# A National Mesh Network Using Optical Cross-Connect Switches

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Networks that transport optical connections using Wavelength Division Multiplexed (WDM) systems and route these connections using intelligent optical cross-connects (OXCs) are firmly established as the core constituent of next generation long-haul networks. In such networks, preventing and restoring link and node failures is increasingly becoming one of the most important network features [1-6]. Dynegy's network implements shared mesh restoration using intelligent optical switches to protect against single link and node failures. In shared mesh restoration (Figure 1), backup paths can share capacity if the corresponding primary paths are mutually diverse. Diversity of routes in Dynegy's optical network is defined using the notion of Shared Risk Groups [7]. A set of optical channels that have the same risk of failure is called a Shared Risk Group (SRG). SRGs are configured by Dynegy's network operators with the knowledge of the physical fiber plant of the optical network.

Compared to dedicated protection, this scheme allows considerable saving in terms of capacity required [7,8]. In addition, the backup resources can be utilized for lower priority preemptible traffic in normal network operating mode. However recovery is slower than dedicated protection in some cases, yet still within the realm of SONET restoration times, essentially because it involves signaling and path-setup procedures to establish the backup path. In particular, we note that the restoration time will be proportional to the length of the backup path and the number of hops, and if recovery latency is an issue this length must be kept under acceptable limits. However this constraint may increase the cost of the solutions, as it is sometime more cost-effective to use longer paths with available shareable capacity than shorter paths where shareable capacity must be reserved. This tradeoff can be handled by an appropriate cost model in the route computation algorithm [9,10,11].

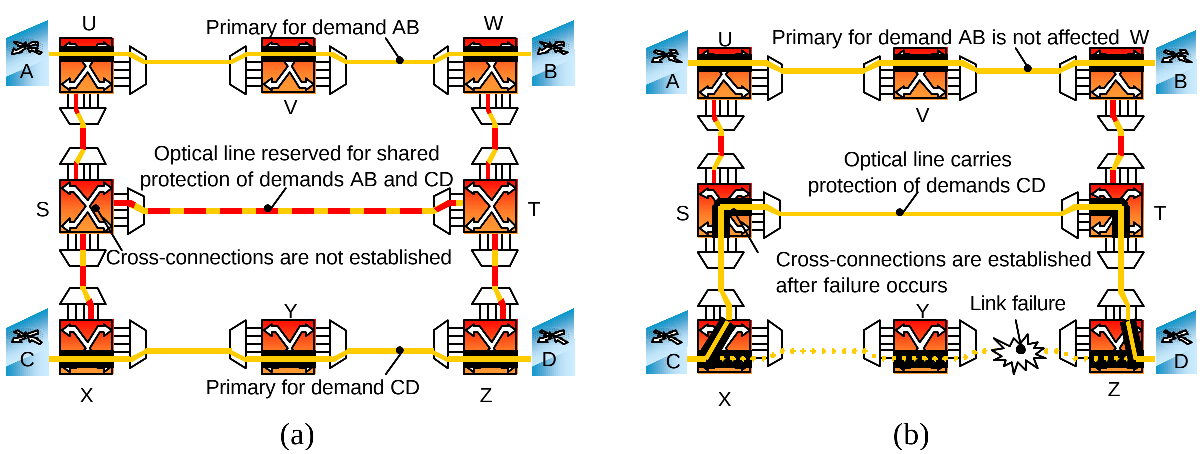


**Figure 1: Shared Mesh Restoration: (a) Network connections before a failure occurs (b) Network connections after a failure occurs**

For routing purposes, the algorithms utilized by the intelligent optical switches use a cost model that assigns costs to links in the network. The policy used for assigning costs to the links is different for primary and backup paths. The weight of a link for a primary path is the real cost of using that link in the path. This is a user-defined cost that reflects the real cost of using a channel on that fiber. The weight of a link for a backup path is a function of the primary path [12]. Backup link $e$ is assigned: (1) Infinite weight if it intersects with an SRG of the primary path. (2) Weight $w_e$ if new capacity is required to provision the path, and (3) Weight $s_e = \varepsilon w_e$ $0 \le \varepsilon \le 1$, if the path can share existing capacity reserved for pre-established backup paths. The routing of each lightpath attempts to minimize the total cost of all channels in the lightpath route, i.e., the goal is to share the existing capacity amongst multiple backup paths.

**Mesh Restoration**

Provisioning of shared mesh restored lightpaths in Dynegy's live network that utilizes Tellium's intelligent Aurora Optical Switches, was achieved by calculating the working and backup paths using the weight assignment as described above. Dynegy's network is on the order of 45 nodes and 75 trunks, and is carrying shared mesh restored demands amounting to several hundred gigabits of service. Upon a single link or single node failure, restoration times ranging from a few tens to a couple of hundred msecs were observed. The maximum restoration times observed were less than 200 msec in the worst case (when a large number of lightpaths have to be restored simultaneously as a result of a single failure). This is in-line with the restoration times predicted by Tellium's Modeler Tool that is designed to run restoration simulation studies. 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 correspond to the last lightpath restored as a result of a conduit failure (indicating the end of the restoration process) [13]. As expected, restoration latency generally increases as more lightpaths are failed, even though there could be variations for a relatively similar number of failed lightpaths. A study presented in [13] is representative of a what-if type study to determine the range of restoration latencies that can be expected from a network upon single link or node failures.

**Mesh Re-provisioning**

In the case of multiple failures, Dynegy's network, utilizing intelligent OXCs, also supports lightpath re-provisioning. Lightpath re-provisioning tries to establish a new backup path when restoration on the original backup path does not succeed. Re-provisioning uses existing spare capacity and unused shared capacity to find a new backup path on which to immediately restore the failed lightpath. There are three conditions that result in lightpath re-provisioning: (a) A failure of the primary path followed by a failure of the backup path prior to repair of the primary path, (b) A failure of the backup path followed by a failure of the primary path prior to repair of the primary or backup path, and (c) A failure of the primary path of a lightpath (B) sharing backup capacity with a lightpath (A), followed by a failure of the primary path of lightpath (A). This last case would cause a contention situation where more than one lightpath needs to use the shared backup capacity. In this case, lightpath (B) is restored onto its backup path after the failure, thus occupying the shared backup resources. When lightpath (A) fails, it cannot restore onto its backup (because resources are being used), resulting in a re-provisioning attempt. Note that re-provisioning may fail if there is not enough capacity available. However, the presence of lightpath re-provisioning increases the service availability of Dynegy's network. Service unavailability occurs as a result of multiple concurrent failure scenarios and the time it takes to fix the failure (e.g., hours if a fiber cut in a remote area needs to be repaired). Re-provisioning a lightpath that becomes unavailable after a double failure will improve the service availability of the network, by reducing the time that the service is unavailable from hours to tens of seconds. Simulation studies showed that compared to default protection, mesh restoration provides higher reliability due to the implementation of re-provisioning after a second failure, resulting in up to a 48% decrease in unavailability [14].

**Mesh Re-optimization**

During the network operation, requests for services are received and provisioned using an online routing algorithm with the cost model defined above. Both the primary and backup paths of each new demand request are computed according to the current state of the network, i.e., the routing algorithm takes into account all the information available at the time of the connection request to make the appropriate routing decision. As the network changes with the addition or deletion of fiber links and capacity and traffic evolve, the routing of the existing demands becomes sub-optimal. Re-optimization by re-routing the backup and/or primary paths gives the network operators the opportunity to regain some of the network bandwidth that is currently in use. In particular, re-routing only the backup paths is an attractive way to regain some of the protection bandwidth and reduce backup path length while avoiding any service interruption. Figure 2 illustrates how re-optimization temporarily eliminates the drift between the current solution and the best-known off-line solution that is achievable under the same conditions.

Table 1 shows the gains achieved when the backup paths in Dynegy's live network are re-routed during a maintenance window. In this case, the network consisted of 45 nodes, 75 links, and 70 shared mesh restored demands with their routes provided by the network operator, and all backup paths were re-optimized and tested. The complete re-optimization procedure, including testing took approximately 5 hours. Note that Table 1 only refers to ports used for the protection channels and it shows the port counts and number of backup hops measured before and after re-optimization. Clearly, re-optimization is beneficial both in terms of the number of protection ports used, as well as the length of the backup paths. Specifically, as shown in the table, backup path re-optimization saved 31% of the protection ports which in turn translated to 20% savings of the total number of ports. Also, the average length of the backup paths decreased from 5.87 to 4.88 hops [15]. The importance of re-optimization to the network is threefold. Firstly, the reduced number of protection ports used translates in freed protection capacity, which could then be used to carry new services. Secondly, the reduction in backup path length translates to the reduction in protection latency. In particular, in the re-optimization of Dynegy's network, the reduction of the average length of the backup path reduced the backup latency (restoration time) by 25.61% (calculated using the average length of the backup path in miles before and after the re-optimization) [15]. Finally, re-optimization allows network operators to make use of new nodes and links that are deployed in the network.

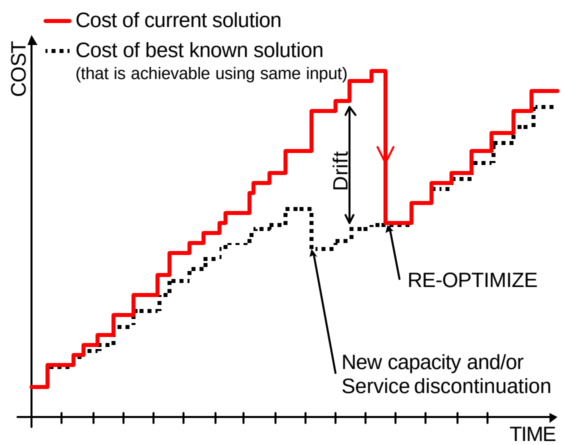


**Figure 2: Current cost versus best possible cost with cost-benefit of re-optimization**

| Scenario | Backup port count | | | Avg. backup hops | | Max backup hops | |
|---|---|---|---|---|---|---|---|
| Name | Before | After | % save | Before | After | Before | After |
| Dynegy Network | 310 | 214 | 30.97% | 5.87 | 4.88 | 15 | 10 |

**Table 1. Backup Path Re-optimization**

Dynegy's long-haul national network utilizing Tellium's optical switches has clearly become an *intelligent network*. It offers end-to-end point-and-click provisioning, shared mesh restoration with a few tens to a couple of hundred msec restoration times, re-provisioning of connections in the event of double failures and network re-optimization to regain some of the network capacity that is not optimally used.

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