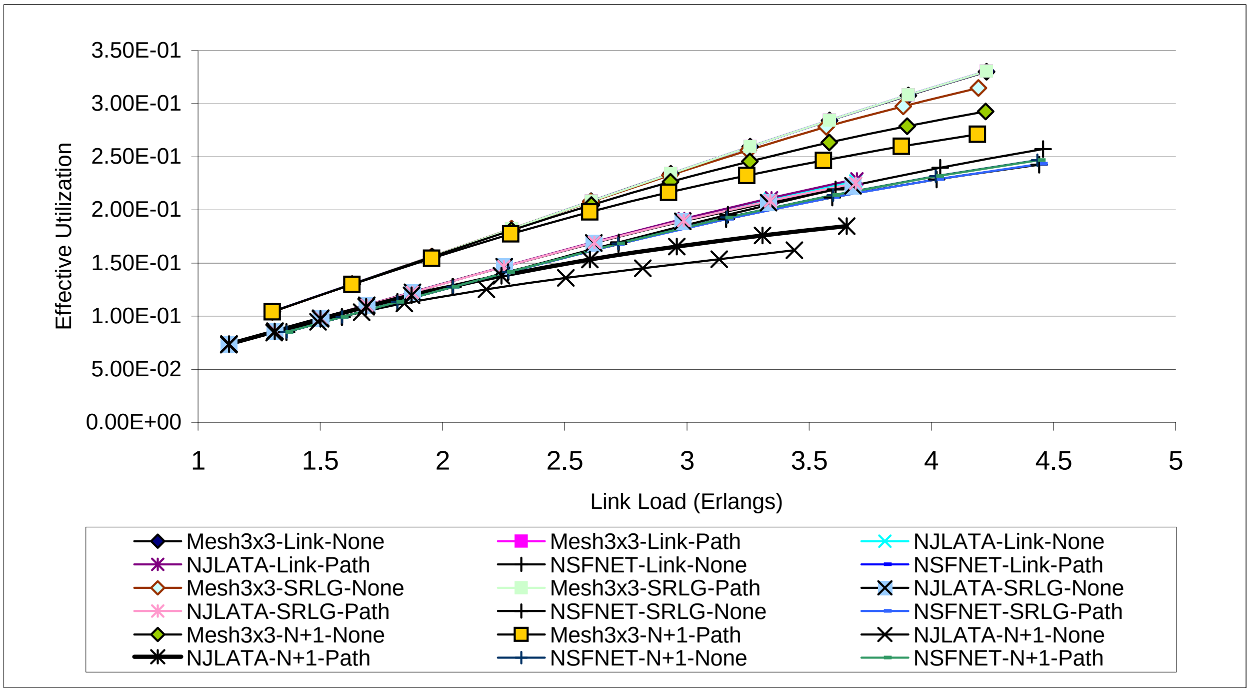

Fig. 13. Effective Network Utilization vs Link Load

graphs slightly outperformed the SRLG based sub-graphs.

Intuitively, one would expect that, in constrained sub-graph routing, forcing the connection to route on the same path on each of the *L* sub-graphs would increase the connection blocking probability. However in simulation, the reverse phenomenon was observed as shown in Fig. 7, 8, 9. In most cases the blocking probability actually decreased slightly when following the path-constrained routing. Path/trunk constrained routing sharply increased overall connection blocking probability and is not seen as a viable solution unless minimization of probability of reassignment is more crucial than the minimization of blocking probability in a particular network.

In Fig. 13 we study the effective utilization of the network for path constrained as well as the unconstrained sub-graph routing. Path/trunk constrained routing is not considered due to its drastically higher blocking probability. For all the topologies, the network utilization for the SRLG sub-graph routing is slightly lower than that of *L+1* sub-graph routing. However, the network utilization for the SRLG sub-graph routing is higher than *N+1* sub-graph routing since *N+1* sub-graph routing offers a higher blocking probability than SRLG sub-graph routing for most topologies.

VI. DISCUSSION

The results obtained using path-constrained routing are very interesting. They indicate that constraining sub-graph routing to a path actually improves the blocking probability. One of the possible explanations for this phenomenon is the increased resemblance each sub-graph takes to the base network. If the path on a sub-graph is distinctly different from the base network, the request might have to traverse through links that a different request regularly utilizes. If a request can't find the necessary resources available on such critical links, it is blocked with a higher frequency. If, however, each sub-graph is required to route each connection in the same way the base network does if the same path exists, the sub-graph utilization of critical links more closely resembles that of the base network. This increases the likelihood that an arbitrary request is accepted on all sub-graphs, and consequently accepted in the base network. We refer to this as *sub-graph shadowing*.

Sub-graph shadowing increases the performance of sub-graph routing because situations exist where there are several different equidistant paths from a source to a destination node. Each ofthese paths can be chosen to route the connection in a fewest hops routing strategy. Constraining the path actually creates sub-graph states that more closely resemble, or shadow, the actual state of the base network. It helps to reduce the occurance of situations where a connection gets blocked because the only possible path where it could have been routed is already occupied by some other connection that should have been routed elsewhere.

A sub-graph shadowing situation is depicted in Fig. 14. In Fig. 14, the base network consists of 6 links and sub-graphs are created based on single link failures, resulting in sub-graphs 1 through 6. Let us assume that each link in the sub-graphs has a total capacity of 1 unit. Let us assume that connection request $R_1 : 1 \rightarrow 5$, is routed on the base network along $R_1 : 1 \rightarrow 2 \rightarrow 5$. Similarly, connection request $R_2 : 1 \rightarrow 3$ is routed on the base network along $R_2 : 1 \rightarrow 3$. Sub-graphs G_1 and G_2 have the option of routing connection R_1, from node 1 to 5, along the paths $1 \rightarrow 2 \rightarrow 5$ or $1 \rightarrow 4 \rightarrow 5$. The path $R_1 : 1 \rightarrow 2 \rightarrow 5$ is chosen. Connection R_2 gets routed in sub-graphs G_1 and G_2. In sub-graphs G_3 and G_4, R_1 has the option to select from either of the two paths, $R_1 : 1 \rightarrow 3 \rightarrow 5$ or $R_1 : 1 \rightarrow 4 \rightarrow 5$. The path $R_1 : 1 \rightarrow 4 \rightarrow 5$ is chosen for routing connection R_1 and connection R_2 can be routed without any problem. In sub-graphs G_5 and G_6, connection R_1 has paths $1 \rightarrow 2 \rightarrow 5$ and $1 \rightarrow 3 \rightarrow 5$ to choose from. Without sub-graph constrained routing, $1 \rightarrow 3 \rightarrow 5$ might be chosen as the path for routing connection R_1. If this path is chosen for routing R_1 in sub-graphs G_5 and G_6, connection request R_2 cannot be accepted and must be blocked by the

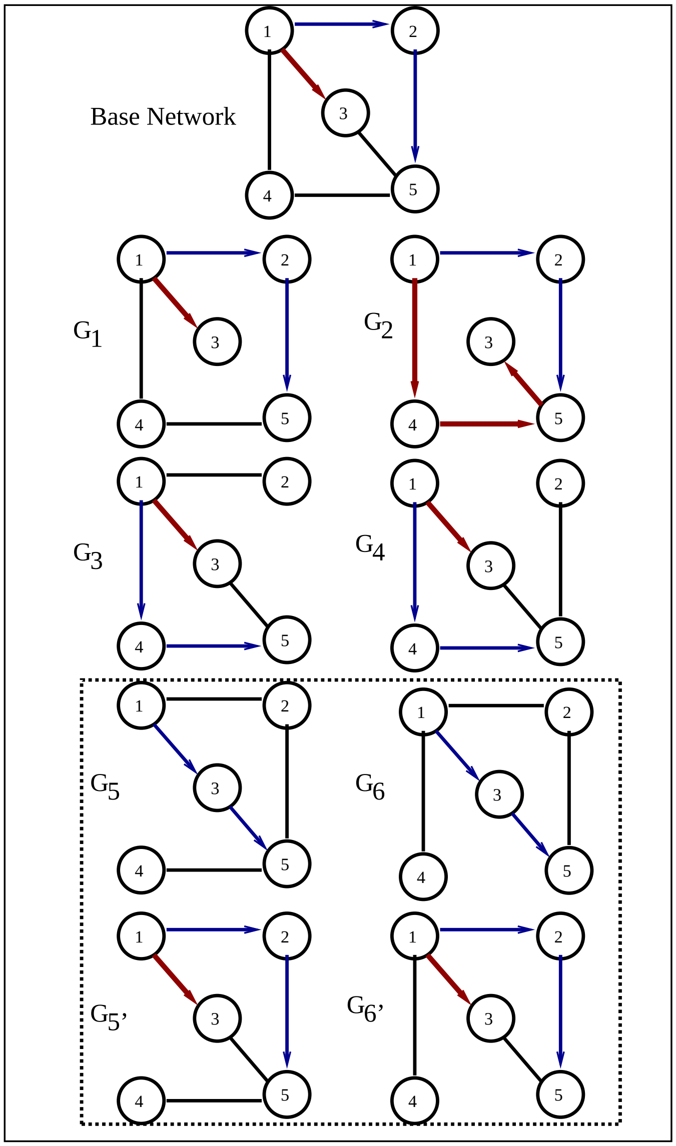

Fig. 14. Sub-Graph Shadowing

base network. However, if we constrain the routing on the same path, connection R_1 is routed along $R_1 : 1 \rightarrow 2 \rightarrow 5$ as shown in sub-graphs G'_5 and G'_6. Furthermore, connection request R_2 can be routed on node path $R_2 : 1 \rightarrow 3$ and both connections can be accepted in the base network.

VII. CONCLUSIONS

In this paper we developed a strategy that enables us to tolerate shared-risk link group failures. We also propose a methodology for tolerating node failures in a network, by creating node-disjoint sub-graphs from the base network. Designing for a node failure actually represents the worst-case SRLG failure involving all links sharing a common node.

One of the elegant features of the proposed strategy is that it can provide 100% restoration guarantee for any number of SRLG failures without any physical allocation of any redundant capacity in the network. It only needs to store the network state information corresponding to the sub-graph generated from the base network due to the SRLG failures. Hence it is aptly suitable for implementation for the current WDM backbone networks.

Given the results that we have presented in this paper, we have shown that sub-graph fault tolerance is a viable means for tolerating link, shared-risk link group and node faults in a wide variety of network topologies. The toleration of shared-risk link group faults is especially appealing in this strategy because the blocking probability doesn't significantly increase relative to single link failure situations. Additionally, path constrained routing can further increse performance in sub-graph fault tolerant optical networks.

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