Active lightpath restoration in WDM networks [Invited]

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The increasing demand for bandwidth that has resulted from the emergence of various bandwidth-thirsty applications has increased the need for employing WDM as a dominant technology for the next-generation optical internet. As these networks carry gigantic amounts of information, survivability has become a primary and basic need for them. Although the available proactive protection schemes provide a 100% restoration guarantee, they require huge redundancy and usually result in a very high blocking probability. We propose a novel active restoration scheme that restores a failed primary lightpath based on multiple predefined but nonreserved backup paths along the primary path. Extensive simulation results based on three typical test networks indicate that with a small increase in restoration time, our new restoration scheme can reduce the blocking probability and the capacity requirement significantly while guaranteeing a very high restoration probability. © 2004 Optical Society of America

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1. Introduction

Wavelength-division multiplexing (WDM) networks have the capability of providing huge bandwidth, and it is expected that WDM will be a dominant technology for the next-generation optical Internet. As WDM networks carry more and more data, failure of any part and the resulting inability to move data around quickly may have a tremendous economic effect. Todimala and Ramamurthy [1] pointed out that fiber cuts occur at the rate of 4.39 cuts per 1000 sheath miles per year, and it takes ~12 h to fix a fiber failure. For this reason, survivability issues in high-bandwidth WDM networks have become an important area of research in recent years.

Survivability is defined as the ability of the network to maintain service continuity to end users in the presence of network failures [2]. The approaches to ensuring survivability can be generally classified as proactive protection and reactive restoration. With the former, a backup lightpath is computed, and wavelength channels are reserved for it at the time the primary lightpath is established. If both primary and backup lightpaths are available for a demand, the demand is accepted. Extensive research has been done on proactive protection of WDM networks [3–6] and various protection schemes, such as automatic protection switching, self-healing ring, dedicated–shared link-based protection, dedicated–shared path protection, and shortest leap shared protection, have been proposed. Although proactive protection yields a 100% restoration guarantee since a backup lightpath is always available to carry the disrupted traffic when a primary lightpath fails, it usually suffers from a high blocking probability and resource redundancy. In reactive restoration a backup lightpath is searched after the primary lightpath is interrupted. Several lightpath restoration schemes for WDM optical networks were reported recently [7, 8]. Although reactive restoration is more efficient in terms of capacity use and blocking probability, it may lead to an unacceptably long restoration time because a global search for a backup lightpath is required.

As proactive protection experiences a high blocking probability and huge network resource redundancy, whereas the reactive restoration results in a unsatisfactory long restoration time, the motivation of this study is to find a compromise between the proactive protection and reactive restoration schemes so that good performance can be achieved. In particular, we propose a novel active restoration scheme in which a primary lightpath is guarded by multiple backup lightpaths that are predefined but not reserved along the primary path before failure occurs. The selection of the backup path to be employed in the restoration process relies on the failure location as well as the availability of resources. The related routing and wavelength-assignment algorithms for the proposed scheme are also developed in this paper. Simulation results based on three well-known networks show that our new scheme, compared with the proactive protection scheme, can reduce the blocking probability and save network resources significantly, with only small sacrifices in restoration time and restoration probability.

The rest of the article is organized as follows: Section 2 presents the problem preliminaries of this work. Section 3 deals with our new scheme and the related routing and wavelength-assignment algorithms. Section 4 presents the simulation results and discussions, and Section 5 presents the concluding remarks.

2. Preliminaries

Given a connected network graph $G(V,E)$ with node set V and edge set E, let $|V|$ be the number of nodes and $|E|$ be the number of edges of G. We assume that there is at most one bidirectional fiber between any two nodes and each fiber carries the same number of wavelengths. The adjacency matrix A of G can be represented as follows:

$$A = (a_{i,j})_{|V|\times|V|}, \tag{1}$$

where

$$a_{i,j} = \begin{cases} 1 & \text{if there is an edge between nodes } v_i \text{ and } v_j \\ 0 & \text{otherwise} \end{cases}.$$

For simplicity, we denote the cost of an edge e as C_e, which is determined as

$$C_e = \begin{cases} \infty & e \notin E \\ W_e & e \in E \end{cases}, \tag{2}$$

where W_e is the edge weighting function of the edge e (in this paper we just take W_e as the physical length of the edge e).

The set of paths $T_{s,d}$ between a node pair v_s and v_d can be represented as a sequence of distinct nodes as follows:

$$T_{s,d} = [(v_0, v_1, \ldots, v_h)\,|\,v_0, v_1, \ldots, v_h \in V, v_0 = v_s, v_h = v_d \text{ and } a_{i-1,i} = 1, \forall\ 1 \le i \le h], \tag{3}$$

where h is the number of hops of a path. If we use $E(P)$ to denote the set of edges a path P travels, then the length $L(P)$ of the path P can be computed as follows:

$$L(P) = \sum_{e\in E(P)} C_e. \tag{4}$$

In this study the primary path between a pair of nodes is defined as the shortest path between them. The length of a primary path P_p between a node pair v_s and v_d can be represented as follows:

$$L(P_p) = \min_{P \in T_{s,d}} [L(P)]. \quad (5)$$

In path-based protection schemes, the immediate downstream node of the failed link in a primary path will be subject to a loss-of-light (LOL) failure and will send a failure notification message (FNM) to the destination node along the primary path. The destination node will conduct a destination-initiated resource reservation mechanism, notifying the source node to set up the backup lightpath so that the affected working traffic can be restored. In such a circumstance, the restoration time t_{restore} for the failure can be simply modeled as $t_{\text{restore}} = (L_{\text{primary}} + L_{\text{backup}})/\mu$, where L_{primary} and L_{backup} are the lengths of the primary and the backup path, respectively, and μ is light speed. Figure 1 exemplifies this case. Let us consider $(v_1, v_2, v_3, v_4, v_5)$ the primary path. If the link between v_1 and v_2 is cut, v_2 will be subject to a LOL failure and send a FNM to the destination node along the primary path. The destination node v_5 then starts to set up the backup lightpath.

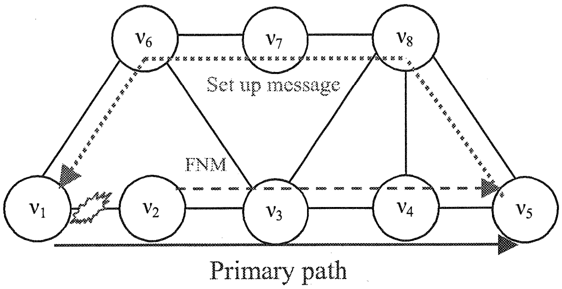


Fig. 1. Path-based protection.

3. Active Light-Path Restoration Scheme

In this section we first introduce our novel active restoration scheme, and then we estimate its restoration time. The complete routing and wavelength-assignment algorithm for our scheme is also included in this section.

3.A. Active Light-Path Restoration

We consider the case in which traffic demands or requests arrive one by one without any prior knowledge of future arrival. In our new scheme we compute for each connection request a primary lightpath. If enough wavelength channels are available along the primary path, we then compute multiple backup paths that start from the nodes along the primary path and end at the source node of the path, respectively (as we show in Section 3.C.1 for a given primary path, our proposed scheme requires no extra computation overhead for finding the multiple backup paths compared with the proactive scheme). Here a backup path starting from a node of the primary path is just the shortest path from that node to the source node that is link-disjointed with the primary path. In this way our proposed scheme guarantees that the selected backup path will never retain any faulty link of the failed primary path. On the other hand, if the primary path cannot be established because of a shortage of resources, the connection is blocked.

In the new scheme we define a node along the primary path, a supported node, if there does not exist a backup path from the node to the source node; we define an unsupported node otherwise. When there is a link failure along the primary path, the immediate downstream node next to the failure checks the availability of the successive backup paths and may send a FNM to the corresponding supported node along the primary path. If the backup path starting from the first node next to the failure is available, then this node will only send a setup message directly to the source node. Otherwise, the FNM may be forwarded to following supported nodes up to the last node. We refer to the supported node through which traffic restoration can be performed as a restoration node. Figure 2 is an example that clarifies the main idea of our scheme.

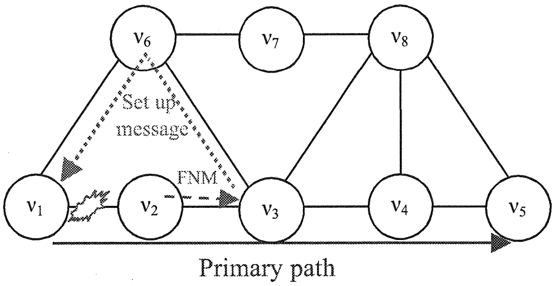


Fig. 2. Active lightpath restoration.

Let node v_1 be the source node, node v_5 be the destination node, and the primary path be $(v_1, v_2, v_3, v_4, v_5)$. If the link between v_1 and v_2 fails, the node v_2 will detect a LOL failure. Since node v_2 does not have any backup path to the source node that is link disjointed with the primary path, node v_2 is an unsupported node. According to the availability of the wavelength channels along the successive backup paths, node v_2 will decide which backup path will be employed in the restoration of the disrupted traffic (assuming that every node keeps all information about other nodes in the network). If wavelength channels are available along the backup path [e.g. (v_3, v_6, v_1)] of the next supported node, v_3, node v_2 sends a FNM to the restoration node v_3. As soon as node v_3 receives the FNM, it will immediately send a setup message to the source node through the backup path (v_3, v_6, v_1). Once the source node v_1 receives the setup message, it reroutes all data to the backup path (v_1, v_6, v_3), then data will go through the rest of primary path to the destination node. If there are not enough resources along the backup path of the first supported node, the backup paths of the following supported nodes will be investigated [e.g. $(v_4, v_8, v_7, v_6, v_1)$ then, $(v_5, v_8, v_7, v_6, v_1)$]. If no backup path is available because of a lack of network resources, restoration of this lightpath fails.

3.B. *Restoration Time*

The restoration process of our scheme consists of two phases.

- Phase 1: Path Determination and Failure Notification

  For a given primary path, the first phase of our scheme involves finding the first available backup path among the set of the precomputed backup paths. The time cost of this phase is related to the computational power of network nodes. Let α be the time required for checking the availability of a free wavelength channel in a single fiber link; then the total time for checking a path can then be estimated by $m\alpha$ under the assumption that each network node has full wavelength conversion capability, where m is the total number of links of the path.

  Once an available backup path is found and reserved, the first node next to the failure location (v_f) will send a FNM to the restoration node (v_r) corresponding to this backup path. The length that the FNM needs to travel (we refer to this length as the FNM length hereafter) is the length of the subpath $P_{f,r}$ along the primary path that initiates from node v_f and terminates at node v_r. Let $E\left(P_{f,r}\right)$ be the set of edges the subpath $P_{f,r}$ travels, then the *FNM* length can be computed as follows:

$$FNM = L\left(P_{f,r}\right) = \sum_{e \in E\left(P_{f,r}\right)} C_e. \tag{6}$$

- Phase 2: Backup Path Activation

  The second phase of our scheme is to activate the reserved backup path. Let L_{setup} be the length that the setup message needs to travel and P_b be the backup path initiated from the first restoration node. Then, L_{setup} is given by

  $$L_{\text{setup}} = L\left(P_b\right) = \sum_{e \in E\left(P_b\right)} C_e, \tag{7}$$

  where $E\left(P_b\right)$ is the set of edges the backup path P_b travels.

The restoration time is defined as the elapsed time from the instant a connection is disrupted to the instant it is restored [9]. The restoration time R_T of our scheme, which is proportional to the sum of the FNM length and L_{setup}, can be represented as follows:

$$R_T \approx m\alpha + \left[\sum_{e \in E\left(P_{f,r}\right)} C_e + \sum_{e \in E\left(P_b\right)} C_e \right] / \mu, \tag{8}$$

where μ is the speed of light.

3.C. Routing and Wavelength Assignment

The RWA algorithm of our scheme involves calculating the primary light path and its related multiple backup paths in advance of failure. To reduce the very high computation complexity of dynamic RWA, the RWA task is divided into two subtasks: a routing problem and a wavelength assignment problem.

3.C.1. Routing Algorithm

Our routing algorithm (Algorithm 1) is based on the two-step-approach algorithm [10], in which a primary path of a connection request is routed by Dijkstra's algorithm [11] between the source and the destination. The corresponding multiple backup paths are derived by erasing the links of the primary path from the network topology and then performing the Dijkstra algorithm on the reduced network topology again. Note that solving Dijkstra's algorithm to find a link-disjoint backup path between a source and destination pair of a given primary path implicitly provides all the shortest paths from the source node to all other nodes in a single run. Therefore, the computation complexity of finding the multiple backup paths for our proposed scheme is identical to that of the proactive path-based algorithm. The routing algorithm of our scheme consists of two phases as follows:

- Before-failure phase

  1. Compute the primary path between node pair (s, d) using Dijkstra's algorithm and the predefined cost matrix.
  2. Use Dijkstra's algorithm to compute a link-disjoint backup path from each supported node along the primary path to the source node.

Algorithm 1

```
. 1. Set $FNM = 0$, and $RT = \infty$ (very high value)
. 2. Select the immediate downstream node of the failed link along the primary path as (CN)
. 3. While ($CN < DN$)
.    a.  If (CN is supported)
.        i.   Compute the restoration time RT from the current node (CN) as in Eq. (8).
.        ii.  If ($RT = \infty$) THEN        //no physical path
.                 Demand is blocked
.             Else
.                 Call wavelength-assignment algorithm
.                 IF (WA algorithm succeeds)
.                     Terminate.
.    b.  $CN = NN$          //select the next node
.    End while
. 4. Terminate
```

- After-failure phase

  Once a failure happens, it is first localized. Then an algorithm is executed, in which, *CN*, *NN*, and *DN* denote the current node being checked, the immediate downstream node of *CN*, and the destination node along the primary path, respectively.

3.C.2. Wavelength Assignment

The task of wavelength-assignment algorithm is to assign a wavelength to each link along the backup route. In our approach, once a failure occurs in the primary path, the wavelength-assignment algorithm will try to assign wavelength channels to all links of the backup path initiated from the first supported node. If the wavelength-assignment algorithm succeeds in reserving the required resources along the backup path, the disrupted traffic will be restored from the first supported node and the after-failure wavelength assignment process is stopped. Otherwise, the wavelength-assignment process will continue for the successive supported nodes until the last one. If the wavelength-assignment algorithm fails to reserve any of these backup paths along the primary path, the restoration for the disrupted primary path fails.

Under the assumption that each network node has the capability of full wavelength conversion, the after-failure wavelength assignment is given by Algorithm 2.

3.D. RWA Time Complexity

In our active lightpath restoration scheme, the before-failure routing phase is responsible for computing the primary path and the backup route segments from the source to every other node along the primary path. This is implemented by iteratively invoking Dijkstra's algorithm; thus the time complexity of the routing phase is $O\left(|V|^2\right)$ for each connection request, where V is the total number of network nodes. The after-failure routing phase in our scheme is responsible for selecting the first available backup path. The worst case time complexity of this phase is $O(|V|)$, which corresponds to the case when the failure occurs at the immediate downstream link of the source node and the primary path has a hop count of $|V|$.

With full-wavelength conversion capability in each node, the worst-case time complexity of the wavelength-assignment algorithm in the after-failure phase is $O\left(|V|^2\right)$. However, our simulation results indicate that we can actually find an available backup lightpath with

Algorithm 2

```
1. $i = 1$
2. FOR the backup path $B_i$
3. IF ( $i\&lt; =$ number of multiple backup paths)
4.       assignedlinks $= 0$
5.    FOR (each link $l$ on $B_i$)
6.       IF (number of free $w > 0$) THEN
7.          assignedlinks $=$ assignedlinks $+ 1$
8.          IF(assignedlinks $=$ no of links of $B_i$) THEN
9.             Restore the traffic
10.                Terminate
11.           ELSE  // still some links need reservation
12.                $w = w - 1$
13.                   Assign $w$ to $l$ and GOTO 6
14.           ELSE  // no available $w$ along this backup path
15.                $i = i + 1$
16.                GOTO 3  //try another backup path
17.        ELSE   // no resources available for any of $B_i$
18.           Restoration Fails
19. Terminate
```

a very high probability by inspecting only the first three predefined backup paths. This indicates that in our scheme the wavelength assignment can be implemented in $O(|V|)$ time with a very high probability ($\sim$0.96).

4. Performance Evaluation

In this section we present extensive simulation results to validate our new scheme. Since the proactive protection is the most promising technique in terms of restoration speed and the 100% protection guarantee, it is used for comparison in our simulation.

4.A. Simulation Environment

In our simulation the arrival rate of requests at a network node follows the Poisson distribution with mean λ. The holding time of a connection follows the exponential distribution with mean $(1/\mu)$. The workload measured in Erlangs is the product of the average arrival rate and the mean holding time of requests. We assume that all nodes have the full-wavelength conversion capability and each fiber has 32 wavelengths. A request is equally likely to have any pair of network nodes as its source destination. A total of five batches was simulated, with 200 sessions generated in each batch. Under a single link failure setup, link failure is generated randomly by use of a uniform distribution with a failure probability of 10^{-3}.

4.B. Test Networks and Performance Metrics

Three typical networks, the NSFNET network [12] (Fig. 3), the test network used in Ref. [13] (Fig. 4), and test network 3 used in Ref [14] (Fig. 5), are employed in our simulation.

Table 1 summarizes the characteristics of the test networks, including the number of nodes, the number of links, and the average nodal degree (defined as the number of links terminating at the node [15]). For performance comparison, we use three performance metrics of blocking probability, restoration probability, and restoration time. Here the blocking probability of a demand is estimated by the ratio of the number of blocked demands to the

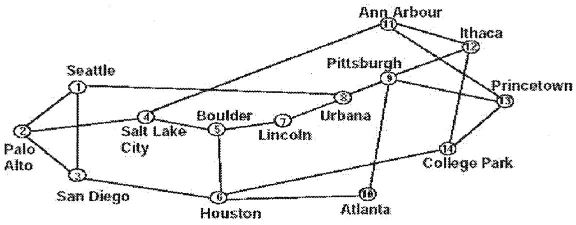


Fig. 3. Test Network 1.

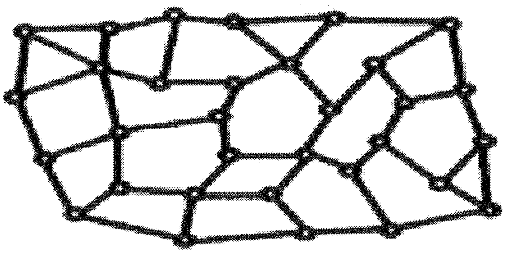


Fig. 4. Test Network 2.

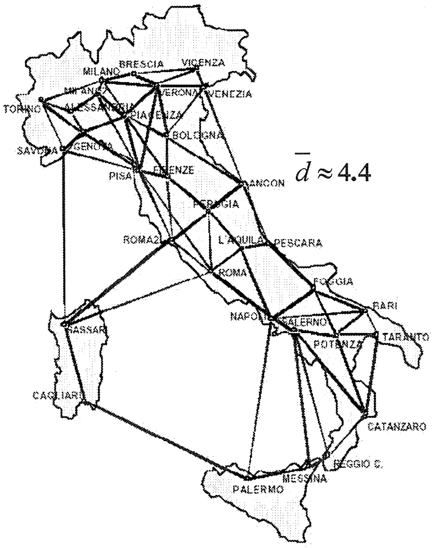


Fig. 5. Test Network 3.

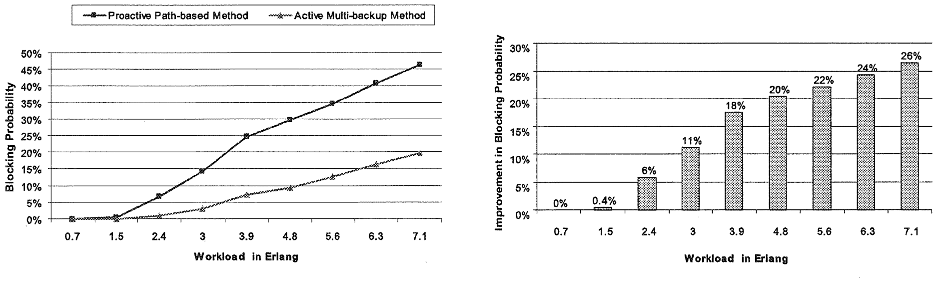
total number of demands generated [16], and the restoration probability is determined by the ratio of the number of successfully restored primary paths to the total number of failed primary paths.

Table 1. Characteristics of Test Networks

Test Network	No. of Nodes (N)	No. of Links (E)	Avg. Nodal Degree
1	14	21	3
2	32	51	3.1875
3	32	70	4.375

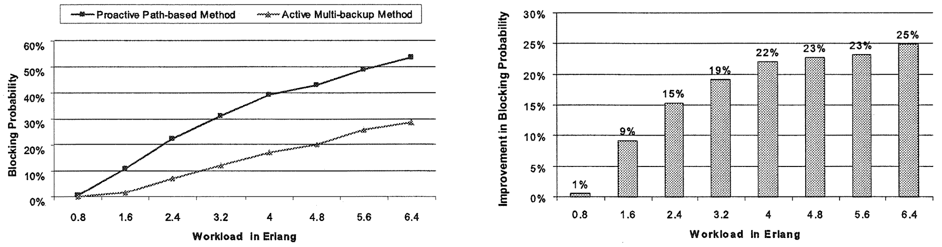
4.C. Simulation Results

We first show in Figs. 6, 7, and 8 the simulation results of blocking probability for the three networks when different workloads are considered.



(a) (b)

Fig. 6. Simulation results of blocking probability for Network 1, $1/\mu = 3$: (a) Blocking probability versus workload, (b) improvement in blocking probability.



(a) (b)

Fig. 7. Simulation results of blocking probability for Network 2, $1/\mu = 3$: (a) Blocking probability versus workload, (b) improvement in blocking probability.

The results shown in Figs. 6, 7, and 8 indicate that our new scheme, compared with proactive path-based protection, can reduce the blocking probability significantly. When the workload is 7.1 for Network 1, Fig. 6 shows that our scheme achieves a blocking probability of 20%, whereas the proactive path-based method results in a 46% blocking probability, two times higher than that of our scheme. When the workload is 4.8 for both Network 2 and 3, the results in Figs. 7 and 8 indicate that blocking probability of path-based method is 42% and 30%, whereas the blocking probability of our scheme is only 20% and 13%, respectively. The results in Figs. 6, 7, and 8 further illustrate clearly that, although

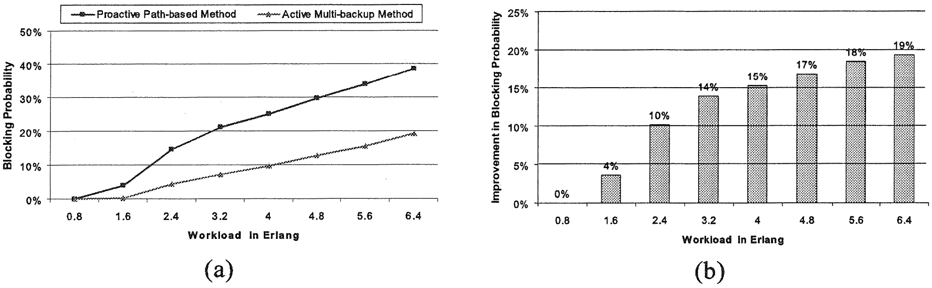


Fig. 8. Simulation results of blocking probability for Network 3, $1/\mu = 3$: (a) Blocking probability versus workload, (b) improvement in blocking probability.

we can always get improvement in the blocking probability by using our active restoration scheme, this improvement actually becomes more significant when the workload becomes heavier. This indicates that our new scheme will outperform the available proactive protection schemes significantly in terms of blocking probability, especially when a network experiences a high workload.

Since the proactive protection schemes can guarantee a 100% restoration, we have only simulated the restoration probability for our scheme. The corresponding results are summarized in Figs. 9, 10, and 11. Although our active restoration scheme does not guarantee 100% restoration probability, the results in Figs. 9, 10, and 11 show clearly that our scheme can always result in a very high restoration probability for different workloads. For Network 3, for example, the restoration probability of our scheme is more than 97% when the workload is less than or equal to 4, and our scheme can still guarantee a 91% restoration probability even when the workload reaches a very high value of 6.4.

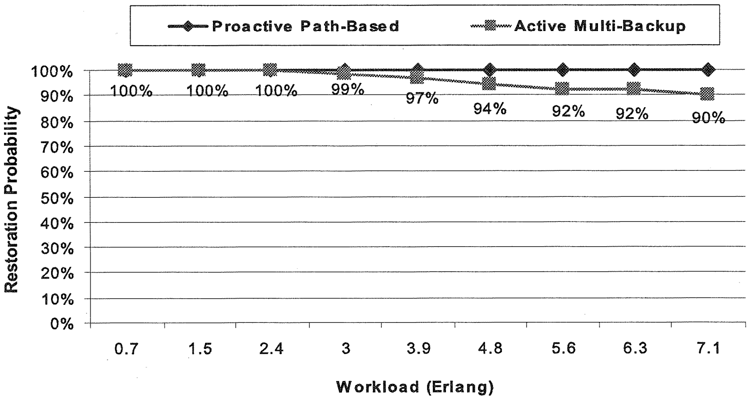


Fig. 9. Restoration probability versus workload for Network 1, $1/\mu = 3$.

To compare the restoration time, we summarize in Table 2 the average restoration time, which is estimated by the average of the restoration time of all workloads, for both the proactive path-based method and our scheme.

From Table 2 it is clear that the restoration time of the proposed algorithm is a little bit higher than that of the proactive path-based method. This is because of the following two factors:

1. When a failure occurs, the proactive path-based method will setup the reserved

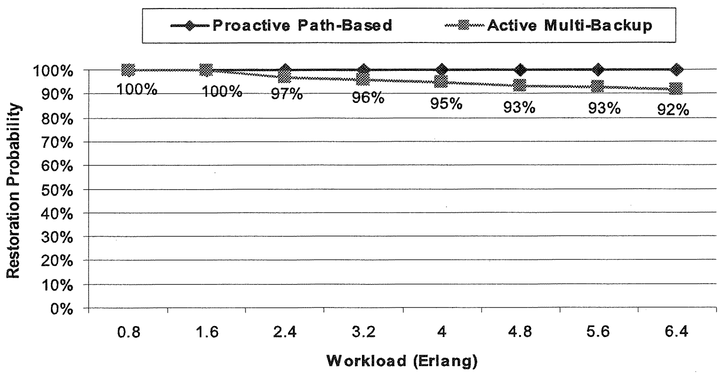


Fig. 10. Restoration probability versus workload for Network 2, $1/\mu = 3$.

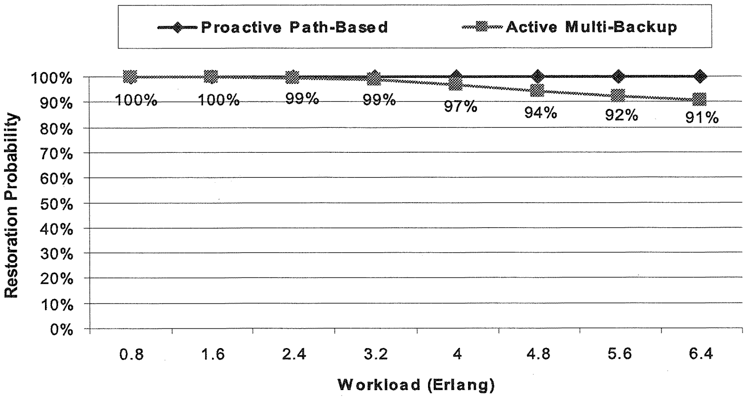


Fig. 11. Restoration probability versus workload for Network 3, $1/\mu = 3$.

Table 2. Average Restoration Time (ms)

Network	Path-Based Protection	Active Restoration	Increase (%)
1	17.6	29.0	39.3
2	34.1	45.4	24.9
3	34.0	39.9	14.8

backup path immediately, whereas the proposed active scheme takes extra time to seek an available backup lightpath among those predefined backup paths.

2. The proposed algorithm results in very low blocking probability (more than two times lower) compared with that of the proactive protection, and thus the number of successfully allocated connections is much higher than that of the proactive scheme, which leads to a higher average restoration time. To investigate the second factor further, consider the case of a failure generated randomly across a link and applied to both schemes simultaneously. We may expect that, as the failure occurs in the same link for both methods, the number of affected connections in both schemes will be identical. In the proactive scheme, what actually happens is that the generated failure may not interrupt any connection as the connections that would go through this link were already blocked because of the high blocking probability of this scheme, especially under a heavy traffic load. Therefore, the average restoration time of the proactive protection in this case is 0. With the active restoration scheme, however, it is very likely that the generated failure will interrupt several accepted connections. As the number of connections affected by the failure in our case is not zero, the average restoration time (ART) of our scheme will definitely be higher than that of the proactive protection scheme.

Although theoretically the worst time complexity of the wavelength-assignment algorithm of our scheme is $O\left(|V|^2\right)$, our simulation results in Table 3 indicate clearly that we can actually find an available backup lightpath with a very high probability by inspecting only the first three predefined backup paths. This indicates that in our scheme the wavelength assignment can be implemented in $O\left(|V|\right)$ time with a very high probability. Our simulation results further indicate that on average the resources occupied by a demand in the proactive protection scheme is twice that of our scheme, so our scheme is actually very efficient in terms of network resources.

Table 3. Probability (%) That a Specific Backup Path is Available for Restoration

Path	Network 1	Network 2	Network 3	Average
First	97.8	93.8	97.1	96.2
Second	1.5	3.2	1.6	2.1
Third	0.5	1.5	0.7	0.9
Others	0.2	1.5	0.6	0.8

To have an overall performance comparison between path-based proactive protection and our active restoration, we summarize further our simulation results of average blocking probability (ABP), average restoration probability (ARP), and ART of the three test networks in Tables 4, 5, and 6, respectively. Here ABP, ARP, and ART are estimated by the average of their values of all workloads, respectively. Although the proactive path-based

Table 4. Overall Comparison Between Proactive Protection and Active Restoration for Network 1

	ABP (%)	ARP (%)	ART (ms)
Proactive protection	22	100	17.6
Active restoration	7.8	96.1	29.0

method guarantees 100% restoration, the results in Tables 4, 5, and 6 indicate that it suffers a very high blocking probability. On the other hand, our proposed scheme can achieve very low blocking probability and also a very high restoration probability with only a small sacrifice in restoration time.

Table 5. Overall Comparison Between Proactive Protection and Active Restoration for Network 2

	ABP (%)	ARP (%)	ART (ms)
Proactive protection	31.3	100	34.1
Active restoration	14.2	95.6	45.4

Table 6. Overall Comparison Between Proactive Protection and Active Restoration for Network 3

	ABP (%)	ARP (%)	ART (ms)
Proactive protection	20.9	100	34.0
Active restoration	8.7	96.5	39.9

5. Conclusion

In this paper we have proposed an active restoration scheme and also developed the routing and the wavelength-assignment algorithm for it. In this scheme a primary lightpath is protected by multiple backup lightpaths that are computed but not reserved along the primary path before failure occurs. Depending on the location of the failure, one of the backup paths will be activated to restore the disrupted traffic. The selection of a backup path depends on both the status of the nodes on the primary path (supported or unsupported) and the availability of the network resources along the backup path. Extensive simulation results based on three typical test networks indicate that the new active restoration scheme can significantly reduce blocking probability and save network resources and can also guarantee a very high restoration probability with only a small increase in restoration time. In the future we will apply our new scheme to other networks and investigate its performance under partial-wavelength conversion and multiple-failure situations.

Acknowledgments

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