OPTICAL MESH NETWORK MODELING: SIMULATION AND ANALYSIS OF RESTORATION PERFORMANCE

Ahmet A. Akyamaç, Jean-François Labourdette, Kuolin Hua, Ziggy Bogdanowicz, Sid Chaudhuri, Stephen French
Tellium Inc., 2 Crescent Place, Oceanport, NJ 07757
Email: aakyamac@tellium.com, Tel: (732) 483-3073, Fax: (732) 483-3357

Abstract

Optical mesh networks using intelligent optical switches are the choice for the next generation optical core. Mesh networks supporting shared mesh restoration provide many advantages over ring networks and can be designed for fast and guaranteed recovery from single link or node failures. The restoration latency performance depends on numerous factors that can have an impact on service level agreements. Network deployment is tedious and making changes after equipment is deployed can be very expensive and time consuming. Thus, it is important to predict restoration performance before deployment and make changes to network design if necessary. Hence, modeling, simulation and analysis of shared mesh restoration performance is an important part of network design and deployment. In this paper, we present two approaches to restoration performance modeling of core mesh networks, namely simulation and analysis, and how they are used as part of the network design and deployment process.

1. Introduction

Dense Wavelength Division Multiplexed (DWDM) optical mesh networks using intelligent optical cross-connect (OXC) switches are the choice for the next generation optical core [1]. Mesh networks provide many advantages over ring networks. These include significant bandwidth and cost effectiveness, dynamic provisioning in the presence of unpredictable traffic, fast setups and interconnections, and smaller footprint [2]. Contrary to rings, the capacity of a mesh network can be increased on a link by link basis, making the network more flexible and scalable. Furthermore, mesh networks can be designed for fast and guaranteed recovery from single link or node failures and can be designed to protect traffic more efficiently via shared mesh restoration [3]. Multiple failures could lead to service outage in ring networks, whereas reprovisioning can be used in mesh networks to find a new backup path. As a result of this, mesh networks are in general more reliable than ring networks [4]. The restoration latency performance depends on numerous factors such as network topology, number of lightpaths that need to be restored after a failure, etc. [5],[6]. These factors can have an impact on service level agreements. Network deployment is tedious and making changes after equipment is deployed can be very expensive and time consuming. Thus, it is important to predict restoration performance before deployment and make changes to network design if necessary. It is imperative to be able to accurately predict network behavior with changing topologies, traffic, failure conditions etc. Hence, modeling, simulation and analysis of shared mesh restoration performance is an important part of network design and deployment.

In this paper, we present two approaches to restoration performance modeling of mesh networks, namely simulation and analysis, and how they are used as part of the network design and deployment process.

The simulation approach relies on an interactive tool that models the details of the restoration architecture and protocols. The tool can provide accurate estimates of restoration performance for various failure scenarios and present the results as a set of statistics. Using a commercially available optical mesh network modeling and simulation tool, we estimate the restoration latency for a set of example networks. The second approach uses a coarse analytical approximation of the restoration latency. This approximation assumes that the topology is a random graph and the demand is uniform. The results are typically of the same order of magnitude as the results from the simulator. We also use the analytical approach to predict restoration times of lower granularity switches and show that restoration using core switches (with STS-48 granularity) can be significantly faster.

This paper is organized as follows: In Section 2, we first give a general description of the network design process that includes simulation and modeling. Next in Section 3, we give a brief description of the network model and shared mesh restoration. This is followed in Section 4 by the simulation approach for core mesh networks and in Section 5 by the approximation approach for core mesh networks and lower granularity switches, both illustrated through example networks. Conclusions are given in Section 6.

2. Simulation as Part of the Network Design and Deployment Process

Fig. 1 illustrates simulation and analysis as part of the network design process. This process can be used for both greenfield network design and incremental network design [7].

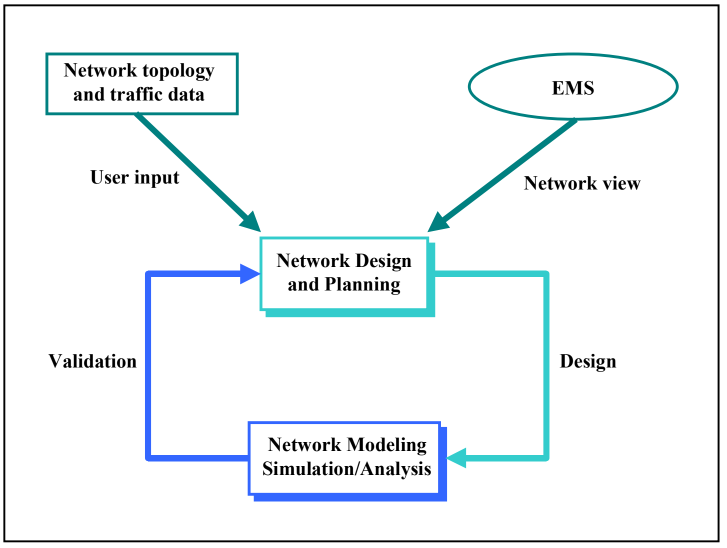

Figure 1: Network design and deployment process

In a greenfield network design, a network design and planning tool can be used to plan the new network based on topological information, equipment and cost information and traffic forecast. Subsequently, simulation and analysis can provide estimates and validate restoration performance based on different failure scenarios. The network design may be revised based on these results, thus initiating a design and validation cycle. Once a design is satisfactory from both a cost and performance point of view and has thus been validated, the planned network can then be deployed.

The design and validation cycle can also be used for already deployed networks in an incremental fashion. This cycle may be required as a result of numerous scenarios. For example, a network may have been deployed without adequate restoration latency planning and may need to be modified to satisfy a set of restoration latency criteria. Furthermore, new service level agreements may have been introduced requiring more stringent restoration latencies. Finally, new traffic forecast and expansion may require incremental changes to the network. In incremental network design, the network topology and traffic data can be input manually through text files or user interfaces or can be downloaded in real-time or discovered through element management systems (EMS).

It is not the scope of this paper to discuss greenfield and incremental network design techniques. For a discussion of such methods, see [7]. In this paper, we focus on simulation and analysis of mesh restoration latency. The subsequent section provides a brief description of shared mesh restoration.

3. Network Model and Shared Mesh Restoration

3.1. Network Model

We consider a network model of optical cross-connect (OXC) switches connected by fibers. The fibers contain multiple optical channels (wavelengths) that carry lightpaths. The lightpaths carry end-to-end traffic between switches and are restorable against link or node failures. We assume the restoration process is performed at the OXC level and do not model WDM systems for the purposes of restoration analysis. Fibers are carried through cables, which in turn pass through conduits, as shown in Fig. 2. A conduit may contain multiple cables, which in turn may contain multiple fibers carrying traffic for different source and destination switches. Failures of optical channels are usually due to fiber, cable or conduit cuts.

If a conduit or cable fails, fibers contained within them will also fail. The concept of shared risk optical group (SROG) expresses the risk relationship that associates all the optical channels with a single failure. The SROG may consist of all the channels in a single fiber, all channels in the fibers inside a single cable, or all channels in the fibers inside cables in a conduit. A fiber may traverse multiple conduits; hence channels may be associated with more than one SROG. If an SROG is failed, all channels in this SROG will fail.

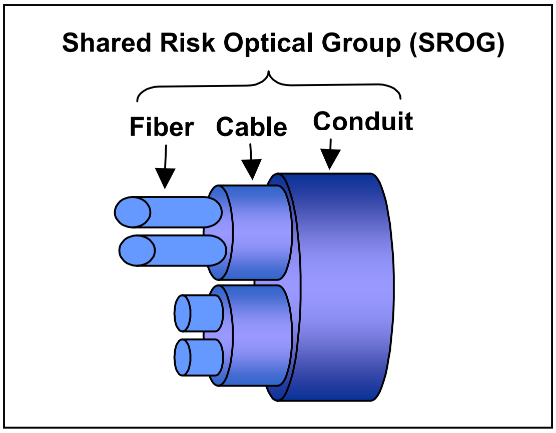

Figure 2: Shared Risk Optical Groups (SROG's)

3.2. Shared Mesh Restoration vs. Dedicated Mesh Protection

Dedicated mesh protection provides a fast and guaranteed 1+1 (i.e. UPSR/path switching) ring-like restoration protocol over a mesh topology, as illustrated in Fig. 3. The network consists of four switches (A to D) and two lightpath demands (AB and CD) routed across an eight node optical network (S to Z). The primary and backup paths for each lightpath are either SROG disjoint (for link disjoint routing) or SROG-and-node disjoint (for node disjoint routing). This path diversity guarantees that the primary and backup paths will not be simultaneously affected by the same failure. During normal operation, both paths carry the optical signal and the egress node selects one of the two copies. This is the fastest restoration scheme since the traffic is simultaneously received from both paths at the end node and for every lightpath one device is responsible for all the necessary failure detection and restoration functions. But it is also the most capacity-intensive since the protocol uses full protection capacity redundancy [8].

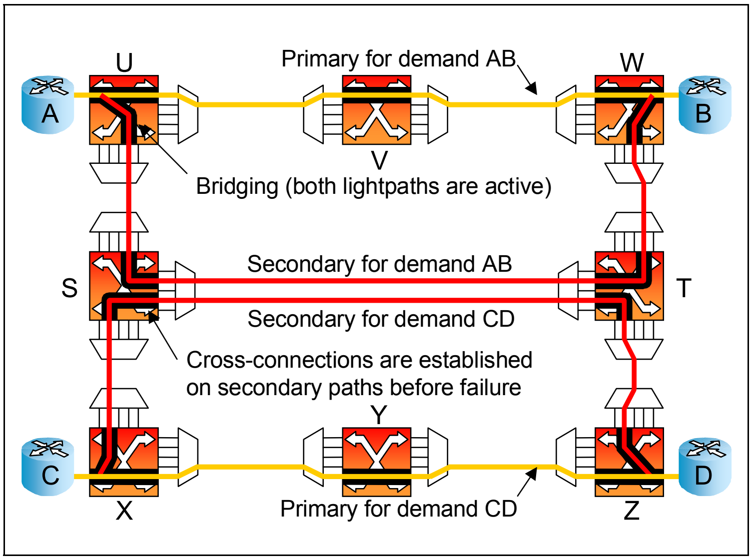

Figure 3: Dedicated mesh protection (1+1)

Shared mesh restoration provides a capacity-shared 1:N (i.e. BLSR/MSSPRING) ring-like restoration protocol in which pre-computed backup paths for multiple primary paths can share protection capacity. Thus, using shared mesh restoration can result in improved bandwidth utilization and lower total network cost. In this protocol, backup paths are pre-defined but the cross-connections along these paths are not created until a failure occurs. This is illustrated in Fig. 4.

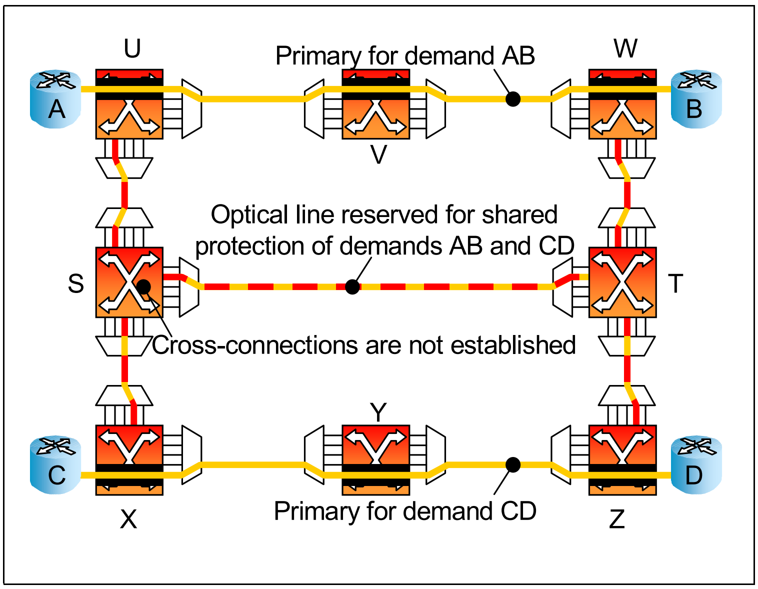

Figure 4: Shared Mesh Restoration (1:N)

In shared mesh restoration the backup paths can share capacity if the corresponding primary paths are mutually diverse (SROG diverse or SROG-and-node diverse). The backup path is reserved (but not *live* since multiple lightpaths can be sharing it). Hence, recovery may be slower than dedicated mesh protection since it involves signaling and path setup to establish the cross-connections on the backup path during restoration. Compared to dedicated mesh protection, this scheme allows considerable savings in terms of capacity required and ultimately, cost [9].

The restoration latency for shared mesh restoration is thus influenced by numerous factors such as topology, traffic load, distribution of lightpath endpoints, etc. In the following, we use simulation and analysis to estimate restoration latencies for different scenarios.

4. The Simulation Approach

4.1. Simulation Tool and Restoration Latency Study Methodology

The simulation approach relies on an interactive tool that accurately models the details of the restoration architecture and protocols. The tool can provide estimates of restoration performance for various failure scenarios and present the results as a set of statistics.

The following is the series of steps typically taken to perform a restoration latency study using the interactive tool:

i. Enter network topology through a GUI, text based interface or input from a planning tool or EMS system.

ii. Enter end-to-end demand information through a GUI, text based interface or input from a planning tool or EMS system.

iii. Provision (route) demands using either SROG or SROG-and-node disjoint shared mesh routing. The output of this step would be a set of primary and backup paths for each of the demands and a set of network channel states (for primary paths and shared backup paths). Alternatively, this information can be obtained from a planning tool or EMS system.

iv. Identify and rank links (SROG's) or nodes to fail in the network based on the expected impact the failures would have on the restoration performance.

v. Define failure events and times for the chosen links (SROG's) or nodes. This step constitutes the definition of the what-if analysis. The failure events defined will potentially cause wavelength services to fail, thus triggering restoration processes.

vi. Run simulation. The event-based simulator will go through the failures, the restoration triggering, the messaging and the restoration protocol itself, and will determine estimates of the restoration latencies and other restoration-related statistics for observation and analysis.

Note that an accurate representation of restoration latencies in this methodology is possible if the simulation tool meets certain requirements. For example, the tool should model the restoration protocols, delays and other processing in the switch hardware, messaging sequences etc. in order to generate statistical estimates of restoration latencies. In this regard, simulation tools are typically product-specific and are ideally offered by switch vendors as part of a total network design and deployment solution [10].

In this paper, we use a commercially available simulation tool called StarNet Modeler to conduct restoration studies. StarNet Modeler is a mesh network restoration modeling, simulation and visualization tool developed by Tellium. It models core mesh network topologies consisting of Aurora Optical Switches (AOS's) with STS-48 wavelength switching interconnected by a hierarchy of fibers, cables and conduits. StarNet Modeler incorporates the same route computation module used in Tellium's EMS (called StarNet Wavelength Management System – WMS) and contains detailed state machines to model

Tellium's mesh restoration protocols (embedded in the StarNet OS). The simulation tool's network and switch models are calibrated using measurements from the AOS and experimental results from testbeds. The restoration simulation is event driven and the simulation engine is provided by Opnet [10]. A typical restoration study using StarNet Modeler would involve steps *i.* to *vi.* above. StarNet Modeler also interfaces with the planning tool StarNet Planner (also developed by Tellium [11]) as depicted in Fig. 1; the latter tool will not be discussed here as it is not in the scope of this paper.

4.2. Simulation Studies

We first present restoration simulation results for a hypothetical 17 node North American carrier network. The screenshot of the simulation tool with this network is shown in Fig. 5. For this network, the average node degree of connectivity is 3.1 and there are 224 OC-48 lightpaths (with randomly selected end nodes) routed using link disjoint shared mesh routing. Fig. 5 shows a geographical layout of the network with office locations (this network has one switch per office), conduits and connections between the offices through these conduits. This view does not show the cables or fibers, but does show the SROG dependencies as indicated on the figure.

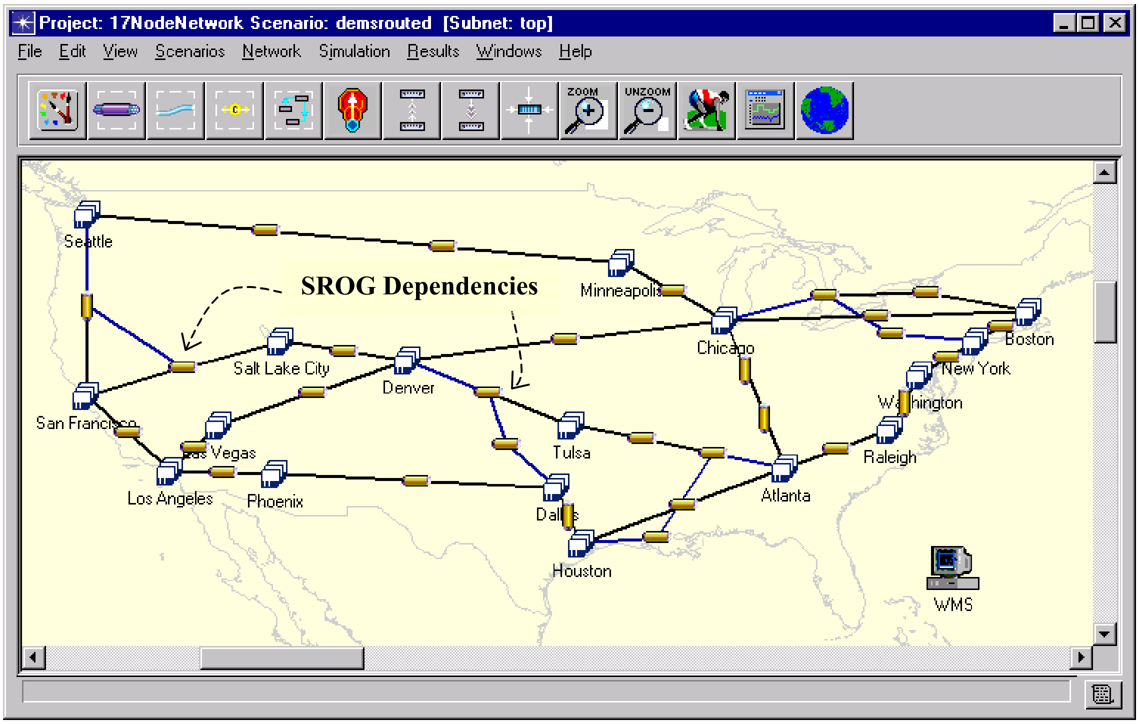

Figure 5: Screen shot of hypothetical 17 node network

The restoration simulation studies involve failing single conduits, which result in the simultaneous failures of the multiple primary lightpaths that traverse these conduits. The maximum restoration times shown correspond to the last lightpath restored (indicating the end of the restoration process).

The first set of results in Fig. 6 shows the maximum restoration latencies observed after failing conduits with 31 to 35 lightpaths. Even though the number of lightpaths failed was relatively close, the restoration latencies varied by ±25 ms. and were not necessarily directly proportional to the number of lightpaths failed. This variation is due to the fact that restoration latencies depend not only on how many lightpaths are to be restored, but also on how many of the failed lightpaths are processed by the same set of end nodes. The worst case occurs when the same set of end nodes processes all of the failed lightpaths. We use these observations in the development of the analytical approach in Section 5.

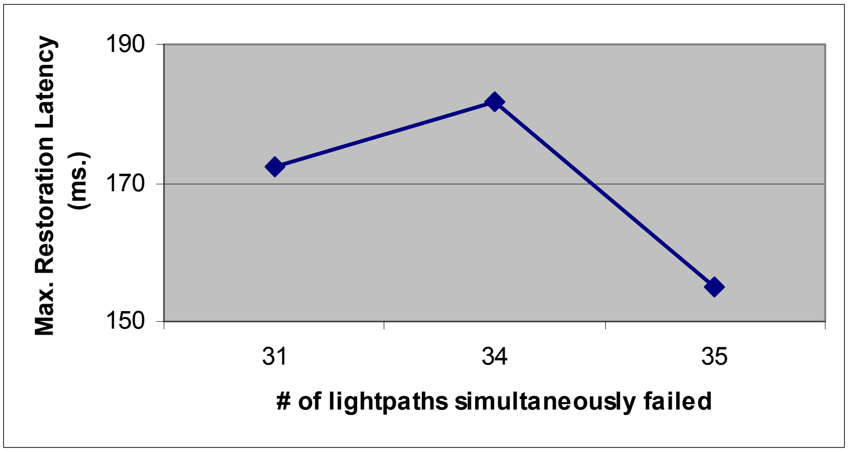

Figure 6: Restoration results for hypothetical 17 node network, 31-35 lightpaths failed

The second set of results for the 17 node network is shown in Fig. 7. This figure shows both the maximum and average restoration latencies after failing five single conduits throughout the network.

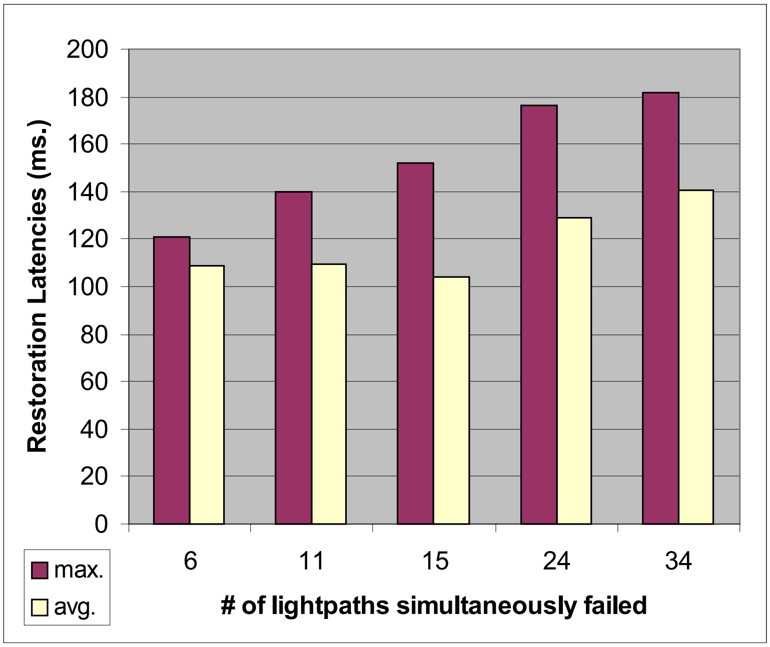

Figure 7: Restoration results for hypothetical 17 node network, 6-34 lightpaths failed

As mentioned above, the maximum restoration latency is for the last lightpath that is restored as a result of a conduit failure. The average restoration latency is calculated from the set of lightpaths that are simultaneously failed as a result of the conduit failure. The results in Fig. 7 show that restoration latency generally increases as more lightpaths are failed, even though there could be variations for a relatively close number of lightpaths as shown in Fig. 6. This study is representative of a what-if type study to determine the range of restoration latencies that can be expected from a network.

Next, we present restoration simulation results for a hypothetical 50 node European carrier network. The screenshot of the simulation tool with this network is shown in Fig. 8. For this network, the average node degree of connectivity is 3.44 and there are 910 OC-48 lightpaths with randomly selected end nodes routed using link disjoint shared mesh routing. For this restoration study, we fail the conduits that carry the maximum number of lightpaths.

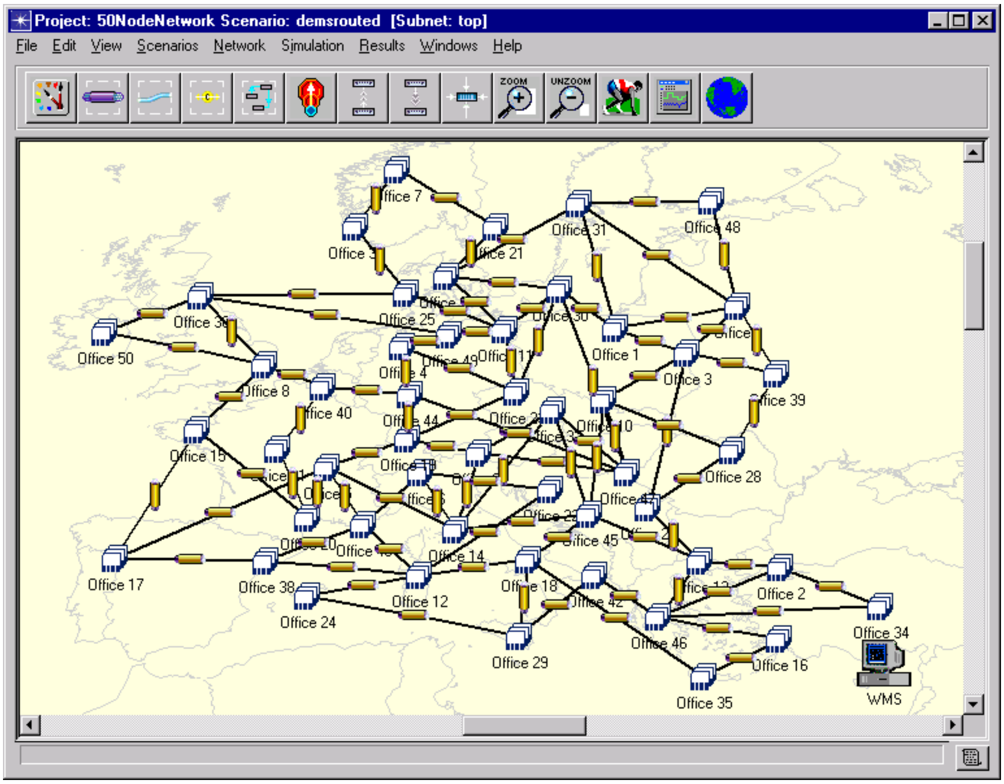

Figure 8: Screen shot of hypothetical 50 node network

The simulation results are shown in Fig. 9 for five different conduits failed. This study is representative of a study to determine the worst case restoration latencies can be expected from a network. We will also use this network for studies using the analytical approach in the next section.

5. The Analytical Approach

Shared mesh restoration studies using the simulation method show that restoration times are mainly influenced by the number of failed lightpaths processed by a switch during restoration. This was also observed in the simulation results shown in Fig. 6 in Section 4 for the hypothetical 17 node network. In particular, the worst case occurs when all lightpaths terminate at the same two end switches rather than at switches distributed throughout the network. Furthermore, simulation studies have shown that, for a given topology and a given set of primary and backup routes, the restoration time increases roughly linearly as the number of lightpaths simultaneously failed is increased. Thus, a coarse analytical approximation can be constructed which assumes the worst case scenario involving the maximum number of lightpaths that are processed by the same number of end nodes. The analytical approximation assumes a linear dependency between the restoration time and number of lightpaths restored.

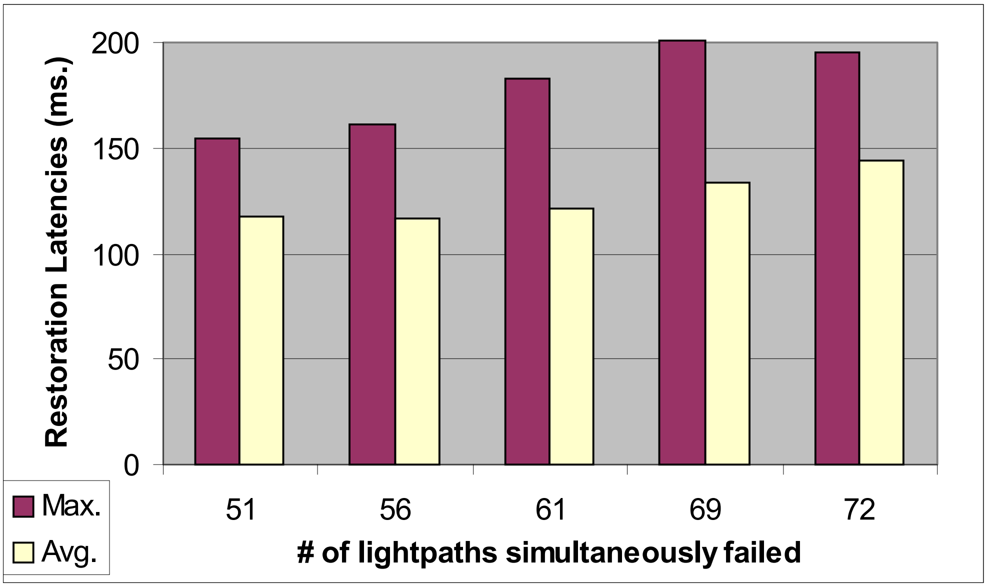

Figure 9: Restoration results for hypothetical 50 node network, 51-72 lightpaths failed

The inputs to the analytical approximation include the following information:

i. Topological information: Number of nodes, average node degree of connectivity, average link length, protection schemes at ingress/egress switches (e.g. linear automatic protection switching [11]).

ii. Traffic information: Network utilization, backup channel sharing ratio.

These inputs can be easily obtained from the simulator or can also be used as parameters for a new network design. Using this information and assuming that the topology is a random graph and that the demand is uniform, it is possible to calculate the average number of lightpaths per link (n) and average number of hops on the primary paths (h) and backup paths (h'). The average path lengths can then be calculated using the average link length (l).

The average restoration latency can then be approximated using the worst case assumption that n lightpaths with h-hop primary paths and h'-hop backup paths all terminate at the same two switches and that a failure occurs in the middle link (SROG) of the primary path (in terms of number of hops).

The analytical approach uses a linear model to approximate the average restoration latency as follows:

$$T_r = T_0 + (n-1)\ L_s$$

where T_r is the final restoration latency for all lightpaths, T_0 is the restoration latency for the first lightpath and L_s is a parameter that represents the slope of the linear tail of restoration latency versus number of lightpaths restored. T_0 is calculated by assuming a single lightpath failure and processing the restoration protocol (triggering, messaging, processing at switches etc.).

Fig. 10 compares the coarse analytical results obtained for the same 50 node network in Section 4 with the simulation results. The analytically calculated restoration latency curve is shown in Fig. 10 versus the network utilization.

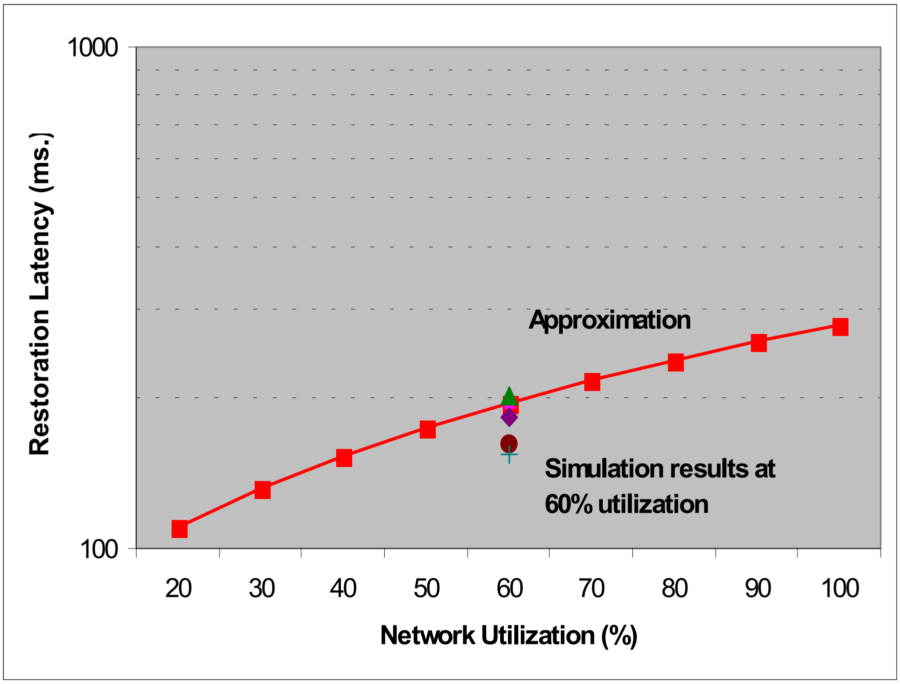

Figure 10: Analytical results vs. simulation results for hypothetical 50 node network

The actual 50 node network studies in Section 4 had a utilization of 60% (where n=36 lightpaths failed for the analytical approximation) and a backup channel sharing ratio of 0.46. In Fig. 10, we superimpose the simulation results for five single failure events affecting the most number of lightpaths at 60% utilization. As can be seen from this figure, the analytical approximation yields a restoration latency which is within the same order or magnitude of the results obtained using simulation. This behavior is typical of similar studies we have performed for different networks.

The analytical approximation can also be used to estimate the effects of lower switching granularity on restoration performance. The results presented in Fig. 10 used an AOS network switching at STS-48 granularity. In Fig. 11, we present analytical approximation results for the same 50 node network with switching performed at the lower STS-1 granularity. This means that, for every OC-48 lightpath to be switched, 48 switching operations have to be performed. Fig. 11 shows the approximation results for STS-48 switching compared to STS-1 switcing. As can be seen from Fig. 11, restoration using STS-48 granularity can be significantly faster than restoration using STS-1 granularity.

6. Conclusion

In this paper, we presented two approaches to restoration performance modeling, namely simulation and analysis, and how they are used as part of the network design process. The simulation approach relies on an interactive tool that accurately models the details of the restoration architecture and protocols. The tool can provide accurate estimates of restoration performance for various failure scenarios and present the results as a set of statistics. Using a commercially available optical mesh network modeling and simulation tool, we estimated the restoration times for a set of example networks. The second approach uses a coarse analytical approximation of the restoration latency. This approximation assumes that the topology is a random graph and the demand is uniform. The results obtained were typically of the same order of magnitude as the results from the simulator. We also used this approach to predict restoration times of lower granularity switches and showed that using STS-48 granularity can be significantly faster.

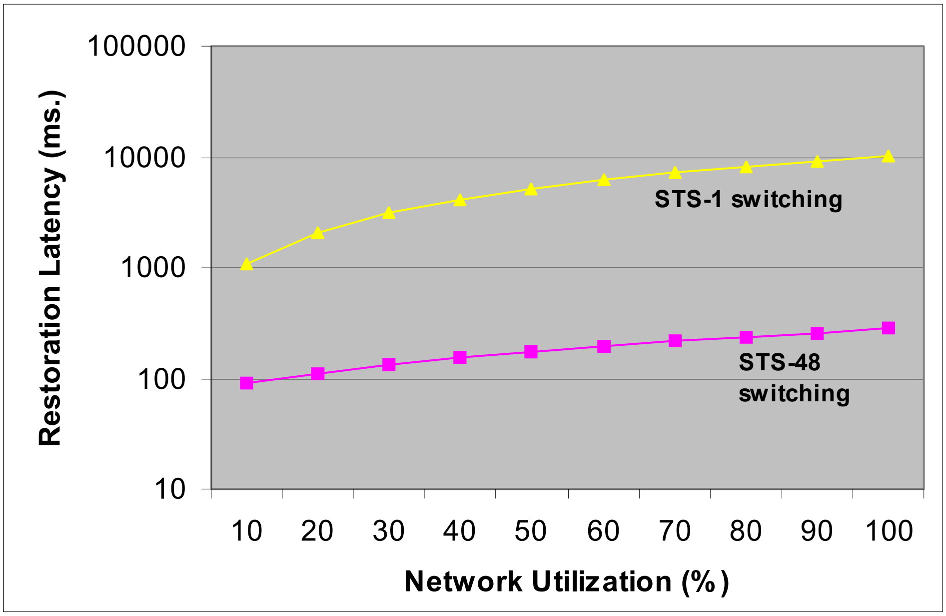

Figure 11: Analytical results comparing STS-48 an STS-1 switching for hypothetical 50 node network

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