RELIABILITY IN SINGLE DOMAIN VS. MULTI DOMAIN OPTICAL MESH NETWORKS

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Abstract

Network reliability is an important element of a service level agreement and is typically evaluated based on the number of unavailable minutes per year. The widespread belief is that networks with faster restoration times are more reliable, created by the assumption that fast restoration from a failure leads to smaller down time. This is not necessarily the case since it has been shown that reliability may have little to do with the restoration speed when the restoration time is small compared to the mean time to repair of the failed elements. In this paper, we compare the reliability of optical mesh networks with multi domain restoration and single domain restoration using both dedicated mesh protection and shared mesh restoration, and show that splitting a network into multiple domains increases the overall reliability.

1. Introduction

Network reliability is an important element of a service level agreement and is typically evaluated based on the number of unavailable minutes per year. The widespread belief is that networks with faster restoration times are more reliable, created by the assumption that fast restoration from a failure leads to smaller down time. It has been shown in [1] that this is not necessarily the case since reliability may have little to do with the restoration speed when the restoration time is small compared to the mean time to repair (MTTR) of the failed elements. For example, it has been shown that optical mesh networks are more capacity efficient than ring networks and, in general, more reliable [1]. The reliability of mesh networks is highly dependent on the restoration scheme, path lengths and MTTR of the elements in the network.

In this paper, we compare the reliability of optical mesh networks with multi domain restoration and single domain restoration. Primary lightpaths are protected by node and link disjoint backup paths through dedicated mesh protection or shared mesh restoration. Service unavailability occurs as a result of multiple concurrent failure scenarios where a failure can be caused by a fiber cut or equipment (WDM, amplifier, transceiver) failure. We use Markov models based on the sequences of events from working state to service outage. The unavailability is computed by assuming that when a lightpath becomes unavailable, it remains in that state until one of the failed components is repaired within the MTTR.

For a single domain network, the probability of failure along end-to-end primary and backup paths can be high, increasing the probability of service outage due to a double failure. A multi domain network consists of independent routing and restoration domains. Routing and restoration is strictly limited to each domain with shorter primary and backup paths. This not only decreases the probability of failure along the primary and backup paths, but also decreases the probability that multiple concurrent failures cause a service outage. We show that splitting a network into multiple domains increases the overall reliability.

This paper is organized as follows: In Section 2, we give a description of the network architecture including the domain structure and restoration methods. In Section 3, we give a brief description of the availability calculations, followed in Section 4 by a description of the Markov models used for the sequence of events. We compute the unavailability for an example system in Section 5 and show that splitting the network into multiple domains increases the overall reliability. We conclude in Section 6.

2. Network Architecture

2.1 Restoration Architecture

We consider a network model of optical cross-connect (OXC) switches connected by fibers through WDM systems. 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 consider two different restoration protocols.

Dedicated mesh protection provides a fast and guaranteed 1+1 restoration protocol over a mesh topology, as illustrated in Fig. 1. 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 link disjoint or link-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 [2].

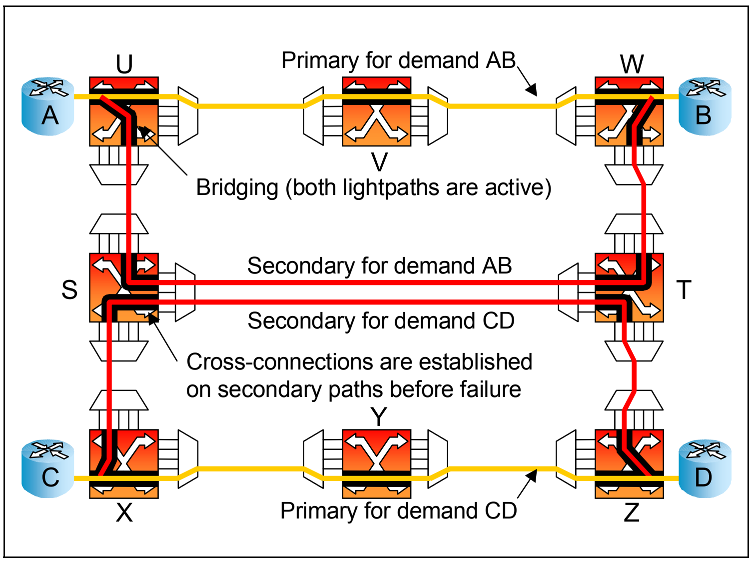

Figure 1: Dedicated mesh protection (1+1)

Shared mesh restoration provides a capacity-shared 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. 2.

In shared mesh restoration the backup paths can share capacity if the corresponding primary paths are mutually diverse (link diverse or link-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 [3].

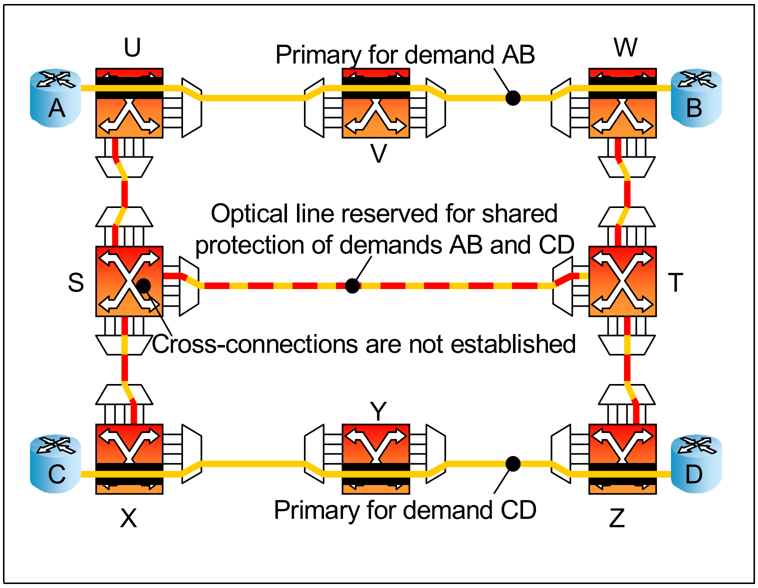

Figure 2: Shared Mesh Restoration

For shared mesh restoration, we also assume that reprovisioning is attempted if both primary and backup lightpaths fail. Reprovisioning involves routing on a newly calculated backup path. Furthermore, from an availability perspective, we also consider a case where local link or span protection is invoked first for channel failure [4]. In this mode, path protection follows if span protection fails or if there are subsequent channel failures.

2.2 Multiple Domains

For a single domain network, the backup lightpath can be routed through any portion of the entire network. Thus, it is possible that a local failure triggers a very long restoration event since the backup path itself may traverse the entire length of the network (see Fig. 3). Furthermore, the probability of failure along a longer lightpath is higher since a longer lightpath would traverse more components prone to failure (fiber, WDM, amplifier, transceiver, etc.).

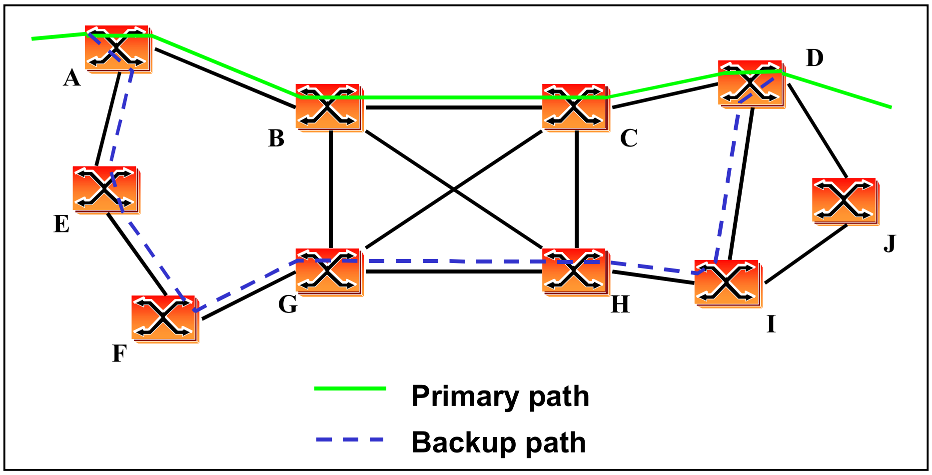

Figure 3: Single domain network

A multi domain network consists of independent routing and restoration domains. The domains are connected by two gateway nodes, primary and secondary, as shown in Fig. 4. The primary gateway acts as the restoration point for cable, equipment and intermediate node failures whereas the secondary gateway node is used to restore against the failure of the primary gateway node (handled via lightpath reprovisioning). Thus, the end-to-end lightpath consists of smaller lightpath segments that are routed between the gateway nodes. Routing and restoration is strictly limited to each domain, thus the backup paths for local failures will be contained in the domain and will not traverse into the neighboring domains [5]. This approach results in shorter local lightpaths and faster restoration [5]. The resulting end-to-end primary and backup lightpaths may be longer than the shortest lightpaths in the flat network; hence the multi domain mesh may achieve less sharing and thus require more capacity than the single domain mesh. However, the probability of failure is smaller along the shorter lightpath segments that are confined to a single domain. Furthermore, it is less likely that multiple failures will occur in the same domain, further reducing the chances of end-to-end service outage.

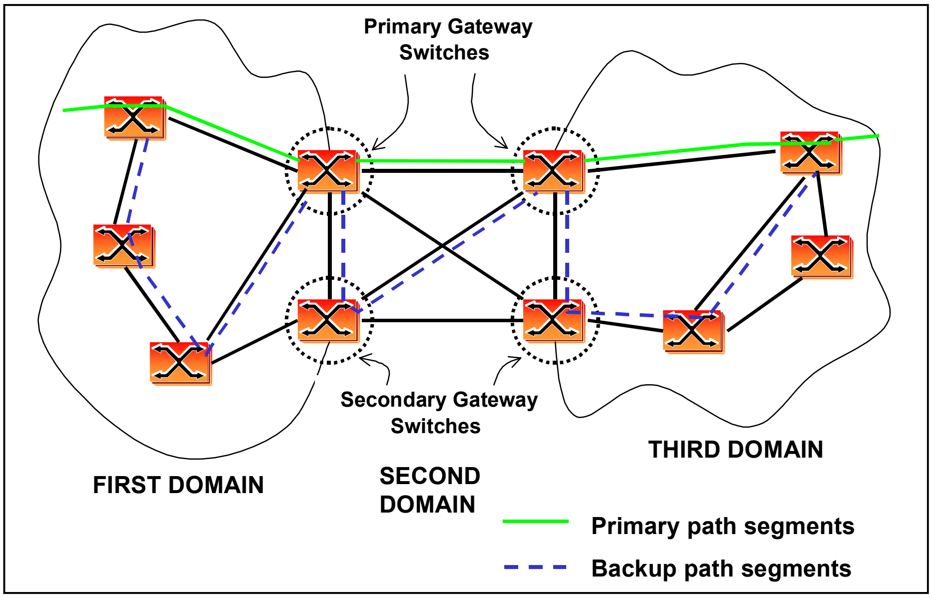

Figure 4: Multi domain network

3. Availability Model

The unavailability of the entire network is not simple to determine because of complex topologies and demand matrices. Furthermore, all connections do not have the same unavailability – longer lightpaths tend to have higher unavailability. We measure unavailability along the longest end-to-end lightpath.

To measure unavailability, we use Markovian models based on the sequences that show the transition from working state to service unavailability in Fig.'s 5 and 6 for dedicated mesh protection and shared mesh restoration, respectively. For dedicated mesh protection in Fig. 5, an outage occurs as a result of a failure on the primary path followed by a failure on the backup path before the failed components on the primary path are repaired. For dedicated mesh protection in Fig. 6, failures on the primary and backup paths are followed by reprovisioning, which attempts to find a new backup path. An outage occurs if reprovisioning fails. Furthermore, we also assume that shared mesh restoration may also include link or span protection, which is invoked in case of channel failures. As seen in Fig. 6, path protection is then invoked if link protection fails or if there are subsequent channel failures. We compute availability for two cases of shared mesh restoration depending on whether or not span protection is included.

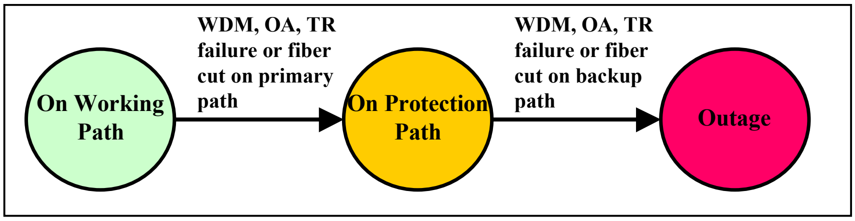

Figure 5: Dedicated mesh protection transition to outage

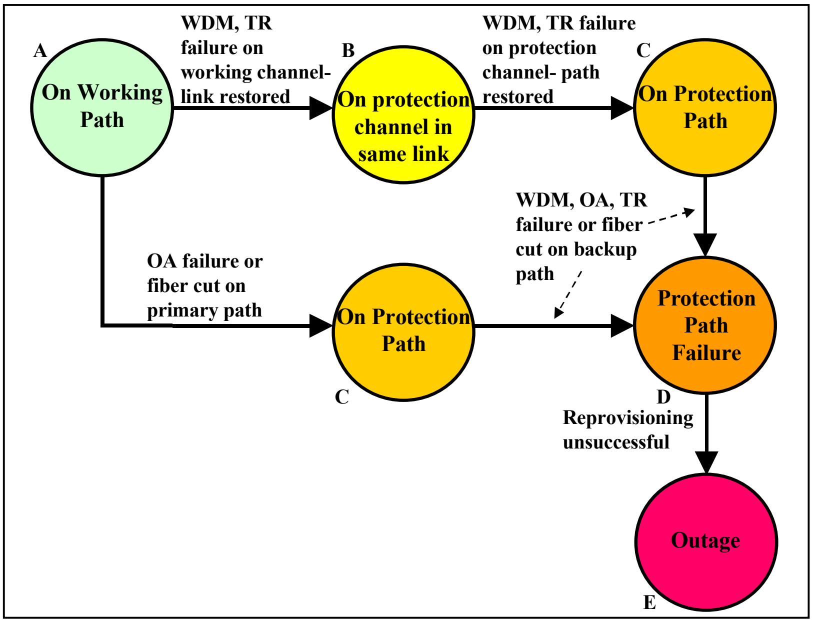

Figure 6: Shared mesh restoration transition to outage

Using the Markov model, we first compute the probability that a lightpath will become unavailable. The unavailability is then computed by assuming that when it becomes unavailable, it remains in that state until one of the failed components is repaired within the repair time MTTR. The failure probability of a lightpath is computed by using the FIT (failure in one billion hours) of all components on the link, the following relationships hold for each:

p_f (failure rate) = FITS*MTTR/1x10^9

MTBF (mean time before failure in mins.) = 1x10^9/FITS*60

Unavailability (mins./year) = p_f*365*24*60, Reliability (%) = (1-p_f)*100

Fig. 7 illustrates the different components traversed by the lightpath that are used in the availability model. The number of components such as WDM mux/demux units and amplifiers depends on the channel length and the number of spans and span length of the WDM systems. Multiple WDM systems are concatenated using transponders.

The overall unavailability is then computed using the overall failure rate for the service. This includes primary/backup path failure for dedicated protection and primary/backup path failure/reprovisioning failure for shared mesh restoration (and channel failure prior to path failure depending on whether or not span protection is used).

For the multi domain case, the unavailability is first computed for each domain since restoration is restricted to each domain. The overall unavailability is then calculated as the sum of the unavailability for each domain.

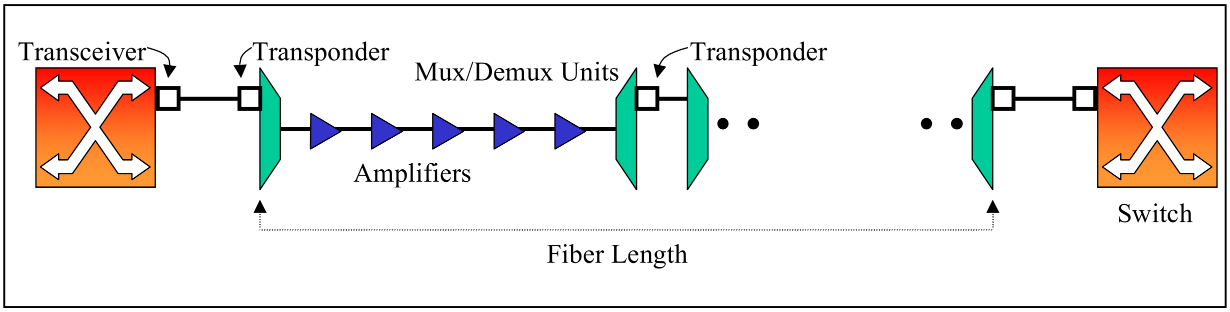

Figure 7: Components traversed by lightpath in availability model

4. Markov Model for Single Domain Availability

In this section, we discuss the mesh reliability model assuming span or link restoration is performed prior to path restoration. Fig. 3 shows a reference primary lightpath, P1 {A-B-C-D}, in a single domain mesh network consisting of optical switches interconnected by DWDM systems. The backup lightpath for P1 is B1 {A-E-F-G-H-I-D}. We consider the outage scenario for P1. There are essentially two types of failures on P1.

- The first one affects only a single channel. An example is the failure of a laser or a receiver on any of the interface ports either in the optical switch or the transponder in the WDM system on the lightpath.

- The other type of failure is when multiple channels fail due to one component failure such as fiber cut or an optical amplifier (OA) failure.

According to restoration protocol sequence, when the first type of failure occurs, the lightpath is restored using another optical channel within the same link, using span or link restoration (LR). However, for the second type of failure the lightpath is restored from the end nodes, using path restoration (PR). For example, if any one of the individual lasers or receivers on the channel in link A-B used by P1 fails, the lightpath may be restored locally by taking up the protection channel on the same link. On the other hand, if the entire link A-B fails, the lightpath is restored on B1. If B1 is also unavailable, a new backup path is computed by the network management system (NMS), or by the end nodes based on the available capacity in the network so the traffic may be restored. If no such alternate route is found, the restoration process is aborted and the service becomes unavailable. A flow chart of this shared mesh restoration process is shown in Fig. 8.

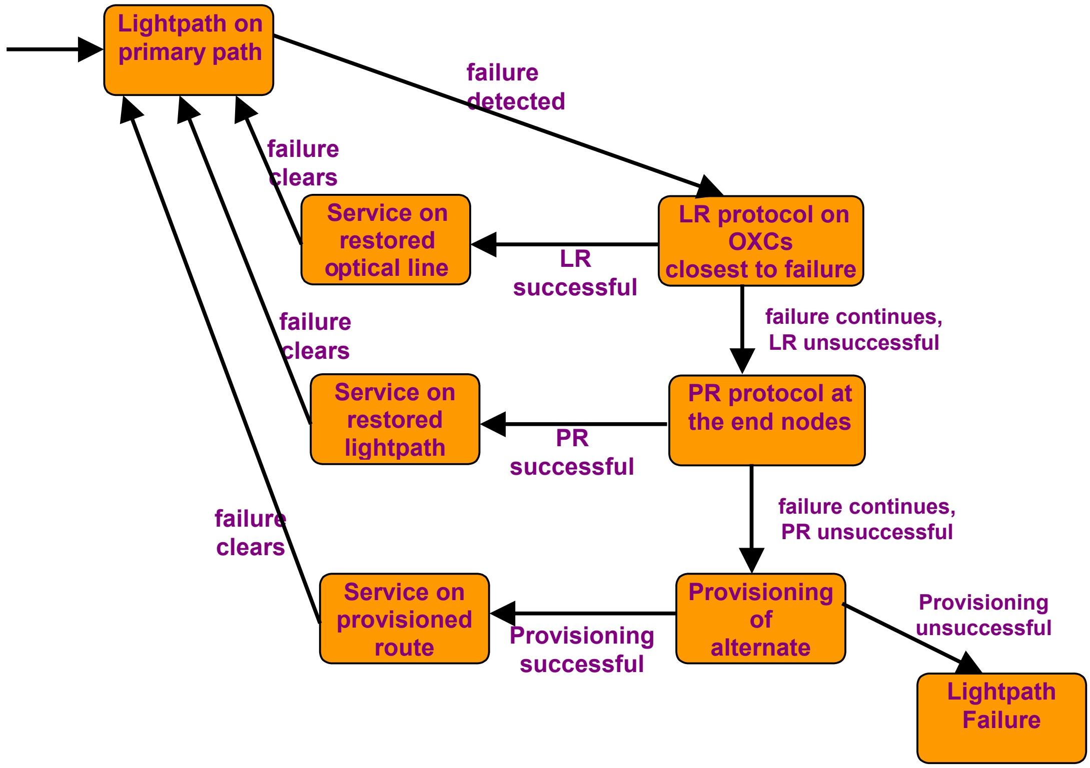

Figure 8: Flowchart of the shared mesh restoration process

The Markov model for a lightpath to transition from the working state to unavailable state is shown in Fig. 6. Using this Markov model, we first compute the probability that a lightpath will become unavailable. The unavailability is then computed by assuming that when it becomes unavailable, it remains in that state until one of the failed components is repaired within the repair time MTTR.

Since the failure events in different links are independent, we obtain the probability of the primary lightpath failure by multiplying the probability for a single link failure with the number of links on the lightpath. If the probability of failure of a single channel within a DWDM link is P_2 that is caused by single laser or receiver failure within a link, then the probability for the lightpath to be in state C in the Markov model is P_2^2. The probability P_2 is calculated by adding the FIT (Failure In Ten billion hours) of all the components on the link (shown in Fig. 7) and using the relationship $P_2 =$ MTTR/MTBF.

The probability of an entire link failure, P_1, is similarly computed by using the FIT of the key components responsible for this type failure, namely, OA failure and fiber cuts. The probability for the transition from C to E is $P_1+(1+r)P_2$, where r is the ratio of working to restoration channels. Note that the restoration path will be unavailable (transition from C to E) for two reasons. First, if the entire link fails, and second, if the restoration channel fails or one of the working channels within the link carrying other lightpaths fails and occupies the restoration channel for local switching by the LR protocol. Thus the probability for the A-B-C-E transition is given by $N_p.N_r.[P_1+(1+r)P_2].P_2^2$, where N_p and N_r are the number of DWDM links on the primary and the restoration paths, respectively. Similarly, the probability of the A-D-E transition is $N_p.N_r.[P_1+(1+r)P_2].P_1$. The total transition probability for state A to E is thus:

$$P(A \rightarrow E) = N_p N_r [P_1 + P_2^2][P_1 + (1+r)P_2].$$

Then assuming that the probability of success that WMS based restoration would succeed when the lightpath is in the state E to be P_w, the unavailability is given by:

$$U = P(A \rightarrow E).T_{lp} + P_w T_w$$

where T_{lp} is the MTTR for the lightpath and T_w is the time that the NMS would take to compute and implement the reprovisioning of the failed lightpath.

5. Example Results

We consider a trans-oceanic network that spans the U.S., Atlantic Ocean and Europe. In the single domain approach, this network is viewed as a single flat network. In the multi domain approach, the network consists of the American, Atlantic and European domains. As in Fig. 4, there are two gateways each at the domain borders. In our experimental network, there are primary gateways at New York and London; and secondary gateways at Philadelphia and Paris. This network is a hypothetical trans-Atlantic carrier's network.

As discussed above, we use the longest end-to-end lightpath to measure the unavailability of the network. For shared mesh restoration, we assume a working to restoration channel ratio of 2. This sharing ratio is based on experiments on this network with numerous lightpaths and is introduced to quantify the probability that the shared backup resources have become occupied by another backup path. Furthermore, we assume conservatively that the reprovisioning success probability is 0.5. The FIT, MTTR and other parameters are given in Tables 1 and 2. Note that here we assume that the transoceanic equipment (optical amplifiers, fibers) is ten times more reliable than the corresponding terrestrial equipment.

Components	FIT
Optical Amplifiers	2000
Transoceanic Optical Amplifiers	200
Mux/Demux Unit	1000
Transponder/TR	1500
Terrestrial Fiber Cut/km	50
Transoceanic Fiber Cut/km	5

Table 1: Component FIT rates

Terrestrail Optical Amplifier Spacing	80 km
Transoceanic Optical Amplifier Spacing	50 km
No of spans/Terrestrial DWDM	7
NO of WDM per link	1
Working/Restoration channel ratio	2
Fiber MTTR	4 hrs.
Equipment MTTR	4 hrs.
Transoceanic Equipment MTTR	48 hrs.
WMS reprovisioning success Probability	0.5

Table 2: Component MTTR and other parameters

We consider an end-to-end lightpath from San Francisco to Copenhagen as shown in Fig. 8. In the single domain mode, both the primary and backup lightpaths traverse all three domains. In the multi domain mode, the primary lightpath consists of segments from San Francisco to New York, New York to London and London to Copenhagen. For each of these lightpath segments, restoration is performed in the corresponding domain. Table 3 lists the hop length and path lengths of the primary and backup paths for both the single domain and multi domain cases.

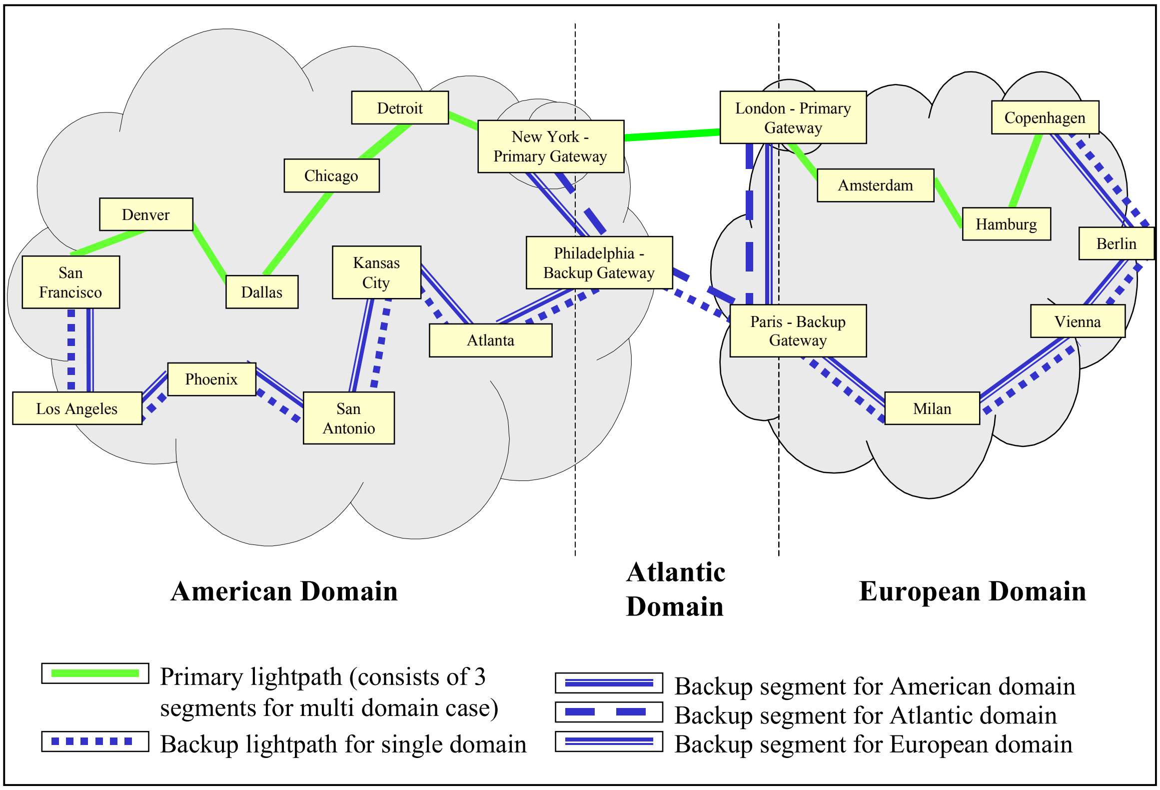

Figure 9: Primary and backup lightpaths in hypothetical network for single domain and multi domain

		Primary Hops	Primary Length (km.)	Backup Hops	Backup Length (km.)
Single Domain Network		9	19100	11	21300
Multi Domain Network	American	5	7450	7	8250
	Atlantic	1	10250	3	11250
	European	3	1650	5	3800

Table 3: Hops and path lengths for primary and backup lightpath segments

The availability calculations were performed for dedicated mesh protection and shared mesh restoration. For shared mesh restoration, we computed the availability for two cases of shared mesh restoration depending on whether or not span protection is included. The unavailability results (and the corresponding reliability results) are given in Table 4.

		Dedicated Mesh Protection		Shared Mesh Restoration – no span		Shared Mesh Restoration – with span	
		Unavail-ability (mins./yr.)	**Reliability (%)**	**Unavail-ability (mins./yr.)**	**Reliability (%)**	**Unavail-ability (mins./yr.)**	**Reliability (%)**
Single Domain Network		33.7	99.994	18.3	99.997	17.5	99.997
Multi Domain Network	American	3.12	99.9994	1.82	99.9997	1.68	99.9997
	Atlantic	12.0	99.998	6.19	99.999	6.15	99.999
	European	0.41	99.99992	0.25	99.99995	0.22	99.99996
	Overall	15.53	99.997	8.26	99.998	8.05	99.998

Table 4: Unavailability and reliability results

The results in Table 4 illustrate three factors that affect network reliability. First, the reliability depends heavily on the length of the lightpath and MTTR. The long Atlantic lightpath segment, which has higher equipment MTTR's, clearly dominates in terms of the unavailability. Second, reliability depends on the restoration mechanism. As compared to dedicated protection, shared mesh restoration provides higher reliability due to the implementation of reprovisioning after a second failure, resulting in up to a 48% decrease in unavailability. A further increase in reliability is achieved if link (span) restoration is implemented prior to path restoration. Finally, implementing a multi domain network rather than a single domain network increases overall reliability as failures in different domains are restored independently, resulting in up to a 55% decrease in unavailability. Using shared mesh restoration in a multi domain network resulted in a 76% combined decrease in unavailability.

6. Conclusion

In this paper, we compared the reliability of optical mesh networks with multi domain restoration and single domain restoration. We showed that despite the widespread belief that networks with faster restoration times are more reliable, reliability is, in fact, heavily influenced by the restoration mechanism. Furthermore, reliability may have little to do with restoration speed when the restoration time is small compared to the mean time to repair of the failed elements. We considered a multi domain restoration architecture using dedicated mesh protection and shared mesh restoration independently in each domain. Using an example network, we showed that implementing such a multi domain network rather than a single domain network resulted in up to a 55% decrease in unavailability. Additionally, using shared mesh restoration in a multi domain network resulted in a 76% combined decrease in unavailability.

7. References

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