

Evaluating Dual-Failure Restorability in Mesh-Restorable WDM Optical Networks

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Abstract—Double link failure models, in which any two links in the network fail in an arbitrary order, are becoming critical in survivable optical network design. A significant finding is that designs offering complete dual-failure restorability require almost triple the amount of spare capacity.

In this paper, networks are designed to achieve 100% restorability under single link failures, while maximizing coverage against any second link failure in the network. In the event of a single link failure, the restoration model attempts to dynamically find a second alternate link-disjoint end-to-end path to provide coverage against a sequential overlapping link failure. Sub-graph routing [1] is extended to provide dual-failure restorability for a network provisioned to tolerate all single-link failures. This strategy is compared with shared-mesh protection.

The results indicate that sub-graph routing can achieve overlapping second link failure restorability for 95-99% of connections. It is also observed that sub-graph routing can inherently provide complete dual-failure coverage for ~ 72 -81% of the connections.

Index Terms—Optical Networks, Wavelength Division Multiplexing, Protection, Restoration, Restorability, Sub-Graph Routing.

I. INTRODUCTION

Optical communication employing wavelength division multiplexing (WDM) has emerged as a viable solution for satisfying the ever-increasing demand for bandwidth. With current technology, each wavelength is capable of supporting a capacity of up to 10 Gbps(OC-192), which will increase to 40 Gbps(OC-768) in the near future. It is imperative to design survivable networks to avoid catastrophic loss of revenue due to link failures.

In order to protect connections from link failures in the network, two paths are often assigned: a primary path on which a connection is established and backup path on which a connection will be re-established in case the primary path fails. Most research to date in survivable optical network design and operation focuses on single link failures [2], however, the occurrence of double-link failures is not uncommon in a network topology[3], [4].

Multi-link failure scenarios can arise out of two common situations. First, an arbitrary link may fail in the network,

and before that link can be repaired, another link fails, thus creating a multi-link failure sequence. Second, it might happen in practice that two distinct physical links may be routed via the same common duct or physical channel. A failure at that shared physical location creates a logical multiple-link failure. Such instances where separate fiber optic links share a common failure structure is often referred to as an SRLG (Shared-Risk Link Group) [5], [6]. Simultaneous link failures can be treated as an arbitrarily ordered sequential failure with no latency. This paper assumes two independent link failures, where the second failure occurs after the first failure is recovered from, but before it is physically repaired.

Link restoration schemes provide a detour around a failed link that does not necessarily affect the entire source-destination path. Path restoration schemes, in general, attempt to provide a backup path from the source to destination that is independent of the working path. Path restoration schemes are classified into two categories based on knowledge of the link failure. A backup path that can be used for any link failure on the working path and is link-disjoint with the working path is referred to as *failure independent path restoration*. Alternatively, a connection may be assigned more than one backup path depending on the failure scenario. Such an approach requires complete knowledge of the failure in the network, hence it is referred to as *failure dependent path restoration*. Path based restoration has been established to be a more capacity-efficient approach for mesh-based networks compared to link-based restoration approaches [7], [8]. This paper employs a failure-dependent path protection scheme.

In order to achieve efficient utilization of network resources, multiplexing of resources across primary and/or backup paths may be employed. More than one backup path may share resources as long as any failure in the network will cause, at most, one of the corresponding working connections to fail. This is often referred to as shared mesh protection or backup multiplexing. These two terms will be used interchangeably throughout the paper. In the first approach, shared-mesh protection is employed to optimize the capacity utilization and provide 100% protection guarantee for all single-link failure scenarios. The performance of backup multiplexing is analyzed to ascertain what percentage of second link failure scenarios can be dynamically tolerated after a single physical link failure occurs.

Protection paths may be also provided by deconstructing

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the network into multiple sub-graphs to mimic each failure scenario [1]. A connection is established if it can be accepted by all the sub-graphs. This method does not require the explicit allocation of backup resources in the network, but it does require the network to reconfigure itself in the event of a fault to adopt a sub-graph state. Reconfiguration can occur according to the work done in [9]. In this paper sub-graph protection is employed to tolerate all single link failures and analyze its ability to restore connections for a second link failure in the network.

II. MOTIVATION

In [10], the capacity required to ensure complete restorability against all dual-failure situations is studied. One of the significant findings is that design for complete dual-failure restorability requires almost triple amount of spare capacity. An Integer Linear Programming (ILP) formulation for supporting multiple restorability service classes at an overall minimum cost is also presented.

In this paper, networks are provisioned to tolerate all single link failure scenarios using both shared mesh protection and sub-graph routing. In the event of the first link failure, the restoration of connections is studied and the ability to tolerate an additional link fault is assessed. In the case of shared mesh protection, additional backup paths are dynamically calculated for all affected connections, be they backup or primary. This approach is similar to the protection-reconfiguration approach taken in [11] to accommodate higher order link failures. With respect to sub-graph routing, the approach is a recursive one in that the set of sub-graphs fails the link that has failed in the original network. Attempted rerouting of the connections affected by the failed link is performed in order to obtain second link failure protection. The idea is recursive because it can be extended to an indefinite number of successive link failures, so long as the network remains adequately connected.

While node, link and shared-risk link group based sub-graph routing [12] have the ability to proactively protect against a wide variety of multiple link failures, they cannot protect against all possible multiple-link failure scenarios. Proactive sub-graph routing has the advantage of providing protection for 100% of the failure scenarios for which sub-graphs are designed. Unfortunately, in the case of link fault tolerant sub-graphs, there are $L(L-1)$ possible dual-link failure states in a network with L links. Hence, far too many sub-graphs would be necessary to provide protection against all such possible dual-failure scenarios, not to mention multi-link failures exceeding two links.

Additionally, there is no mechanism provided to accommodate overlapping sequential failures, only simultaneous related ones. Fortunately, the flexibility of the sub-graph strategy also allows it to be used in the reactive tolerance of link failures. The ability to tolerate a high percentage of multiple overlapping sequential or unrelated simultaneous link failures,

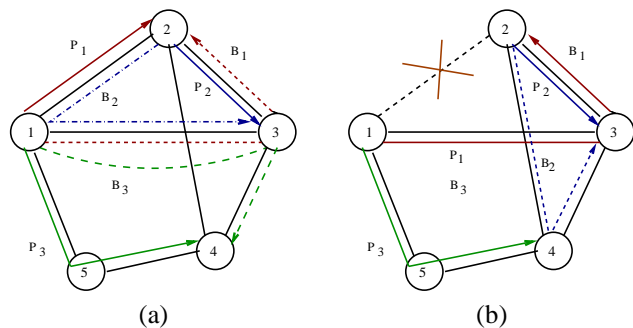


Fig. 1. (a) Routing of requests using shared mesh protection. (b) Rerouting of requests on failure of link $1 \rightarrow 2$.

using the merits of sub-graph fault tolerance in a reactive manner is the subject of this work.

III. COVERAGE FOR DUAL-LINK FAILURE SCENARIOS USING SHARED-MESH PROTECTION

Let the primary path of a request R_i be denoted by P_i and the two link-disjoint end-to-end backup paths for tolerating two independent link failures e and f be $B_i(e)$ and $B_i(f)$. Fig. 1(a) indicates the primary and backup routes and wavelength assignment using backup multiplexing or shared mesh protection for three requests ($R_1 - R_3$). The routes and the wavelengths assigned for each request are also shown in Table I. The primary and backup connections for request R_1 are given by $1 \rightarrow 2$, and $1 \rightarrow 3 \rightarrow 2$, respectively, and are assigned wavelength λ_1 . Similarly request R_2 is assigned primary and backup routes $2 \rightarrow 3$, and $2 \rightarrow 1 \rightarrow 3$, respectively. Since the primary routes of the requests R_1 and R_2 don't share common links their backup paths can share wavelength λ_1 .

Connection request R_3 is routed using primary and backup routes $1 \rightarrow 5 \rightarrow 4$, and $1 \rightarrow 3 \rightarrow 4$ on wavelength λ_1 . The backup route for R_3 can be assigned the wavelength λ_1 and it can share this wavelength with the two other backup paths, since the corresponding primary paths are link disjoint.

TABLE I
PRIMARY AND BACKUP PATHS BEFORE FAILURE.

Requests	Primary Lightpath	Backup Lightpath
$R_1 (1 \rightarrow 2)$	$(1 \rightarrow 2) - \lambda_1$	$(1 \rightarrow 3 \rightarrow 2) - \lambda_1$
$R_2 (2 \rightarrow 3)$	$(2 \rightarrow 3) - \lambda_1$	$(2 \rightarrow 1 \rightarrow 3) - \lambda_1$
$R_3 (1 \rightarrow 4)$	$(1 \rightarrow 5 \rightarrow 4) - \lambda_1$	$(1 \rightarrow 3 \rightarrow 4) - \lambda_1$

Let there be a failure at link $e (1 \rightarrow 2)$ as shown in Fig. 1(b). The effected primary route is $P_1 : 1 \rightarrow 2$. The effected backup connections which were multiplexed on the effected link e correspond to requests R_2 and R_3 , whose primary and backup path combinations are shown in Table I.

After the failure of link e , $B_1(e) : 1 \rightarrow 3 \rightarrow 2$ restores P_1 and P_2 , respectively, as shown in Fig. 1 and Table II. A

new alternate backup connection corresponding to P_1 should be found on the graph so that the connection can tolerate a second failure in the network. This backup connection is referred to as $B_1(f)$, since it guarantees restoration for the second failure f in the network. Assuming each request is of unit capacity and each link is a bidirectional link having a capacity of one unit in each direction, in the above example $B_1(f)$ doesn't exist. Thus, this request cannot be restored in the event of a second failure overlapping in time and incident on one of the links of $B_1(e)$.

TABLE II
PRIMARY AND BACKUP PATHS AFTER FAILURE OF LINK 1-2.

Requests	Primary Lightpath	Backup Lightpath
R_1 (1→2)	(1→3→2) - λ_1	No routes possible
R_2 (2→3)	(2→3) - λ_1	(2→5→3) - λ_1
R_3 (1→4)	(1→5→4) - λ_1	No routes possible

P_2 corresponding to the backup connection $B_2(e)$ that was multiplexed on the failed link 1 → 2, needs to find $B_2(f)$. Since P_2 remains unaffected by the link failure, it can potentially reroute its backup such $B_2(f)$ can also be multiplexed. However, this is constrained by the available capacity on a link and more importantly, the availability of an alternate backup path in the first place because the failure of a critical link may cause complete disconnection of the graph. It is important to note that primary and backup connections that are unaffected by any link failures remain uninterrupted in their service and are not re-routed.

The second alternate backup path for the connection R_2 is given by $B_2(f) : 2 \rightarrow 4 \rightarrow 3$. Moreover, the routing of request R_1 along $B_1(e)$ would force R_3 to search for a new alternate backup path to tolerate a second link failure, due to the capacity constraint on link 1 → 3. However, request R_3 fails to find $B_3(f)$ and hence cannot be recovered in the event of a second overlapping link failure along its primary path.

IV. COVERAGE FOR DUAL FAILURE SCENARIOS USING SUB-GRAPH ROUTING

In this section, the capability of the sub-graph routing scheme, presented in [1], to tolerate sequential overlapping link failures in the network is studied. A network comprised of nodes and links can be viewed as a graph G , defined as a set of V vertices and E edges, or in mathematical terms $G = (V, E)$. Hence, there exists a set of sub-graphs of G , denoted by G_i , where one edge e_i is removed from the graph, $\exists_{\forall i \leq |E|} G_i = \{V_i = V, E_i = E - \{e_i\}\}$, where $|E|$ is the cardinality of the set of edges in the graph G . Therefore there exists $|E|$ sub-graphs of graph G , each one missing link e_i .

The set of $|E|$ sub-graphs represent all possible single-link failures in the network. The original graph is referred to as the *base network*. The base network's constituent sub-graphs

are not referred to as networks because they correspond to a base network state reached through failure of any one link.

In the sub-graph routing strategy, a connection request is accepted in the base network only if it can be routed in all the sub-graphs. Hence, the accepted connections are guaranteed restorability against all single link failure scenarios. If any link, e_i , fails in the network, the network transitions to the state of the sub-graph, G_i , and some of the connections directly unaffected by the failure in the base network are potentially re-routed corresponding to the routing of the requests in sub-graph G_i . Let us consider that the link 1 → 3 fails. The network tries to restore all the present connections by migrating to the sub-graph G_4 as shown in Fig. 2.

In order to ensure that these requests also have complete coverage against a second link fault in the network, we delete the corresponding failed link e_i from the other $|E| - 1$ sub-graphs, and route the compromised connections in G_4 on the remaining sub-graphs. The connections that get accepted in all the remaining sub-graphs satisfy complete 100% coverage against all overlapping dual-failure scenarios. However, the connections which are unsuccessful in being rerouted in the remaining sub-graphs are guaranteed restorability only against the initial single link failure. Thus we can efficiently route connections that are protected against all single link failures, and hopefully a high percentage of all possible sequential overlapping dual link failures, using a heuristic best-effort strategy.

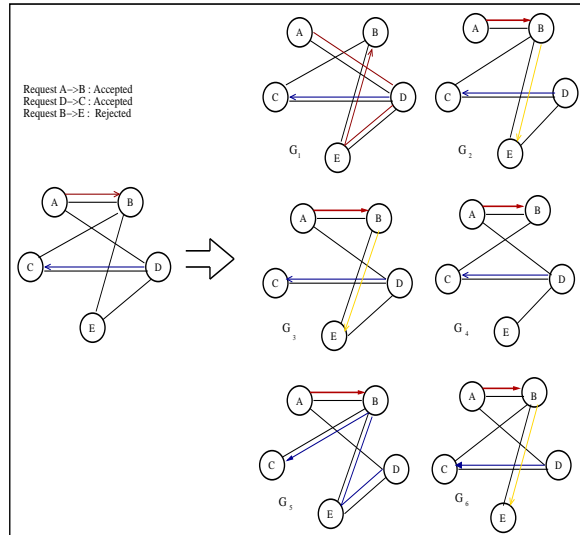


Fig. 2. Rerouting of requests upon failure of link 1 → 3.

V. COMPLEXITY ANALYSIS FOR SUB-GRAPH ROUTING

The following section analyzes the complexity of the sub-graph routing algorithm while ensuring complete dual-failure coverage. In order to route a connection R_i in the *base*

network, the connection needs to be routed in all the $L = |E|$ sub-graphs. The time complexity of routing a request R_i in a network is governed by the complexity of the routing algorithm. In our case, Dijkstra's shortest path algorithm can be used for routing the connections in each of the L sub-graphs. The complexity of the Dijkstra's shortest path algorithm is given by $O(N^2)$ [13], where N is the total number of nodes in the network. Thus, the overall complexity of routing these requests using Dijkstra's is $O((L + 1) \cdot N^2) \approx O(L \cdot N^2)$. It is important to note that sub-graph routing is not limited to using only shortest path routing, but rather can accommodate any other desired routing metric.

After the failure of the first link e , the network makes a transition from the base network to the G_e^{th} sub-graph. Now to ensure restorability against failure of another link f , a sub-set of connection requests need to be re-routed on the remaining $L-1$ sub-graphs, that is all sub-graphs except the G_e^{th} graph. The requests that need to be re-routed on all the $L-1$ sub-graphs in order to tolerate a second fault would require an additional worst case computation of $O((L - 1) \cdot N^2)$. Thus the worst case complexity for routing each request for dual-failure survivability is $O((L + 1)(L - 1) \cdot N^2) \approx O(L^2 \cdot N^2)$. However, in the following section we will show that the size of the sub-set of requests that have this worst case routing complexity is relatively small.

In [12], the concept of constrained sub-graph routing is presented. Constrained sub-graph routing requires that each sub-graph containing all of the links of a request's selected path in the base network use the same path. In other words, if a request's path contains l links, that request, if accepted, will be routed on the same path in the base network as well as $L-l$ sub-graphs. Constrained sub-graph routing has been shown to increase network performance by decreasing blocking probability and the probability of reassignment. The probability of reassignment is the probability that an active connection in the network will have to be reassigned in the event of a fault. Constrained sub-graph routing also lowers the time complexity of routing in sub-graph routed networks. Instead of a complexity of $O((L + 1) \cdot N^2)$, assuming the use of Dijkstra's, an overall time complexity of $O((L + 1 - (L - l)) \cdot N^2) \approx O(l + 1 \cdot N^2) \approx O(l \cdot N^2)$, where l is the length of the path, is achieved because a path need only be selected for the base network and the l sub-graphs that don't contain all of the links of the path selected by the base network. The path in $L-l$ sub-graphs is already selected through constraining the path to be the same as in the base network.

As a result of sub-graph routing being a recursive technique, the time complexity of connection recovery from a link failure also changes. $O(((L + 1 - 1) - 1 - (L - l - 1)) \cdot N^2) \approx O(l \cdot N^2)$ is needed for the recovery because the connection doesn't have to be routed on the G_e^{th} or the base network, and due to path constraining, $L - l - 1$ sub-graphs will route the connection exactly like the G_e^{th} sub-graph. This, along with the original routing time complexity discussed in the

previous paragraph, yields an overall time complexity for a single overlapping sequential link failures of $O(l^2 \cdot N^2)$ instead of the $O(L^2 \cdot N^2)$ time needed in unconstrained sub-graph routing.

This formulation can be extended in a recursive fashion for any number of sequential overlapping link failures. Let r ($r > 0$) be the recursive depth of the recovery, i.e. the number of sequential overlapping link failures. If $r = 1$, there have been no single link failures (100% link failure protection), $r = 2$ there has been 1 link failure (heuristic best-effort overlapping sequential link failure protection), and so on. This yields the complexity $O(l^r \cdot N^2)$, and indicates a network capable of providing 100% single link failure protection for $r = 1$ and heuristic best-effort protection for r overlapping sequential single link failures.

VI. RESULTS

The performance of both the backup multiplexing and the sub-graph routing schemes are evaluated through simulation. Three topologies were used: the 14 node, 23 link NSFNET; the 11 node, 22 link NJLATA; and a standard 9 node, 18 link 3x3 mesh torus.

The blocking probabilities for both schemes are computed in the absence as well as presence of faults in the system. The sub-graph routing strategy had shown considerably lower blocking in the absence of faults as compared to the backup multiplexing scheme [1]. In this paper, we primarily focus on the blocking probabilities in the presence of faults for backup multiplexing, and the blocking probability for sub-graph routing with and without randomly occurring single-link faults. For simulation purposes, each link is assumed to be composed of two-unidirectional links, each with only one fiber. The total number of wavelengths used are $W = 16$ for each fiber in each unidirectional link.

The performance of the network in the presence of faults has been assessed in two ways. In the first, an arbitrary link is failed randomly and repaired during the simulation time frame as a fault would occur in a real world situation. In the second scenario, the simulation is paused periodically, and the network state is tested against all possible link failures. The simulation then continues without the network state being altered by the occurrence of any fault.

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 unit wavelength. The random link faults are assumed to occur following a Poisson distribution.

Link load is a measure of the load placed on each link in the network at any given time. It is useful in providing a baseline for the comparison of the effectiveness of routing strategies across different network topologies. The link load can be calculated by the formula, $\gamma = \frac{N \cdot \lambda \cdot H}{L}$, where N is the number of nodes in the network, λ is the arrival rate of

the requests per node, H is the average hop length of each connection and L is the total number of links in the network.

Blocking probability, as illustrated in Fig. 3, shows how the backup multiplexing and sub-graph routing perform with and without the presence of random faults. The blocking probabilities of the sub-graph routing strategy are extremely low compared to the backup multiplexing scheme and reasonably close to the blocking probability achieved in the presence of no faults.

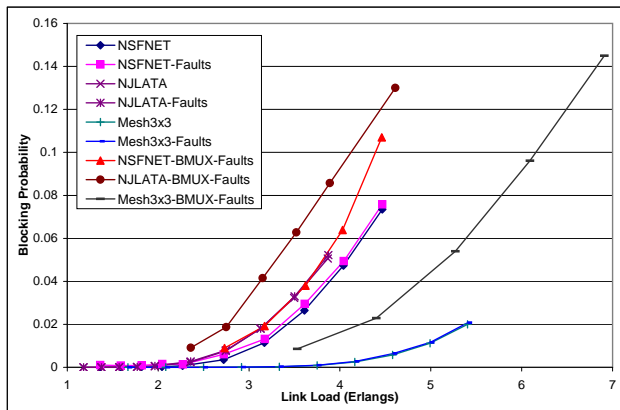


Fig. 3. Blocking Probability vs. Link Load

Depicted in Fig. 4, **automatic sequential overlapping fault coverage**, indicates that around 72-81% of connections are automatically covered for all possible dual-failures, across different topologies, without being rerouted, in the sub-graph scheme as compared to 49-70% for the backup multiplexing routing strategy. The automatic dual-failure coverage in the sub-graph routing strategy is calculated as the number of connections in the final sub-graph G_e (reached by the failure in the link e), that don't need to be rerouted in the other $L-1$ sub-graphs, and hence are automatically covered for two link failures, the first failure being on link e .

High automatic coverage is important because it means that fewer connections will have to be rerouted in the event of a single link failure, in order to provide protection against a second overlapping failure. Section V discussed the time complexity of the proposed sub-graph routing scheme in terms of the amount of time required to recover from a single fault on a per connection basis. Having said this, the fewer connections, the less work that needs to be done to recover.

Additionally, higher automatic coverage means that active connections also have a better chance of being protected against a second link failure because the connection does not have to attempt rerouting. The total capacity reservation for tolerating a single fault in the backup multiplexing scheme has been shown to be around 150-160% [14]. Thus the probability of reserving a second path, in the event of a fault, to tolerate a second failure is extremely low either due to lack of capacity in the network or due to graph disconnection

caused by the first failure.

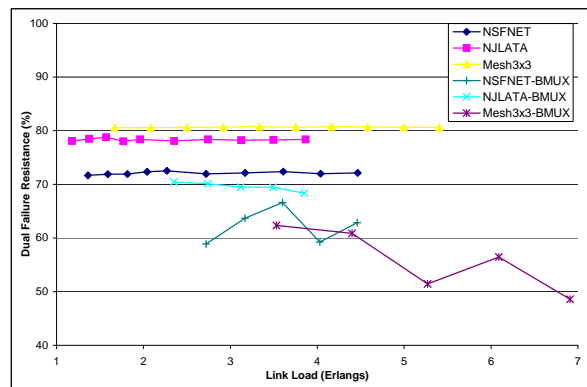


Fig. 4. Automatic Dual-failure Coverage vs. Link Load for Periodic Testing

Dual-failure restorability in the presence of random faults is shown in Fig. 5 and is an indication of the degree of restorability that can be achieved by both algorithms in the event of random faults in the system. The sub-graph routing strategy achieves a significantly higher degree of restorability when compared to the backup multiplexing scheme. Although the backup-multiplexing scheme is able to achieve total restorability varying between ~ 60 -97% across different topologies, the sub-graph routing scheme achieves a restorability over 95% for all topologies.

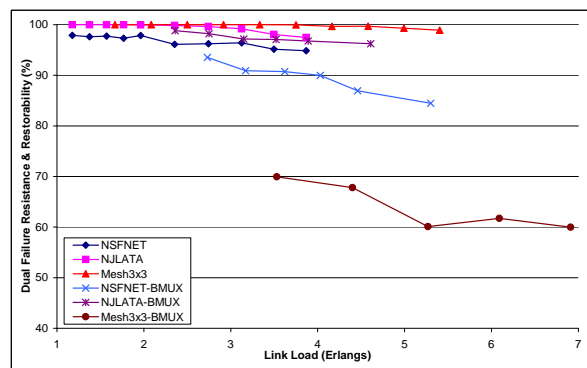


Fig. 5. Total Restorability vs. Link Load for Random Testing

Dual-failure restorability in the presence of periodic faults, depicted in Fig. 6, indicates the complete network wide dual-failure restorability achieved by both the restoration algorithms. In the presence of periodic faults, restorability is computed by successively failing each link in the network, computing the coverage for a second failure, and averaging it over all possible dual-failure scenarios. The network is left in its original state. The total dual-failure restorability achieved by both the algorithms is quite high (~ 62 -96%) except for MESH3x3 where the sub-graph routing strategy out-performs the backup multiplexing scheme.

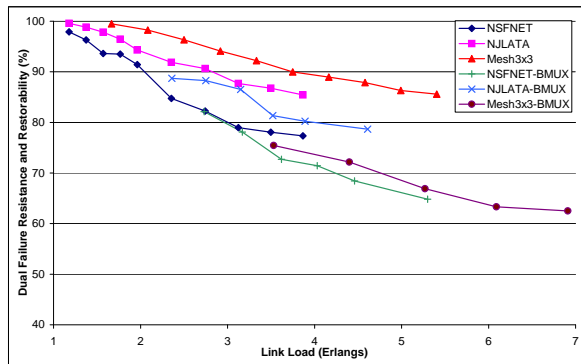


Fig. 6. Total Restorability vs. Link Load for Periodic Testing

Sub-graph routing provides a passive form of redundancy without any physical allocation of any redundant capacity in the network, by maintaining the state information of L distinct sub-graphs of the network. Effectively, there is a trade off between the physical redundant capacity that needs to be stored in the network to achieve fault-tolerance in the case of backup multiplexing, and the reconfiguration and redundant network states that need to be maintained in the sub-graph routing strategy. However, since network state information is always cheaper to maintain than physical allocation of spare capacity, the sub-graph routing strategy is a viable alternative routing methodology in WDM optical networks.

VII. CONCLUSION

In this paper the performance of the sub-graph routing strategy and the backup multiplexing scheme for tolerating a second link fault in a network was evaluated and compared. The sub-graph routing strategy attempts to maximize the number of connections covered for all second-link faults ensuing an arbitrary link failure by allowing connections automatically covered against a second failure to remain and attempting to reroute compromised connections.

Proactive sub-graph fault tolerance has the ability to protect against all possible multi-link failures for which its sub-graphs are designed. It also has the advantage of having pre-determined sub-graph states that the base network can emulate in the event of a failure. However, proactive fault tolerance has the drawbacks of not being able to handle all possible multiple link failure situations, as well as sequential overlapping link failures.

Reactive sub-graph fault tolerance addresses some of these pitfalls by employing a recursive method for tolerating numerous sequential overlapping failures. It can also tolerate simultaneous multiple link failures simply by serializing the handling of each individual fault. One of the drawbacks of reactive fault tolerance is that it can rarely provide 100% protection for all connections against subsequent link failures, although simulation results have shown that protection against

a subsequent link failure is on the order of 75-96%. Another drawback is that it can't simply begin reconfiguring the network as soon as a multi-link fault occurs, but must first attempt to reroute all compromised connections for one fault, and then handle another. For example, if an SRLG were to fail in a reactive sub-graph fault tolerant network, each of the link failures in the multi-link failure would have to be handled sequentially. Network reconfiguration cannot occur until all faults are processed and recovered from.

The best solution to multi-link fault tolerance would be to employ a hybrid of reactive and proactive sub-graph fault tolerance. Initially sub-graphs will be defined taking into account link, SRLG, or node failures, and could, in the event of an unrelated or subsequent multi-link failure, incorporate the reactive form of sub-graph fault tolerance. Incorporating a hybrid approach to fault tolerance using sub-graph fault tolerance provides a complete solution to the problem of multiple link failures in optical networks.

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