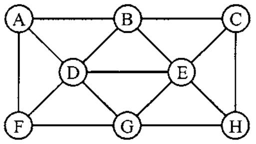
3.3 Backup path reconfiguration

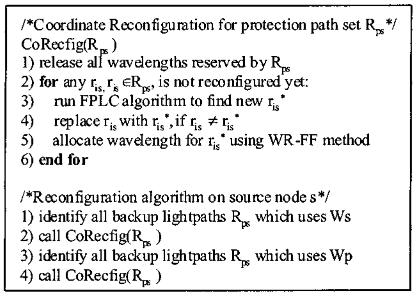
Backup path reconfiguration aims to approximate optimal layout of the existing BPs. Since the BPs are used as cold standby, the traffic in the network is not disrupted. We propose a distributed coordinate backup-path reconfiguration algorithm. Unlike per flow based reconfiguration,[2] our method works in a coordinated manner by utilizing the ready information of BPs on each source node. Each edge node periodically activates the reconfiguration procedure to optimize the allocation of BPs whose source nodes are the initiating edge node. The objective of the reconfiguration is increase reusability of W_b by rerouting some backup paths that are using W_s. Table 1 illustrates an example of backup path reconfiguration over an example network, as shown in Fig. 1. Coordinate reconfiguration algorithm is shown in Fig. 2.

ThW1 Table 1. Example of protection path reconfiguration. WP: working path; PP_1: protection path before reconfiguration; λ_1: reserved wavelength for PP_1; PP_2: protection path after reconfiguration; λ_2: reserved wavelength for PP_2

WP	PP1	λ1	PP2	λ2
ABC	ADEC	2	ADEC	3
FGHC	FDC	3	FDEC	3



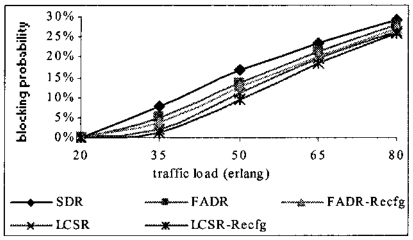
ThW1 Fig. 1. Example network topology.



```
/*Coordinate Reconfiguration for protection path set $R_{ps}$*/
CoRecfig($R_{ps}$ )
1) release all wavelengths reserved by $R_{ps}$
2) for any $r_{is,}$ $r_{is}$ $\in R_{ps}$, is not reconfigured yet:
3)     run FPLC algorithm to find new $r_{is}^*$
4)     replace $r_{is}$ with $r_{is}^*$, if $r_{is} \neq r_{is}^*$
5)     allocate wavelength for $r_{is}^*$ using WR-FF method
6) end for

/*Reconfiguration algorithm on source node s*/
1) identify all backup lightpaths $R_{ps}$ which uses Ws
2) call CoRecfig($R_{ps}$ )
3) identify all backup lightpaths $R_{ps}$ which uses Wp
4) call CoRecfig($R_{ps}$ )
```

ThW1 Fig. 2. Coordinate backup path reconfiguration.



ThW1 Fig. 3. Comparison of survivable routing schemes over 23-node network.

4. Simulation and performance analysis

As shown in Fig. 3, the comparison of the adaptive method and static methods is carried out over the 23-node network used in Liu et al.[2] There are two fibers for each direction on a link. The total number of wavelengths per fiber is 16. Connection requests arrive at each node according to a Poisson process with rate λ. The holding time for a connection is exponentially distributed with mean 1/μ. We take blocking probability as an evaluating criterion. In the simulations, each data point was obtained using 10^5 call arrivals. The adaptive LCSR algorithm outperforms static algorithms, i.e. SDR and FADR. Performance improvement has also been observed by applying periodic reconfiguration of backup paths at each source node.

5. Conclusions

We have developed an on-line shared path protection algorithm featuring adaptive alternate routing for primary and backup paths, wavelength reservation based first-fit wavelength allocation, and coordinate backup path reconfiguration. Results show that the proposed scheme performs better than the shortest disjoint path routing and better than the fixed disjoint alternate path routing in terms of blocking probability.

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ThW2 **2:15 pm**

Enhanced Algorithm Cost Model to Control tradeoffs in Provisioning Shared Mesh Restored Lightpaths

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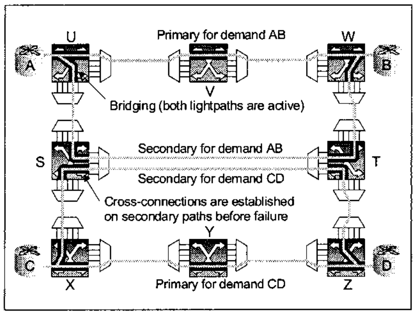
1. Introduction

Wavelength Division Multiplexed (WDM) networks that route optical connections using intelligent optical cross-connects (OXCs) is firmly established as the core constituent of next generation networks. With connection rates reaching tens of Gigabits/s, preventing and repairing failures is increasingly becoming an integral part of the network design process. In this work we consider two categories of end-to-end path restoration as supported in Tellium Aurora Optical Switch™ (see also [1]).* In end-to-end dedicated (1 + 1) mesh protection (Figure 1), the ingress and egress OXCs of the failed connection attempt to restore the signal on a predefined backup path that is disjoint, or diverse, from the primary path. Path diversity guarantees that primary and backup paths will not simultaneously succumb to the same failure. This approach requires large amount of capacity, that is more than the working capacity since backup paths are longer than working paths. However the backup path remains "live" in permanence, thus saving crucial path-setup latency when recovery takes place. In shared mesh restoration (Figure 2), backup paths can share capacity if the corresponding primary paths are mutually diverse. Compared to dedicated (1 + 1) mesh protection, this scheme allows considerable saving in terms of capacity required.[1] In addition, the backup resources can be utilized for lower priority pre-emptible traffic in normal network operating mode. However recovery is slower than dedicated (1 + 1) mesh protections, 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 constraints 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.

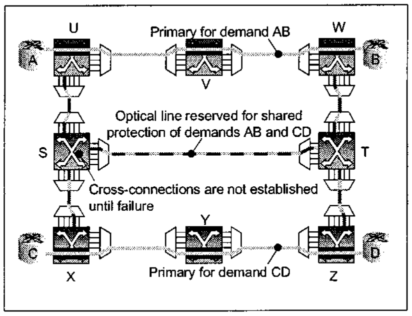
In this write-up we propose an algorithm-centered metric to vary the weight put on the solution's cost and on the average backup lengths while selecting a primary-backup pair from a set of candidate routes. We assess the effect of our metric on these two contradicting objectives and show that it offers the leverage to achieve the desired compromise. We first present the cost model, we then describe the algorithm used in our experiments to illustrate the effect of this cost model, and we finally conclude with the results of our experiments.

2. Cost model

We use the term Shared Risk Optical Group (SROG) to indicate a group of optical equipment



ThW2 Fig. 1. Dedicated (1 + 1) Mesh Protection.



ThW2 Fig. 2. Shared Mesh Restoration.

that share a common risk of failure. For the cost model we define the length of a path as the sum of the predefined weights of the edges that constitute it. The metric or policy used for weighting the edges is different for primary paths and backup paths. For primary paths it is the real cost of using the edges. For backup path it is a function of the primary path. A backup edge *e* is assigned: (1) infinite weight if it intersects with an SROG of the primary path. (2) weight w_e if new capacity is required to provision the path, and (3) weight $s_e \leq w_e$ if the path can share existing capacity reserved for pre-established backup paths. The cost of a primary and its protection is then the sum of their respective lengths. Quite evidently, the underlying idea here is to encourage "sharing", whereby existing capacity can be reused for provisioning multiple backup paths. The condition for sharing is that the backup paths must not be activated simultaneously, or in other words that their respective primaries must be pair-wise SROG-disjoint so that they do not fail simultaneously. The ratio s_e to w_e can be adjusted for the desired level of sharing. For smaller values of s_e, backup paths will be selected with the minimization of the number of non-shareable edges (weights w_e) in view, eventually leading to arbitrary long paths (as expressed in number of hops) that consist uniquely of shareable edges (weights s_e.) For larger values of s_e routing is performed regardless of sharing opportunities and backup paths will end-up requiring substantially more capacity.

3. Illustrative Routing Algorithm

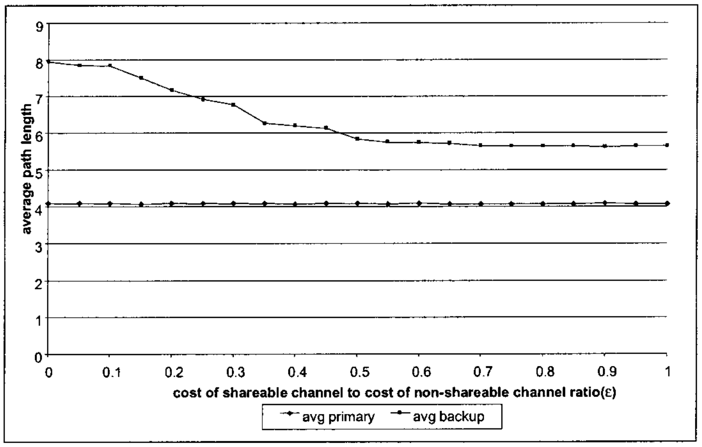
Assume that provisioning of a lightpaths is performed in two steps: (1) computation of a primary-backup pair of routes, and (2) assignment of channels along the routes. Ideally the two steps are solved simultaneously and step (1) is optimized so that channel-assignment in step (2) reuses existing capacity for backup paths. For the only purpose of illustrating the cost model we present a K-shortest path based algorithm, keeping in mind that any other algorithm whose objective minimizes this cost model would convene. The K-shortest path algorithm operates as follows:

```
1. For every edge e set weight to cost $c_e$ of one channel in edge (cost of transponders, regenerators and OAs.)
2. Compute set P of $k$ minimum-weight paths connecting node-pair A-Z, or all feasible paths if they are less than $k$ of them.
3. Set $min\_weight$ = infinity, and $\{p^*, q^*\}$ = INFEASIBLE.
4. For each path p and P, do
5. Assign weight to every edge e
   a. If e intersects SROG of primary path p, set weight to infinity.
   b. If e has at least one channel that is shareable with p, set weight to $s_e = \varepsilon c_e$.
   c. Otherwise, set weight to $w_e = c_e$.
6. Using metric defined in a., compute minimum-weight path q connecting node pair A-Z.
7. If q does not exist, continue at step 4. with next path p in P.
8. If $min\_weight <$ combined weight of p and q, then $\{p^*, q^*\} = \{p, q\}$ and $min\_weight$ = combined weight of p and q.
9. Return $\{p^*, q^*\}$
```

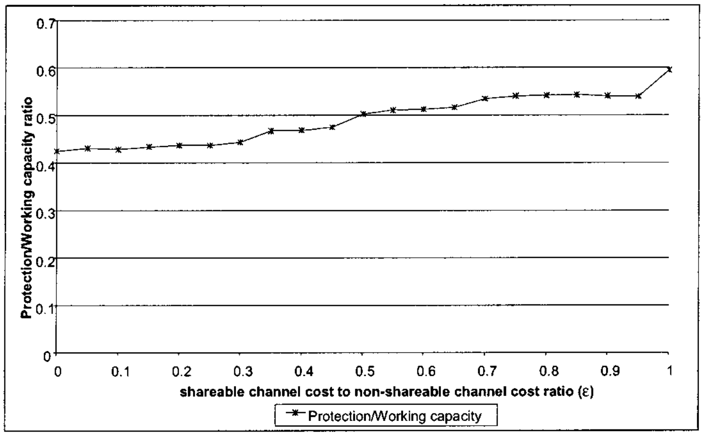
If the minimum cost is sought (maximum sharing), the value of ε in step 5.b. determining the cost of "shareable" protection channels is set to 0. Otherwise if shorter backup lengths, and faster restoration are desired, ε is set to a positive value. In the reminder of this paper we study the effect of varying ε between 0 and 1. Extensive study has already been performed for ε = 0 in.[1] When ε tends toward 1, we expect the lengths of primary and backup paths, as expressed in number of hops, to resemble that of dedicated (1 + 1) mesh protection, though sharing is still implemented when available on the backup path and the capacity required remains lower than for dedicated (1 + 1) mesh protection.

4. Experiments and conclusion

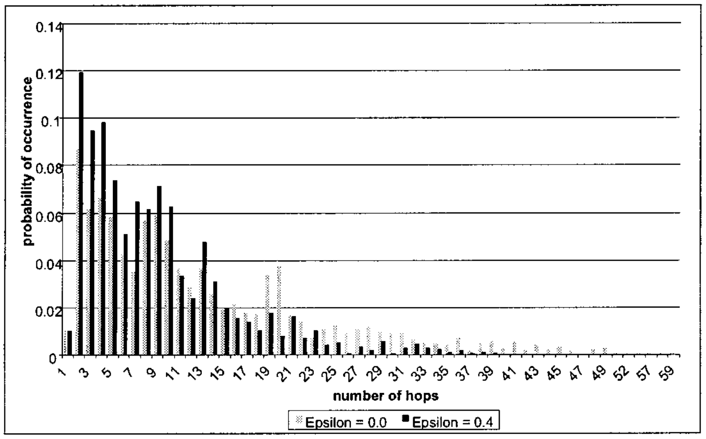
Figure 3 to 5 are representative samples of our experiments. Figures 3 and 4 summarize respectively the effect of ε on the average primary and



ThW2 Fig. 3. Effects of shareable channel cost to non-shareable channel cost ratio on average path length (50 nodes and 85 edges network).



ThW2 Fig. 4. Effect of shareable channel cost to non-shareable channel cost ratio on protection to working capacity ratio (50 nodes and 85 edges network).



ThW2 Fig. 5. Effect of shareable channel cost to non-shareable channel ratio on backup length histograms (200 nodes, 300 edges network).

backup lengths and the ratio of protection capacity (number of channels) to working capacity. The topology of the network used in these experiments is typical of an existing network. It consists of 50 nodes 85 edges network with realistic demand traffic. For this experiment the average backup length gradually decreases from 8 hops to less than 6 hops, a 25% reduction, as ε increases from 0 to 1. In the same time the protection capacity increases from 40% to 60% of the working capacity. The working capacity remained roughly constant across the experiments. Notice that in Figure 4, the ratio is still less than one while it would be larger than 1 for dedicated (1 + 1) mesh protection. Figure 5 illustrates the backup path histograms for two values of ε. The network used in this experiment is also representative of an existing network with 200 nodes and 300 edges. At ε = 0 the figure exhibits a long-tail path length distribution (path lengths are expressed in number of hops) and even show the existence of paths up to 60 hops. As ε increases, the width of the distribution decreases, and reduce the maximum path length to 40 hops at ε = 0.4. In the same time the protection capacity increased 14%. The average path lengths and protection capacity increase shows the same behavior as in Figures 1 and 2.

* Other categories include line protection and re-provisioning. These are not considered here.

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ThW3 **2:30 pm**

Novel models for efficient shared-path protection

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1. Introduction

As widespread deployment of high-capacity dense wavelength-division multiplexing (DWDM) systems is envisioned, achieving efficient *shared-path protection,* which protects a bandwidth guaranteed connection from a single link (node) failure using a link (node) disjoint pair of *active path* (AP) and *backup path* (BP), becomes a key design consideration. Since the restoration time (the BP set-up signaling delay) mainly depends on the BP length, long BPs will not only violate a given restoration time guarantee, but also introduce negative effects on the optical signal transmission quality (in terms of SNR, BER, etc).

In a dynamic provisioning environment under the bandwidth-on-demand paradigm, connection requests arrive one by one and future demands are unknown. So online algorithms that determine the AP and BP for a new request without disturbing existing APs and BPs are desirable. Such an online scheme, named *Sharing with Complete Information* (SCI), was proposed, which determines an optimal pair of AP and BP by solving an Integer Linear Programming (ILP) model.[1] The ILP model, however, focuses only on minimizing the total cost, in terms of total bandwidth (TBW) consumption but does not consider the need to limit the BP length. As a result, a BP may contain many links of *zero* (0) cost in terms of *additional* backup bandwidth (or BBW) the BP incurs due to BBW sharing among this BP and existing BPs. In Refs. 2–4 (where fixed APs are used), the tradeoff between the BP length and BBW sharing was investigated, and found that in order to reduce the BP length, one has to sacrifice BBW sharing or in other words, increase TBW consumption.

In this paper, we will devise a novel ILP model based on the SCI model,[1] which can be used to significantly reduce the BP length while reducing the TBW consumption as well. This model is applicable when complete aggregate (or per-flow) information on all existing APs and BPs is available to a centralized controller.[1] We will also devise a corresponding model for the case where only *partial aggregate* information is available and *distributed control* is adopted, based on the DPIM model in[5] (DPIM is chosen because it is the most efficient shared-path protection scheme requiring only partial information and distributed control). Note that since one only needs to obtain an optimal solution for the new request, instead of all requests as in the off-line case, the time required to solve the ILP models in the on-line case becomes not so unreasonable. Besides, the ILP models can also be solved by using speedy algorithms that take advantage of the proposed improvements to yield a solution that is even closer to the optimal one than what is possible using speedy algorithms based on the original ILP models.

2. Improving over existing ILP models

We now describe two proposed modifications to the existing ILP models, one for SCI[1] and the other for DPIM.[5] Both modifications affect only the objective functions (i.e., the cost function which is to be minimized) in the ILP models, and hence we will not describe the rest of the ILP formulation.[1,5]

To facilitate the informal description of the objective function, let w be the bandwidth requested by the new connection to be established. In addition, let a and b denote an link along an AP and BP, respectively, and $|AP|$ and $|BP|$ denote the length of the AP and BP, respectively. Finally, let BC_b denote the cost of link b (i.e., additional BBW to be reserved on link b for the new BP). It is clear that the total cost (TBW consumption) is:

$$w \cdot |AP| + \sum_{b \in BP} BC_b \tag{1}$$

The objective function used in SCI is to minimize Eq. (1). To explain the second term in more detail, let S_a^b be the total amount of ABW required by the existing connections whose APs traverse link a and whose BPs traverse link b, and B_b be the amount of BBW already reserved on link (for these as well as possible other connections whose APs do not use link a). Then the additional BBW needed on link b for the new connection, in order to protect against the failure of link a, is $BC_a^b = \max\{S_a^b + w - B_b, 0\}$.[1,5] Since link b needs to be used to restore all the traffic affected by the failure of any one of the links along the AP, we have:[1]

$$BC_b = \max_{\forall a \in AP}\{S_a^b + w - B_b, 0\} \tag{2}$$

It is clear that if the objective function in Eq. (1), which focuses only on the TBW, the ILP solver will not (and cannot) distinguish between two pairs of AP and BP with the same TBW, but the first pair has a longer AP (and hence a larger ABW) and a shorter BP (and hence a smaller BBW) than the second pair. In other words, the ILP solver may end up choosing the first pair. Since the BP is shorter, such a choice may affect BBW sharing among this BP and future BPs, thus increase the TBW consumption in the end.

Based on the above observation, the first improvement is to introduce parameter ε (where 0 < ε < 1) in the objective function in order to assign less weight to BBW. More specifically, the objective function can be improved as follows:

$$\text{minimize: } w \cdot |AP| + \varepsilon \sum_{b \in BP} BC_b \tag{3}$$

This objective function makes the second pair containing a shorter AP and a longer BP more appealing to the ILP solver because the TBW of the second pair is now smaller than that of the first pair. Note that ε = 1 in the original model. In addition, if ε = 0, the objective function becomes simply the minimization of ABW, which is equivalent to finding a shortest AP.

As mentioned earlier, a BP chosen by an ILP solver, based on the objective function in Eq. (3) (or Eq. (1)), may contain many links with zero cost. In order to reduce the BP length, and also in part, compensate for the effect of using 0 < ε < 1, the second improvement is made, which introduces parameter μ (where 0 < μ ≤ 1) in Eq. (2) to assign a non-zero (virtual) cost to links that would otherwise have zero (actual) cost. That is, we will plug in the following value, instead of the value given in Eq. (2) to the objective function in Eq. (3) (or Eq. (1)):

$$BC_b = \max_{\forall a \in AP}\{S_a^b + w - B_b, \mu w\} \tag{4}$$

Because every link will now have a non-zero cost, virtual or actual, an ILP solver may favor a BP consisting of a fewer links, most or all of which have a non-zero (actual) cost, instead of a longer BP consisting of many links which have a non-zero (virtual) cost of μw because the former now has a lower total cost (virtual or actual). Note that μ = 0 in the original ILP model, and μ never needs to be larger than 1 as the additional BBW to be reserved never needs to exceed w.

We now describe the ILP model for DPIM. Define:

$$P_A a = \max_{\forall b} S_a^b$$

which is part of the partial aggregated information maintained by each node. The only significant difference in the objective function between DPIM and SCI is that here, the BBW is estimated as follows:[5]

$$BC_b = \min\{\max_{\forall a \in AP}(P_A a + w - B_b, 0), w\} \tag{5}$$

Since the original ILP model for DPIM used the same objective function as Eq. (1), it can be firstly improved by introducing parameter 0 < ε < 1 as in Eq. (3). In addition, Eq. (5) can be improved as follows:

$$BC_b = \min\{\max_{\forall a \in AP}(P_A a + w - B_b, \mu w), w\} \tag{6}$$

Note that, by definition, $P_A a + w - B_b$ in Eq. (5) is no smaller than $S_a^b + w - B_b$ in Eq. (2), that is, the former gives an over-estimation of the BBW cost. Therefore, as to be shown next, the effect of hav-