

Efficient Algorithms for Routing Dependable Connections in WDM Optical Networks

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Abstract—We consider the problem of establishing *dependable connections* in WDM networks with dynamic traffic demands. We call a connection with fault-tolerant requirements as a *dependable connection (D-connection)*. We consider the *single-link failure model* in our study and recommend the use of a proactive approach, wherein a D-connection is identified with the establishment of the primary lightpath and a backup lightpath at the time of honoring the connection request. We develop algorithms to select routes and wavelengths to establish D-connections with improved blocking performance. The algorithms use the *backup multiplexing* technique to efficiently utilize the wavelength channels. To further improve channel utilization, we propose a new multiplexing technique called *primary-backup multiplexing*. Here, a connection may not have its backup lightpath readily available throughout its existence. We develop algorithms based on this technique to route D-connections with a specified *restoration guarantee*. We present an efficient and computationally simple heuristic to estimate the average number of connections per link that do not have backup lightpaths readily available upon a link failure. We conduct extensive simulation experiments on different networks to study the performance of the proposed algorithms.

Index Terms—Dependable connection, lightpath, link failure, wavelength division multiplexing.

I. INTRODUCTION

WAVELENGTH-DIVISION multiplexing (WDM) technology offers the capability of building very large wide-area networks with throughput of the order of terabits per second. Optical networks employing WDM technology provide very high data rates, low error rates, and low delay. These networks are a viable solution to meet the bandwidth demand arising from several emerging applications such as Internet and web browsing, graphics and visualization, medical image access and distribution, multimedia conferencing, and broadband services to home [1].

A WDM optical network consists of a set of *wavelength cross-connects (WXC)* interconnected by point-to-point

fiber links in an arbitrary topology. A *wavelength-selective cross-connect (WSXC)* is capable of optically switching an optical signal from an incoming fiber to an outgoing fiber on the same wavelength. WDM networks that use WSXCs are referred to as wavelength-selective networks. Here, a message is transmitted from one node to another node by using a *lightpath* without requiring any electro-optical conversion and buffering at the intermediate nodes. A lightpath uses the same wavelength on all the links along its route [2]. In a WDM-based transport network architecture, a set of lightpaths constituting an *optical layer* provides protocol-transparent service to the client layer such as SONET, ATM, and IP.

Unlike a WSXC, a *wavelength-interchange cross-connect (WIXC)* is capable of changing the wavelength of an incoming signal by using *wavelength converters*. WDM networks that use WIXCs are referred to as wavelength-convertible networks. Wavelength converters are very expensive. Therefore, it is preferred to use converters only at a few strategic nodes. Such a network is called a network with *sparse wavelength conversion* [3]. Due to technological constraints, the number of wavelengths that can be supported on a fiber is limited. Therefore, multiple fibers can be used in a link to satisfy the traffic demand. The networks that employ multiple fibers in a link are known as *multifiber networks*. Multifiber networks can also be used as an alternate to compensate for the lack of converters [4].

A. Routing and Wavelength Assignment

As WDM networks impose a wavelength continuity constraint, a good *routing and wavelength assignment (RWA)* algorithm is important to improve the wavelength channel utilization. Several heuristic solutions for the RWA problem have been proposed in the literature [2], [5]–[7]. The routing methods such as fixed routing, fixed alternate routing, and several wavelength assignment methods have been evaluated analytically and experimentally in [3], [7], [8]. These methods have been proposed to route lightpaths with no fault-tolerance capability.

The traffic demand assumed by an RWA algorithm can be either static or dynamic. In a static traffic demand, the set of connection requests (or demands or source–destination pairs) is given *a priori*. The objective is to assign lightpaths to all of them so as to minimize the resources required. The resources could be wavelengths or fibers. This problem is relevant for the capacity planning phase to determine the capacity needed in the near future, based on current and expected demands [9].

In a dynamic traffic environment, the connection requests arrive at a network one by one in a random manner. Once a request

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is honored, the connection is held for a random finite time before being terminated. Here, the objective is to increase the *acceptance ratio* (or equivalently, to decrease the *blocking probability*) of the connections. The dynamic traffic demand results in several situations as discussed in [10]. First, it may become necessary to reconfigure the network in response to changing traffic patterns. Second, with the rise in broadband traffic it is expected that the leased-line rates for private virtual networks and Internet service provider links will reach 2.488 Gb/s and higher. The demand for such services will change with time. Recently, there has been a growing interest in integrated IP/WDM routing [11]. In IP-over-WDM networks, lightpaths are established between any two IP routers. The routers between which a lightpath exists become neighbors, changing the network topology perceived by all participating IP routers. The IP layer and optical layer may interact to route the traffic efficiently. The traffic on a lightpath connecting two routers can be monitored continuously and appropriate changes can be made to the optical layer.

B. Lightpath Restoration

WDM networks are prone to component failures. A fiber cut causes a link failure. When a link fails, all its constituent fibers will fail. A node failure may be caused due to the failure of the associated WXC. A fiber may fail due to the failure of its end components. Failure detection, correlation, and root cause analysis is a difficult problem in WDM optical networks [12]. The nodes adjacent to the failed link can detect the failure by monitoring the power levels of signals on the link [12]. In [13], some mechanisms to detect and isolate faults such as fiber cuts and router and amplifier failures have been presented.

Since WDM networks carry high volumes of traffic, failures may have severe consequences. Therefore, it is imperative that these networks have fault-tolerance capability. Fault-tolerance refers to the ability of the network to reconfigure and reestablish communication upon failure. The process of reestablishing communication through a lightpath between the end nodes of a failed lightpath is known as *lightpath restoration*. A lightpath that carries traffic during the normal operation is known as the *primary lightpath*. When a primary lightpath fails, the traffic is rerouted over a new lightpath known as the *backup lightpath*. A lightpath can be protected against failures by pre-assigning resources to its backup lightpath statically. This approach is referred to as *protection* [14]. Alternatively, resources can be searched dynamically to establish a backup lightpath after the component failure. This approach is referred to as *dynamic restoration* or *restoration* [12], [14]. In this paper, we use the term “restoration” to mean “service restoration” in a generic sense as in [9], [15]–[17]. We use the terms “proactive” and “reactive” to mean “protection” and “dynamic restoration,” respectively.

C. This Work

This work is concerned with lightpath restoration in WDM networks with dynamic traffic demands. We assume that the networks do not have wavelength conversion capability. We consider a *single-link failure model* in our work. This model assumes that at any instance of time, at most one link can fail. In other words, failures do not accumulate and when a link

fails, any link that has failed earlier has been repaired. We develop efficient algorithms for establishing *dependable connections* (D-connections) in these networks. We call a connection with fault-tolerant requirements a dependable connection.

Our algorithms use a proactive approach wherein a D-connection is identified with the establishment of a primary and a backup lightpath at the time of honoring the request itself. The algorithms use *backup multiplexing* technique to share wavelength channels among several backup lightpaths to improve the channel utilization. They yield 100% *restoration guarantee* as the backup lightpaths are readily available upon failures. We define the restoration guarantee as the guarantee with which a failed lightpath finds its backup readily available.

The performance improvement obtained by using backup multiplexing is not sufficient. We propose a new multiplexing technique called *primary-backup multiplexing* to further improve the performance. This technique allows a primary lightpath and one or more backup lightpaths to share the same channel. By doing so, channel utilization increases and the network blocking performance improves. However, this technique may sacrifice 100% guarantee on backup lightpath availability for all the failed lightpaths.

We develop efficient algorithms using the primary-backup multiplexing technique to route D-connections with specified restoration guarantees. The objective is to maximize the acceptance ratio of D-connections while keeping the reduction in restoration guarantee within an acceptable limit. We develop an efficient and computationally simple heuristic to estimate the average number of connections per link which do not have their backup lightpaths readily available. The proposed algorithms are flexible to choose a tradeoff between performance improvement and restoration guarantee.

D. Organization of the Paper

The rest of this paper is organized as follows. In Section II, a classification of restoration methods is presented and the related work on lightpath restoration in WDM networks is discussed. The proposed primary-backup multiplexing technique is explained with an illustration in Section III. In Section IV, the proposed algorithms based on backup multiplexing are presented. In Section V, the proposed algorithms based on primary-backup multiplexing are presented. The proposed heuristic method for estimating the average number of non-recoverable connections per link is described in Section VI. The results of the simulation experiments are discussed in Section VII. Finally, some concluding remarks are made in Section VIII.

II. LIGHTPATH RESTORATION METHODS

A. Classification of Restoration Methods

The restoration methods can be broadly classified into reactive and proactive methods. While the proactive methods use the protection-based approach, the reactive methods use the dynamic-restoration-based approach. The reactive method is the simplest way of recovering from failures. In this method, when an existing lightpath fails, a search is initiated for a new lightpath that does not use the failed components. This has an advantage

of low overhead in the absence of failures. However, this method does not guarantee successful recovery. To overcome the shortcomings of the reactive methods, proactive methods can be employed. In a proactive method, backup lightpaths are identified and resources are reserved along the backup lightpaths at the time of establishing the primary lightpath itself. By doing so, this method yields 100% restoration guarantee and ensures fast recovery.

A proactive or reactive restoration method is either *link-based* or *path-based* [9], [14]. A link-based method employs *local detouring* while a path-based method employs *end-to-end detouring*. A link-based method reroutes traffic around the failed component. When a link fails, a new path is selected between the end nodes of the failed link. This path along with the working segment of the primary path will be used as the backup path. In case of wavelength-selective networks, the backup path must necessarily use the same wavelength as that of the primary path as its working segment is retained. In a path-based restoration method, a backup lightpath is selected between the end nodes of the failed primary lightpath. This method shows better resource utilization than the link-based restoration methods. However, it requires excessive signaling and results in longer restoration time.

A proactive restoration method may use a dedicated backup lightpath for a primary lightpath. This is known as *dedicated backup reservation* method. This method has an advantage of shorter restoration time, as the WXC's are configured for the backup path at the time of establishing the primary path itself. However, this method reserves excessive resources. For better resource utilization, multiplexing techniques can be employed. If two primary lightpaths do not fail simultaneously, their backup lightpaths can share a wavelength channel. This technique is known as *backup multiplexing*. In a dynamic traffic scenario, a proactive method can employ *primary-backup multiplexing* to further improve resource utilization. This technique is explained in detail in Section III.

A path-based restoration method could be either *failure-dependent* or *failure-independent*. In a failure-dependent method, associated with the failure of every link traversed by a primary lightpath, there is a backup lightpath. When a primary lightpath fails, the backup lightpath that corresponds to the failed link will be used. In a failure independent method, a backup lightpath which is link-disjoint with the primary lightpath is chosen. This backup path is used upon occurrence of a link failure, irrespective of which of its links has failed.

B. Related Work

The problem of restorable network design for a static traffic demand has been dealt with in [15], [9], [16], [14], [17]. While the work in [15]–[17] considers multifiber networks, that in [9], [14] considers single-fiber networks.

In [15], iterative algorithms have been proposed for designing restoration network minimizing the number of fibers in case of multifiber wavelength selective and wavelength-convertible networks. They use proactive path-based and failure-dependent restoration employing backup multiplexing. The restoration network design for multifiber wavelength selective networks has been addressed in [16]. The work considers proactive

failure-dependent path-based restoration. Backup multiplexing is used to improve wavelength channel utilization. Designing multifiber networks has been considered in [17] for both the wavelength convertible and wavelength selective networks. Three proactive restoration methods have been proposed. They include path-based failure-independent and failure-dependent, and link-based methods. ILP formulations and heuristic algorithms have been developed.

In [9], the problem of designing the restoration network for a given set of demands for wavelength-convertible networks has been considered. The problem has been formulated as an integer programming problem. The objective function is to minimize the weighted number of wavelengths required. The links are weighted by capacity consumption per wavelength. Single-link and node failures are considered. The failure-independent path-based restoration is used. Also, a distributed control protocol for selecting primary and backup lightpaths has been presented. It basically uses the proactive path-based restoration approach.

In [14], ILP formulations have been developed for three different proactive restoration methods: dedicated backup reservation, path-based restoration using backup multiplexing, and link-based restoration using backup multiplexing. The objective here is to minimize the number of wavelengths in a single-fiber wavelength-selective network.

A distributed control protocol for reactive methods has been proposed in [12]. Upon a link failure, this protocol searches for backup lightpaths for the failed lightpaths. Both the link-based and path-based restoration have been considered.

III. PROPOSED PRIMARY-BACKUP MULTIPLEXING TECHNIQUE

We propose the primary-backup multiplexing technique to combine the advantages of reactive and proactive methods. This technique allows a primary lightpath and one or more backup lightpaths to share a channel. By using this technique, increased number of lightpaths can be established at the expense of reduction in restoration guarantee. This technique is useful in case of dynamic traffic where the lightpaths are short-lived. A D-connection loses its recoverability when a channel on its backup lightpath is used by some other primary lightpath. It regains its recoverability when the other primary lightpath terminates. When a primary lightpath fails, the source node sends control messages along the route of the backup path to configure WXC's. If any channel in the route is used by some other primary lightpath, the establishment process fails.

The motivation for this technique stems from the following factors. First, faults do not occur frequently in practice to warrant full reservation all the times. Second, every connection must not necessarily have fault-tolerance capability to ensure network survivability. Third, at any instant of time, only a few connections require fault-tolerance capability critically. For such connections, backup lightpaths may be exclusively reserved, and for others, the restoration guarantee could be less than 100%.

A D-connection loses its recoverability only when the following three events occur simultaneously: 1) a link fails during the period of its existence; 2) the failed link is used by its primary lightpath; and 3) a channel on its backup lightpath is used

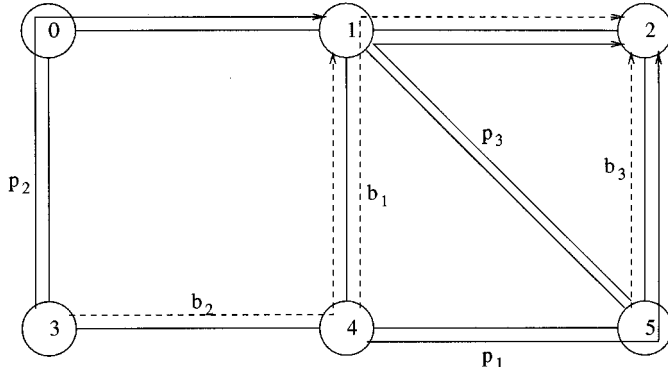


Fig. 1. Illustration of primary-backup multiplexing technique.

by some other primary lightpath. However, such a situation is less probable. The probability of occurrence of event 1 depends on the *holding time* of a connection and the *mean time between failures* (MTBF). Normally, the holding time is much smaller than MTBF. If we assume a single-link failure model, and every link is equally likely to fail, then the probability of occurrence of event 2 depends on the number of physical links used by a connection and the total number of links in the network. The occurrence of event 3 depends on the physical network topology, the offered load, and the routing algorithm used. For a good routing algorithm, the probability of this event decreases as the network connectivity increases and the offered load decreases.

We illustrate this technique in Fig. 1. It shows three primary lightpaths p_1 , p_2 , and p_3 and their respective backup lightpaths b_1 , b_2 , and b_3 on a wavelength. The backup lightpaths b_1 and b_2 share the channel on link $4 \rightarrow 1$, as p_1 and p_2 are link disjoint. The channel on link $1 \rightarrow 2$ is shared by p_3 and b_1 and the channel on link $5 \rightarrow 2$ is shared by p_1 and b_3 . Therefore, both p_1 and p_3 are nonrecoverable. However, if one of them terminates, the other regains recoverability immediately.

IV. BACKUP-MULTIPLEXING-BASED ROUTING ALGORITHMS

We now describe our algorithms for routing D-connections. Our algorithms are proactive and use the failure-independent path-based restoration approach. The algorithms use the backup-multiplexing technique to improve wavelength channel utilization. A D-connection consists of a primary and a backup lightpath. In response to a D-connection request, our algorithms choose a primary-backup lightpath pair so as to minimize the blocking probability. We present two algorithms, namely, *primary dependent backup wavelength assignment* (PDBWA) and *primary independent backup wavelength assignment* (PIBWA). While PDBWA assigns the same wavelength to a primary and its backup, PIBWA does not impose such restriction on wavelength assignment. These methods differ in their complexity and performance.

A. Preliminaries and Definitions

The proposed algorithms use the alternate routing method, wherein a set of candidate routes for every source-destination (s-d) node pair is precomputed. The candidate routes of an s-d pair are chosen to be link-disjoint. This ensures failure-independent lightpath restoration. Another advantage is that in a

distributed implementation, all the link-disjoint routes can be searched in parallel without any contention among themselves. Let K be a predefined constant denoting the maximum number of candidate routes for any s-d pair. Let H be the hop length of the longest candidate route. The network is assumed to have N nodes and W wavelengths per fiber.

A physical link (or simply a link) connects two nodes in a network. A link consists of one or more unidirectional fiber links (or simply fibers). A *simplex link* or a *unidirectional link* is realized by a single unidirectional fiber. A *duplex link* or a *bidirectional link* is realized by two unidirectional fibers in opposite directions. A fiber consists of a certain number of wavelengths. A wavelength on a fiber is referred to as a *wavelength channel* or simply a *channel*. A route (or a path) consists of a sequence of links. A lightpath is uniquely identified by a path and a wavelength. Therefore, a lightpath consists of a sequence of channels with each channel using the same wavelength.

A channel which is not currently used by any primary or backup lightpath is called a free channel or simply an *f-channel*. A channel which is being used by a primary lightpath is called a *p-channel*. A channel which is currently shared by a set of backup lightpaths is called a *backup-multiplexed channel* or simply a *b-channel*.

The path used by a lightpath can be represented as a *path vector* P . It defines the set of links used by the route of a lightpath. If L is the number of links in the network, then path vector P of a lightpath can be represented as an L -bit binary number, $\langle p_{L-1}p_{L-2} \dots p_1p_0 \rangle$ such that the links corresponding to 1 bit form the physical path used by the lightpath. Here, a link may refer to a unidirectional fiber link in case of the algorithms dealing with simplex link failures and may refer to a link with two unidirectional fibers in opposite direction in case of the algorithms dealing with duplex link failures.

A *conflict vector* (CV) is associated with a channel. It defines the set of links used by the primary lightpaths whose backup lightpaths use this channel. If L is the number of links in the network then the CV of a channel can be represented as an L -bit binary number, $\langle c_{L-1}c_{L-2} \dots c_1c_0 \rangle$. Here, a bit value of 1 in position i means that link i is used by a primary lightpath whose backup lightpath uses this channel.

B. Cost Function

In response to a new request, a minimum-cost primary-backup lightpath pair is chosen by our algorithms. The key idea here is to choose the pair which requires minimum number of extra free wavelength channels. Thus, our algorithms ensure that at the time of routing a new lightpath pair, the network is taken to a new state so as to maximize the total number of free channels in the network. We now describe the cost function used by our algorithms to compute the cost of a primary-backup lightpath pair $\langle L_p, L_b \rangle$.

We use $C_p(L_p)$ to denote the cost of a primary lightpath L_p . We use $C_b(L_b, L_p)$ to denote the cost of a backup lightpath L_b whose primary lightpath is L_p . The cost of a D-connection using the pair $\langle L_p, L_b \rangle$ is given by $C_D(L_p, L_b) = C_p(L_p) + C_b(L_b, L_p)$.

The cost of a primary lightpath is the sum of the cost of its channels. The cost of an f-channel is one and that of any other

channel is infinity. It is to be noted that the cost of a primary lightpath depends on the status of its channels only. Here, the cost of a channel can be computed in constant time. However, the cost of a backup lightpath depends on its primary lightpath also. The cost of a backup lightpath L_b whose primary lightpath is L_p is the sum of the cost of the channels of L_b . The cost of an f-channel is one. The cost of a p-channel is infinity. The cost of a b-channel is zero if there is no common link between its CV and the path vector of L_p . Otherwise, the cost of a b-channel is infinity. Here, the time required to compute the cost of a b-channel is proportional to the length of the route used by L_p .

C. PDBWA Method and Its Complexity

In this method, in response to a request for a D-connection, a primary and backup lightpath on the same wavelength are chosen. Since there is a restriction on choosing the wavelength, it may not yield the best performance. For example, there may arise a situation wherein there exist wavelength-continuous routes for the primary on one wavelength and for the backup on some other wavelength, but there are no wavelength-continuous routes available on the same wavelength for the primary and backup. In such a case, the request will be rejected by this method. Similarly, there may arise a situation, wherein a pair of lightpaths with higher cost is chosen, degrading the network performance. In spite of these disadvantages, this method has several advantages. First, it is simpler, having less computational complexity as all the possible lightpaths are not examined. Second, it does not require complex procedure to check if two backup routes could be multiplexed on a channel or not. Third, in case of transport network applications, it does not require coordination from electrical level cross-connection [15].

1) *Simplex Link Failure*: First, we consider failures at simplex link (single fiber) level. This could happen due to the failure of components associated with a fiber. From the constraints of WDM networks, it is clear that two primary lightpaths on the same wavelength do not share any fiber. Therefore, if some backup routes are multiplexed on a channel, then a new backup route can always be multiplexed on the channel. This means that the cost of a backup lightpath is independent of any primary lightpath. Now, we describe the procedure to choose the least-cost lightpath pair on a given wavelength for a given node pair $\langle s, d \rangle$. We recall that there are at most K link disjoint candidate routes for any node pair. Therefore, there could be at most K lightpaths for a given node pair and a given wavelength. Associated with every lightpath L_i , there are two values, $C_p(L_i)$ and $C_b(L_i)$. The value of $C_p(L_i)$ is the cost of using L_i as a primary lightpath and the value of $C_b(L_i)$ is the cost of using L_i as a backup lightpath. The following steps find a (C_p, C_b) for a given wavelength and node pair.

- 1) For each of the possible K lightpaths, compute C_p and C_b .
- 2) Choose a lightpath L_p whose C_p is minimum.
- 3) Among the lightpaths other than L_p , choose a lightpath L_b whose C_b is minimum.

The value of C_p and C_b for a lightpath can be found in $O(H)$ time. The above procedure is repeated for every wavelength to find the least-cost lightpath pair. Therefore, the worst-case time

complexity of the PDBWA method for the simplex link case is $O(KNW)$ as the value of H could be $N - 1$ in the worst case.

Claim: The pair of lightpaths on a wavelength chosen by the above method has the minimum C_D value among all the lightpath pairs on the wavelength.

Proof: It is to be noted that for a lightpath L , if $C_p(L)$ is finite, then $C_b(L)$ is equal to $C_p(L)$. Let $\langle L_1, L_2 \rangle$ be the pair chosen by the above method. Let $C_p(L_1)$ be c_1 and $C_b(L_2)$ be c_2 . Assume that there exists some other pair $\langle L_3, L_4 \rangle$ with a lesser cost than $\langle L_1, L_2 \rangle$. Let $C_p(L_3)$ be c_3 and $C_b(L_4)$ be c_4 .

By way of working of the algorithm we make the following arguments.

- 1) If L_3 is the same as L_1 then $c_1 = c_3$ and $c_2 \leq c_4$. The claim follows immediately. Therefore, consider the case where L_3 is different from L_1 .
- 2) Cost of any backup lightpath $\geq \min(c_1, c_2)$.
- 3) Since L_3 is different from L_1 , it follows that $c_3 \geq c_1$.
- 4) If c_3 is less than c_2 then our method must have chosen L_3 as the backup lightpath L_2 . Therefore, $c_3 \geq c_2$.
- 5) From 3) and 4), it follows that $c_3 \geq \max(c_1, c_2)$.
- 6) From 2), it follows that $c_4 \geq \min(c_1, c_2)$.
- 7) From 5) and 6) it follows that $c_3 + c_4 \geq c_1 + c_2$. Therefore, the cost of $\langle L_3, L_4 \rangle$ can not be less than that of $\langle L_1, L_2 \rangle$.

Hence, our claim is correct. \square

2) *Duplex Link Failure*: Now we consider the case wherein a link failure causes failure of all the fibers constituting the link. We consider networks wherein two adjacent nodes are connected by a duplex link which is realized by a pair of simplex links (fibers) in opposite directions. Here, when a link failure occurs both the fibers fail.

A primary lightpath p_1 is said to share a link l with another primary lightpath p_2 , if both use the same wavelength and one fiber of link l is used by p_1 and the other fiber is used by p_2 . Two primary lightpaths are said to intersect if they share at least one link. It is to be noted that the intersecting primary lightpaths can not share any channel for their backup.

A primary lightpath with H hops can intersect a maximum of H other primary lightpaths. Now consider a wavelength i . There are K possible primary lightpaths. Process the primary lightpaths one by one. Consider a primary lightpath L_p with some finite cost. Disable temporarily the channels used by the backup lightpaths of every other primary lightpath that intersects L_p . This requires $O(H^2)$ time units. For this primary lightpath, choose the least-cost backup lightpath. While computing C_b of a backup lightpath, the cost of a channel on it is computed as follows: If the channel is free, its cost is one. If it is disabled, its cost is infinity. Otherwise, its cost is zero, implying that it can be multiplexed with other backup routes on the channel. This requires $O(KH)$ time units. Similarly, for every other primary lightpath, choose the least-cost backup lightpath. Repeat this for each of the W wavelengths to choose the minimum-cost lightpath pair. The worst-case time complexity of the PDBWA method for this case of duplex links thus becomes $O((KN^2 + K^2N)W)$ as the value of H could be $N - 1$ in the worst case.

D. PIBWA Method and Its Complexity

This method does not impose any restriction on the use of wavelength for the primary and backup lightpaths. Therefore,

we can choose the best possible primary-backup lightpath pair to satisfy a D-connection request. This method has the advantage of better network performance in terms of connection blocking probability. However, it has some disadvantages. First, it is computationally more complex. Second, it requires additional data structures such as the conflict vector to keep information which would help to determine the cost of a channel on a backup lightpath for a given primary lightpath. We describe below the procedure to select the minimum-cost lightpath pair.

- 1) Consider a candidate route R . For each of the W lightpaths that uses this route, compute $C_p()$. Choose the one with the minimum $C_p()$ value. Let this lightpath be L_p .
- 2) For each of the $(K-1)W$ lightpaths (say L) using a route other than R , compute $C_b(L, L_p)$. Choose the one with the minimum cost. Let this lightpath be L_b .
- 3) The pair $\langle L_p, L_b \rangle$ has minimum cost among all the pairs whose primary route is R .
- 4) Repeat steps 1 and 2 for each of the K possible routes.
- 5) Among the K minimum-cost pairs thus found, choose the one with the least cost.

We now compute the computational complexity of the PIBWA method. Step 1 requires $O(HW)$ time units. To compute the cost of a backup lightpath for a given primary route, it requires $O(H^2)$ time units. Therefore, step 2 requires $O(KH^2W)$ time units. Since steps 1 and 2 are repeated for K times, the worst-case time complexity of the PIBWA method becomes $O(K^2N^2W)$ as the value of H could be $N-1$ in the worst case. Although theoretically the worst-case value for K and H could be $N-1$, in practice these values are low. Therefore, the actual running time will be low and acceptable.

Remark: The conflict vectors and path vectors could be implemented as bit vectors that can fit in a computer word. This is possible, when the number of links in the network is less. In such a case, the cost of using a channel by a backup lightpath for a given primary lightpath can be computed in constant time by using a bit-AND operation of the conflict and path bit vectors. This will reduce the worst-case computational complexity of the PIBWA method to $O(K^2NW)$.

V. PRIMARY-BACKUP-MULTIPLEXING-BASED ROUTING ALGORITHMS

In this section, we describe our algorithms based on the primary-backup multiplexing technique. The algorithms use proactive path-based failure-independent restoration approach. Here, a wavelength channel can be shared by a primary lightpath and one or more backup lightpaths. We call this channel a *pb-channel*. All the D-connections whose backup lightpaths use a pb-channel lose their restoration capability. Such D-connections are called *orphans*. A p-channel used by a primary lightpath of an orphan is called as a *weak channel*. A b-channel is said to *cover* a p-channel if the primary lightpath that uses the p-channel has a backup lightpath that uses the b-channel. When the b-channel becomes a pb-channel, the p-channels covered by it become weak. The weak channels induced by a pb-channel are the p-channels used by those primary lightpaths whose backup lightpaths use the pb-channel.

The weak channels induced by a primary lightpath are the set of distinct weak channels induced by the pb-channels on the lightpath. The number of weak channels on a link is a measure of the number of connections that do not find their backup lightpaths readily available upon the failure of the link.

We propose two algorithms, *Limited Average Orphans* (LAO) and *Limited Orphans* (LO). The key idea behind the LAO algorithm is to ensure certain restoration guarantee by limiting the average number of orphans created per link upon occurrence of any single-link failure to a predefined value. The LO algorithm ensures it by limiting the number of orphans on any individual link to a predefined value. The algorithms use an alternate routing method. For every pair of source and destination, a set of candidate routes are precomputed off-line. The candidate routes for an s-d pair are chosen to be link-disjoint.

A. Description of the LAO Algorithm

When a new request arrives for a D-connection between a node pair $\langle s, d \rangle$, a primary-backup lightpath pair $\langle L_p, L_b \rangle$ is to be chosen to satisfy the request. It is chosen in such a way that it is admissible and its cost is minimum. We say that the network state is safe if the average number of orphans per link does not exceed a predefined orphan threshold value T . A lightpath pair is said to be admissible if its establishment does not take the network to an unsafe state. This algorithm has two components: cost computation and admissibility test.

1) *Cost Function:* A primary lightpath can use an f-channel or a b-channel. The cost of using an f-channel is one and the cost of using a b-channel is zero. Once a b-channel is used by a primary lightpath, the b-channel becomes a pb-channel. The cost of using a p-channel or a pb-channel is infinity. The cost of the primary lightpath L_p , denoted by $C_p(L_p)$, is the sum of the cost of its channels.

The cost of a backup lightpath L_b for a given primary lightpath L_p , denoted by $C_b(L_b, L_p)$ is defined as the number of free channels used by it. If a channel is an f-channel, then the cost of using it is one. If a channel is currently used only by a primary lightpath then the cost of using it is zero and the channel becomes a pb-channel. If a channel is currently used by a set of backup lightpaths S , then it can be used by L_b with no extra cost, only if the primary route of L_p is link-disjoint with the primary route of each and every backup lightpath in the set S . In other words, the intersection of the CV of the channel and the path vector of L_p should be empty in order for L_b to use the channel. Otherwise, the cost of using the channel is infinity. The cost of a D-connection using the primary-backup lightpath pair $\langle L_p, L_b \rangle$ is given by

$$C_D(L_p, L_b) = C_p(L_p) + C_b(L_b, L_p) + \text{PenaltyCost} * N_d$$

where PenaltyCost is a predefined constant representing the cost of a pb-channel and N_d is the number of pb-channels on both the primary and backup lightpaths. The value chosen for PenaltyCost is such that it is larger than the cost of any lightpath pair with no pb-channels. Since the cost of a lightpath with no pb-channels is less than N , the value of PenaltyCost may be chosen to be $2N$.

Computational Complexity: The computational complexity of finding the cost of a primary lightpath is $O(H)$. This is because the cost of a channel can be computed in constant time. Since the path vector P can have at most H links, $O(H)$ time is required to find $P \cap CV$. Therefore, the time complexity of finding the cost of a backup path is $O(H^2)$. However, $P \cap CV$ can be found in constant time if P and CV are implemented as bit vectors. This is possible when the number of nodes and links in the network is less.

2) *Admissibility Test:* The admissibility test for a pair $\langle L_p, L_b \rangle$ is performed as follows. At every node, for every channel on an incoming link, the following information is maintained. For every channel on an incoming link, the count of number of p-channels covered by it is kept track of. Similarly, the count of the number of p-channels covered in common by this channel, and the next channel on an outgoing link is also kept track of. This information is updated whenever a backup lightpath is established and released. The update for a channel requires only a constant number of operations. It computes the approximate value of the number of orphans per link, denoted by L_{orp} . Initially, the value of L_{orp} is zero. Let x and y be the number of orphans created per link by routing L_p and L_b , respectively. If L_p has at least one pb-channel, then the number of weak channels (m) induced by L_p is computed using the estimator function presented in Section VI. The value of x is then computed as m/L . If the backup lightpath L_b has at least one pb-channel, then the channels used by the primary lightpath L_p are made weak. If h is the hop length of L_p then the value of y is computed as h/L . The pair is admissible if $L_{orp} + x + y$ does not exceed the orphan threshold value T .

The minimum cost pair among those which are admissible is chosen by the algorithm. Once the pair is established, the value of L_{orp} is updated by adding $x + y$ to it. When L_p is released, the number of orphans per link induced by it (say, x') is calculated and L_{orp} is updated by subtracting x' from it. It is to be noted that the computation of x for L_p does not require the global knowledge.

It may so happen that a p-channel of a primary lightpath L_p^1 may be made weak by many other primary lightpaths. This happens when the channels on its backup lightpath L_b^1 are used by some other primary lightpaths, say, L_p^2 and L_p^3 . In that case, orphan count is updated by both L_p^2 and L_p^3 . This would introduce an error in estimating L_{orp} . However, this error is corrected when L_p^2 and L_p^3 are released before L_b^1 is released, as a similar situation arises. If L_b^1 is released first, then the error gets corrected by the following update. When a backup lightpath is released, the number of distinct primary lightpaths traversed by it (say n') is computed using the estimator function with a suitable definition of the variables used. This backup lightpath would have been counted by the n' number of primary lightpaths, and hence the value of L_{orp} is updated by subtracting $(n' \times h)/L$ from it. Here, h is the hop length of L_p^1 .

The choice of a value for the orphan threshold parameter T has an effect on the blocking probability and restoration guarantee of connections. A low value for T will result in higher blocking probability and higher restoration guarantee. On the other hand, a high value for T will result in lower blocking probability and lower restoration guarantee. Therefore, we can

achieve a desired tradeoff between the network blocking performance and restoration guarantee by choosing an appropriate value for T .

B. Description of the LO Algorithm

The LO algorithm chooses the minimum-cost lightpath pair among all the admissible pairs to satisfy a new connection request. The cost of a lightpath pair is calculated in the same way as the LAO algorithm. However, the admissibility criterion is different from that used by the LAO algorithm. A lightpath pair is said to be admissible by this algorithm, if establishing it does not result in the number of orphans on any link exceeding the orphan threshold T . While the LAO algorithm limits the average number of orphans per link to T , the LO algorithm limits the number of orphans on any link to T . So, this algorithm guarantees that the number of orphans created upon occurrence of any link failure is at most T .

It does not make any estimation of the average number of orphans per link. Instead, it computes the actual number of orphans on any link. This is possible, as this algorithm keeps track of the orphans on every link. It needs to know the identity of all the connections which make a p-channel weak. Also, it keeps the identity of the connections whose backup lightpaths are multiplexed onto a channel.

Admissibility Test: To decide the admissibility of a lightpath pair $\langle L_p, L_b \rangle$ the following steps are followed.

- 1) Determine the set of D-connections whose backup lightpaths use some pb-channel(s) on L_p . Call this set as S . If L_b has any pb-channel then add the new connection $\langle L_p, L_b \rangle$ to the set.
- 2) Let S_l be the set of links used by the primary lightpaths of the connections in S .
- 3) Temporarily transform the network state into a new state by marking as weak, the channels that are used by the primary lightpaths of the connections in the set S .
- 4) If the number of weak channels on every link from the set S_l does not exceed the orphan threshold T , then the pair $\langle L_p, L_b \rangle$ is admissible. Otherwise, it is not admissible.

When compared to the LAO algorithm, the LO algorithm is computationally more complex. It is less amenable for distributed implementation as it requires global network state information. However, it has some advantages over the LAO algorithm. The algorithm guarantees that the number of orphans created by any single-link failure is within a predefined value. Also, this algorithm is more flexible, when compared to the LAO algorithm. This means that different levels of performance-guarantee tradeoff can be achieved by this. Our experimental results presented in Section VII substantiate this claim.

VI. ESTIMATING THE NUMBER OF ORPHANS

A. Need for an Estimator Function

If B_p is the set of distinct backup lightpaths that use some channels of a primary lightpath L_p , then the sum of hop lengths of the primary lightpaths that correspond to the backup lightpaths from the set B_p gives the required number of weak channels induced by L_p . In order to compute the exact number of

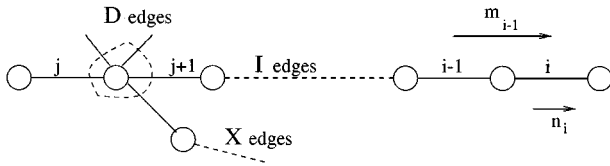


Fig. 2. Estimating the number of weak channels induced by a path.

weak channels induced by L_p , we need to keep the identity of all the backup lightpaths that are multiplexed onto a channel. Also, we need to keep track of the identity of all D-connections that make a channel weak. This requires computationally expensive operations. On the other hand, keeping track of the number of backup lightpaths and the sum of the hop count of their corresponding primary lightpaths can be done with simple operations. However, this has a shortcoming. Since, the same backup lightpath can use more than one channel of L_p , counting the number of distinct backup lightpaths in B_p and also the number of channels used by their corresponding primary lightpaths is not trivial.

We develop a computationally faster heuristic method to make an estimation of the number of weak channels induced when a primary lightpath L_p is established. This can be used to estimate the average number of orphans created per link. The number of operations required by the proposed estimator is proportional to the hop length of L_p . Further, an important feature of this function is that it can be used in a distributed protocol. This is due to the fact that the function uses some information associated with the channels on the route of L_p only.

B. Estimator Function

We now describe a method to estimate the number of distinct backup lightpaths in B_p , denoted by $N(B_p)$. We then explain how the same method can also be used to estimate the number of weak channels induced by L_p .

Consider a primary lightpath L_p as shown in Fig. 2. In the graphical representation, an edge corresponds to a channel. Let n_i be the number of backup lightpaths multiplexed onto edge i . Let m_i be the number of backup paths that use edge i and continue to the next edge $i + 1$.

Let e_i , $1 \leq i \leq H - 1$ be the number of backup lightpaths that use edge i and do not use any of the edges 0 through $i - 1$. The value of e_0 is n_0 . The value of e_1 is $n_1 - m_0$. The value of $N(B_p)$ is computed as $N(B_p) = \sum_{i=0}^{H-1} e_i$.

Computation of e_i : The value of e_i for edge i can be estimated as follows.

Let t_i be the number of backup paths that use some edge $j < i$, use edge i , but do not use any of the edges $j + 1, j + 2, \dots, i - 1$.

The value of e_i is computed as $e_i = n_i - t_i - m_{i-1}$.

Computation of t_i : The value of t_i is computed as follows.

Let k_j be the number of backup paths that use edge j , but do not continue to the next edge $j + 1$. Therefore, $k_j = n_j - m_j$.

Let $k_{j,i}$ be the number of backup paths that use edge j and use edge i without using any of the edges $j + 1, j + 2, \dots, i - 1$.

We now explain how the value of $k_{j,i}$ can be computed.

Let D be the degree of the end vertex v of edge j , I be the number of intermediate edges on the path L_p between and including $j + 2$ and $i - 2$, and L be the total number of links in the network. Let an arbitrary path p among the k_j paths traverse X edges excluding the edges incident on v . We assume that, other than the D edges incident on v and the I intermediate nodes, every edge is equally likely to be traversed by it. Although this assumption depends on the factors such as the topology of the network and the choice of alternative routes for the node-pairs, it is not unrealistic as the value and range of I is small for practical networks, and also among D edges incident on v , one or two are traversed by p and the other edges cannot be traversed by it. On such a path p , edge i appears with the probability $r = X/(L - (D + I))$.

If q_i denotes the probability that a backup path on edge i does not enter from edge $i - 1$, then it is calculated as $q_i = (n_i - m_{i-1})/n_i$, for $n_i \neq 0$, otherwise $q_i = 0$. The probability that the path p enters edge i other than edge $i - 1$ is then given by $r \times q_i$.

The value of $k_{j,i}$ is then computed as $k_{j,i} = k_j \times r \times q_i$.

We choose appropriate values for X , D , and I depending on the topology and hop counts of the alternative routes and make r a constant. An appropriate choice of these values will make the computation of $k_{j,i}$ and t_i simpler. The values of D and I depend on j for any given value of i . However, the range of possible values of D and I is small and also the deviation of the assumed value of $D + I$ from the actual value is not significantly comparable with L . Therefore, choosing a constant value for r does not introduce any significant error as confirmed by our experimental results presented in Section VII. Note that the estimator function is only a heuristic. Instead of considering r as a constant, we can compute it for every possible value of j for a given i . But, this increases the complexity of the estimator function without any significant improvement. The prefix sum S_i is defined and computed as

$$S_i = k_0 + k_1 + \dots + k_i.$$

The value of t_i is then computed as

$$t_i = \sum_{j=0}^{i-2} k_{j,i} = r \times q_i \times S_{i-2}.$$

Computing the Number of Orphans: The above estimator function can also be used to determine the number of weak channels created by routing a primary lightpath L_p with slight modifications. Let n_i be used to denote the number of p-channels covered by edge i . Let m_i be used to denote the number of common p-channels covered by edge i and edge $i + 1$. Let the other variables be accordingly changed. Then the same estimator function will determine the number of distinct weak channels induced by the entire path L_p . If m is the number of weak channels induced by L_p and every link is equally likely to be the failed link, then the average number of orphans created per link by establishing L_p is given by m/L , where L is the total number of links in the network.

We now give below the pseudocode for estimating the number of weak channels induced by a primary lightpath L_p . It can be

noted that all the steps can be performed in linear time proportional to the hop length of L_p .

function *Estimate* (L_p): Given a path L_p with h edges and their n and m values.

This procedure estimates the number of weak channels induced by L_p .

```

Step 1) (* process edges 0 and 1 *)
     $e_0 \leftarrow n_0; e_1 \leftarrow n_1 - m_0; val \leftarrow e_0 + e_1$ 
     $k_0 \leftarrow n_0 - m_0; k_1 \leftarrow n_1 - m_1;$ 
     $S_0 \leftarrow k_0; S_1 \leftarrow k_0 + k_1;$ 
Step 2) (* process edges 2 through  $h - 1$  *)
    For  $i = 2$  to  $h - 1$  do
    begin
        If  $n_i = 0$  then  $q_i \leftarrow 0$  else  $q_i \leftarrow (n_i - m_{i-1})/n_i$ 
         $t_i \leftarrow r \times q_i \times S_{i-2}$ 
         $e_i \leftarrow n_i - t_i - m_{i-1}$ 
         $val \leftarrow val + e_i$ 
         $k_i \leftarrow n_i - m_i$ 
         $S_i \leftarrow S_i + k_i$ 
    end
Step 3) Return( $val$ ).

```

VII. PERFORMANCE STUDY

We evaluate the effectiveness of the proposed algorithms by extensive simulation. The simulation networks considered are the 21-node ARPA-2 network with 26 duplex links and 16-node Mesh-torus network with 32 duplex links. A duplex link is comprised of two simplex links in the opposite directions. Every simplex link is assumed to have eight wavelengths, and therefore a duplex channel consists of 16 wavelength channels. These networks have different connectivity and topology. For the torus network, any s - d pair has a set of four link-disjoint candidate routes. On the other hand, in the ARPA-2 network, many s - d pairs have only two link-disjoint candidate routes. For the primary-backup multiplexing-based algorithms, the values chosen for X and $D+I$ for the Mesh-torus network are 3 and 5, respectively, and for the ARPA-2 network, 4 and 6, respectively. The connection requests arrive at a node as a Poisson process with exponentially distributed holding time with unit mean. Every node is equally likely to be a destination node for a connection request.

A. Performance Metrics

We use the metrics, *connection blocking probability*, *relative performance gain*, and *reduction in guarantee*, to measure the performance of the proposed algorithms. We compare the performance of our algorithms with that of an algorithm that uses dedicated backup lightpaths and with that of an algorithm that does not use any backup lightpath. The algorithm that uses dedicated backup paths is called NO_BM (no backup multiplexing) and its blocking probability is denoted by b_d . The algorithm that uses no backup paths is called NO_BP (no backup path) and its blocking probability is denoted by b_n .

The relative performance gain of the backup multiplexing-based algorithms (BM) is measured as how close its performance is to that of NO_BP with reference to that of NO_BM.

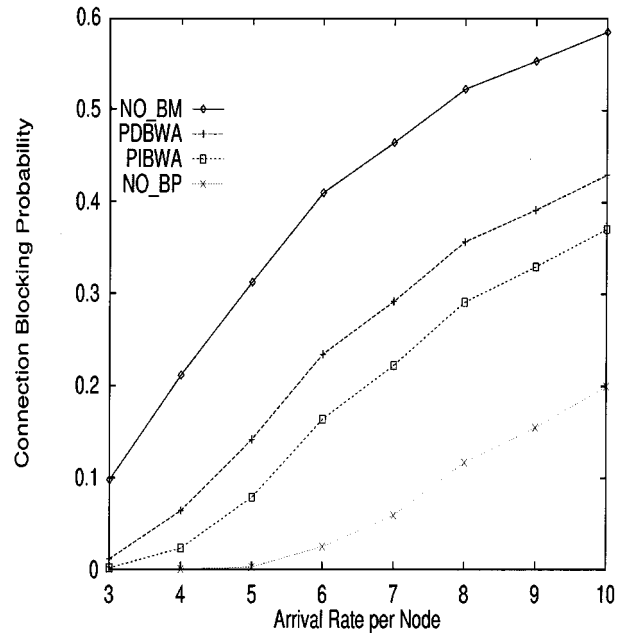


Fig. 3. Performance of D -connections for different traffic loading for the Mesh-torus network.

Let b_{bm} be the blocking probability obtained by a BM algorithm. Then, the relative performance gain is calculated as $(b_d - b_{bm})/(b_d - b_n)$.

The relative performance gain of the primary-backup multiplexing-based algorithms (PBM) is measured as how close its performance is to that of NO_BP with reference to that of BM. Let b_{pbm} be the blocking probability obtained by a PBM algorithm. Then, the relative performance gain is calculated as $(b_{bm} - b_{pbm})/(b_{bm} - b_n)$.

The reduction in guarantee is defined in terms of the probability that a failed connection does not find its backup lightpath readily available upon a link failure.

B. Performance of Backup Multiplexing-Based Algorithms

The performance of the proposed algorithms PDBWA and PIBWA is plotted in Figs. 3–6. In Figs. 3 and 4, the connection blocking probability is plotted as a function of traffic load for the mesh-torus and ARPA-2 networks, respectively. The plots demonstrate the usefulness of backup multiplexing. Compared with the NO_BM method, the performance achieved by our algorithms is significantly higher. The plots also show that PIBWA performs better than PDBWA. The reason is that PIBWA is more flexible in choosing wavelengths for a primary lightpath and its backup lightpath. We can also observe that the effectiveness of backup multiplexing is not sufficient to achieve the performance of NO_BP.

In Figs. 5 and 6, the percentage of relative performance gain is plotted as a function of traffic load for the mesh-torus and ARPA-2 networks, respectively. The plots show that backup multiplexing is more useful in mesh network when compared to ARPA-2 network. The usefulness of backup multiplexing increases as the network connectivity increases. This is because, in a densely connected network, the candidate routes are usually shorter and many possible link disjoint candidate routes exist for

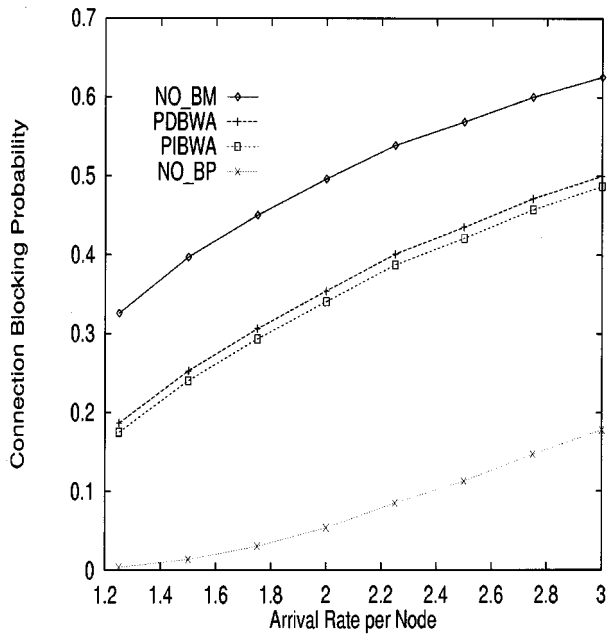


Fig. 4. Performance of D -connections for different traffic loading for the ARPA-2 network.

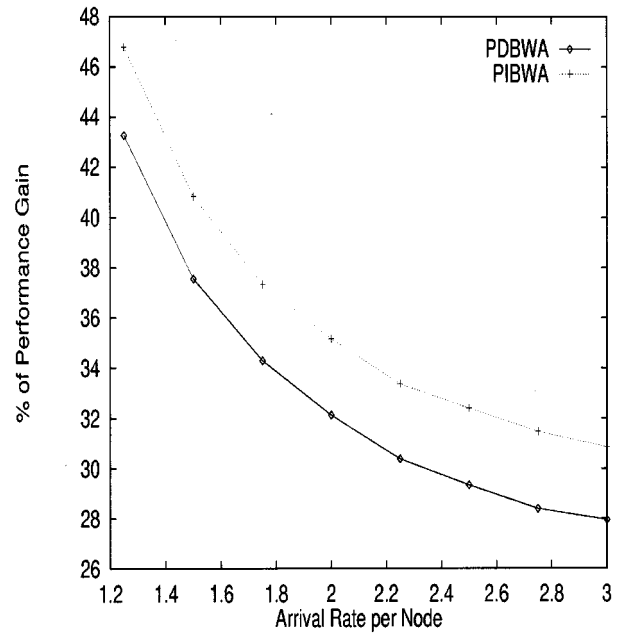


Fig. 6. Performance Gain by the proposed algorithms for different traffic loading for the ARPA-2 network.

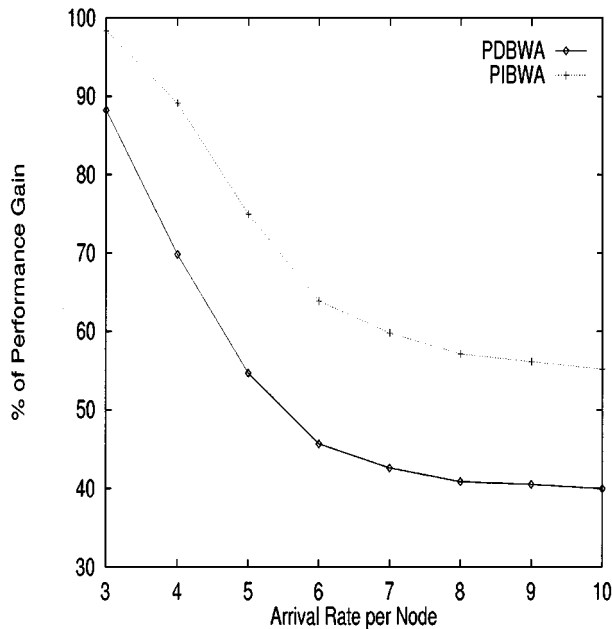


Fig. 5. Performance Gain by the proposed algorithms for different traffic loading for the Mesh-torus network.

a node pair. For the same reasons, the difference in performance gain achieved by PIBWA and PDBWA is small in sparsely connected networks such as ARPA-2. The plots also show that the performance gain decreases as the offered load increases.

C. Performance of Primary-Backup Multiplexing-Based Algorithms

The performance of the *LAO* algorithm is plotted in Fig. 7 for the mesh-torus network. The relative performance gain and reduction in guarantee for three different arrival rates per node (r), 4, 7, and 10 are plotted as a function of the orphan threshold

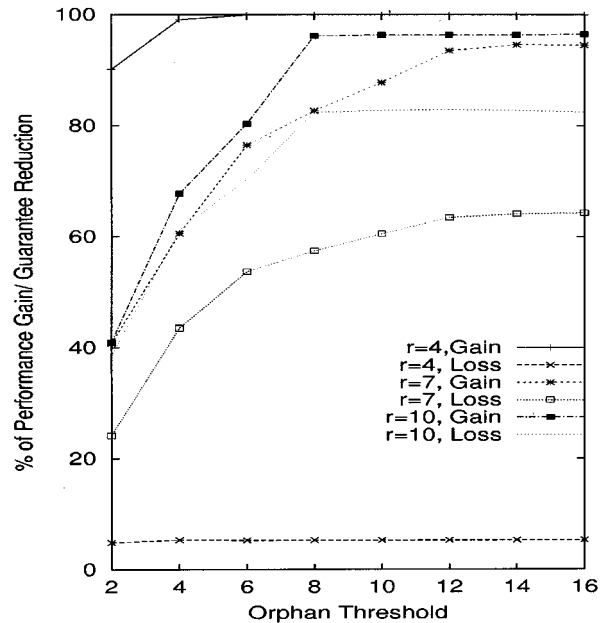


Fig. 7. Performance of the *LAO* algorithm for the Mesh-torus network.

T . The BM algorithm considered here is PIBWA. The chosen arrival rates reflected the light, medium, and heavy traffic load conditions of the network. For the BM algorithm, these arrival rates correspond to the blocking probability of 0.024, 0.224, and 0.372, respectively.

The curves show that under light load conditions, more than 90% performance gain can be achieved at the expense of less than 10% reduction in guarantee. This is because, when the load is light, the number of backup lightpaths multiplexed on a pb-channel is less and the shorter hop routes are more likely to be used by the primary lightpaths. Therefore, at any instant of time, the number of weak channels per link and also the number of orphan connections in the network is much less. As the traffic

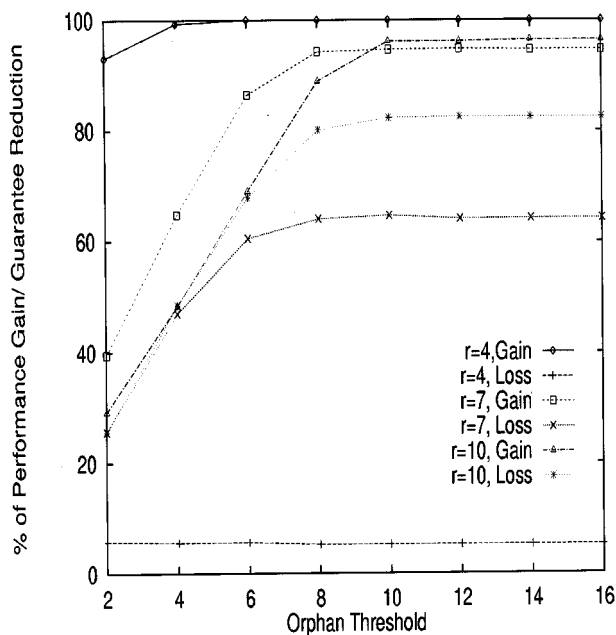


Fig. 8. Performance of the LAO-actual algorithm for the Mesh-torus network.

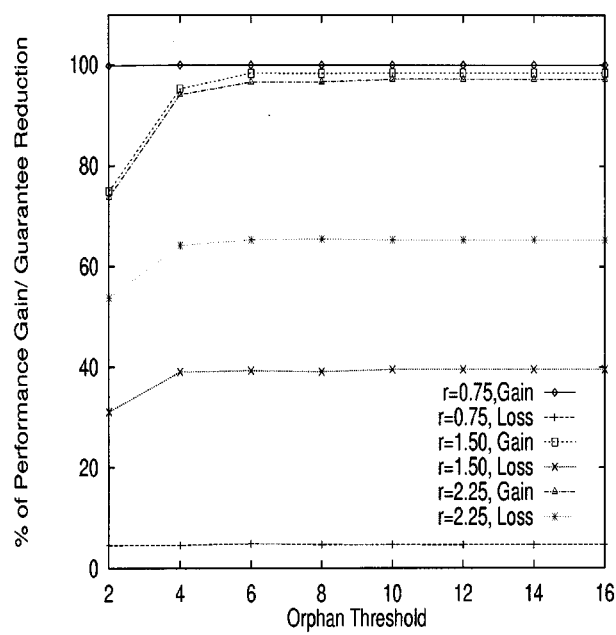


Fig. 10. Performance of the LAO-actual algorithm for the ARPA-2 network.

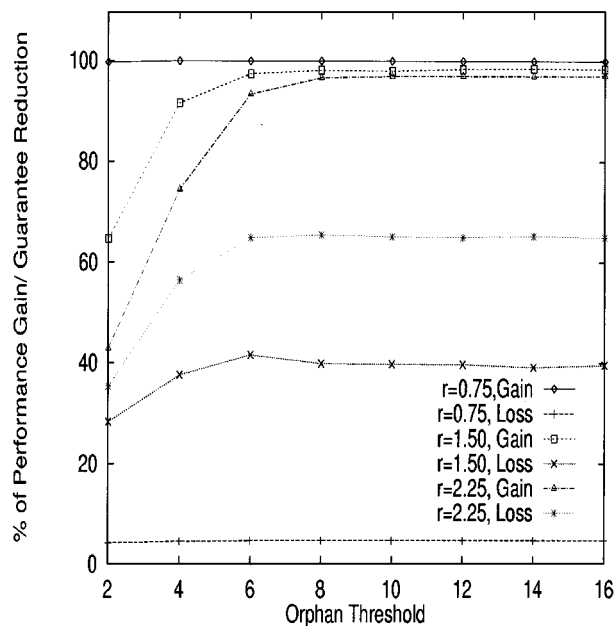


Fig. 9. Performance of the LAO algorithm for the ARPA-2 network.

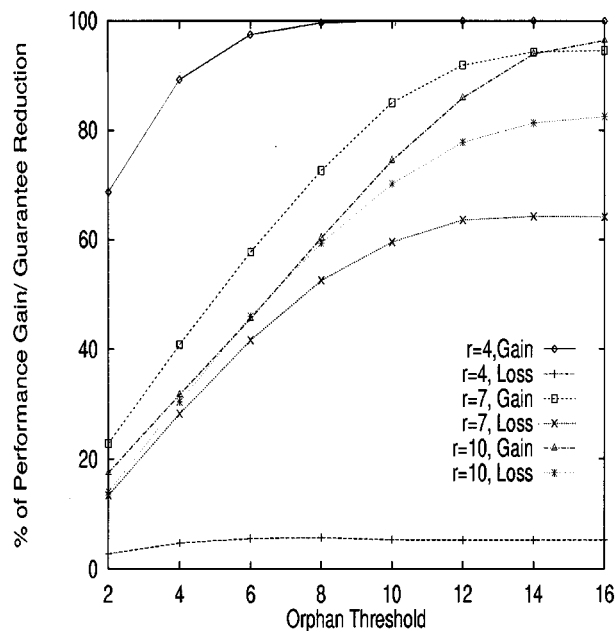


Fig. 11. Performance of the LO algorithm for the Mesh-torus network.

loading increases, the gap between these two metric decreases. However, even for the heavy load condition, the performance gain is more when compared to the reduction in guarantee. This demonstrates the usefulness of the algorithm.

To evaluate how good or accurate the estimator function is, we plot the performance of the algorithm *LAO-actual* in Fig. 8. This algorithm is the same as the *LAO* algorithm except that the average number of orphans per link is actually measured instead of estimated. It is observed that the estimator function is accurate except when the traffic load is high and the threshold value is small. The reason for this can be explained as follows. When the threshold value is less, the error introduced by the estimator function is comparable to the threshold value, consequently, the

result of admissibility test goes wrong. Also, if the load is high, the number of connections arrived during the period of error will be high. However, this error does not undermine the usefulness of the algorithm using the estimator function.

The performance of the LAO and LAO-actual algorithms for the ARPA-2 network is plotted in Figs. 9 and 10, respectively. The relative performance gain and reduction in guarantee for three different arrival rates per node (r), 0.75, 1.50, and 2.25 are plotted as a function of orphan threshold T . The chosen arrival rates reflected the light, medium, and heavy traffic load condition of the network. For the backup multiplexing-based algorithm (PIBWA), these arrival rates correspond to the blocking probability of 0.052, 0.244, and 0.389, respectively.

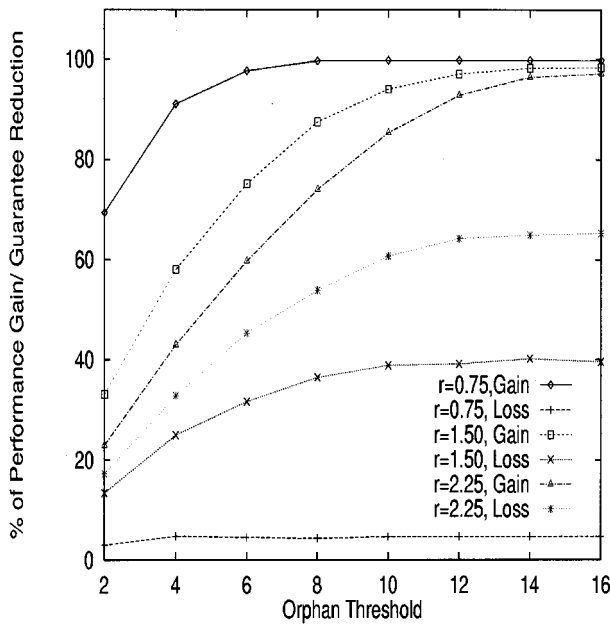


Fig. 12. Performance of the LO algorithm for the ARPA-2 network.

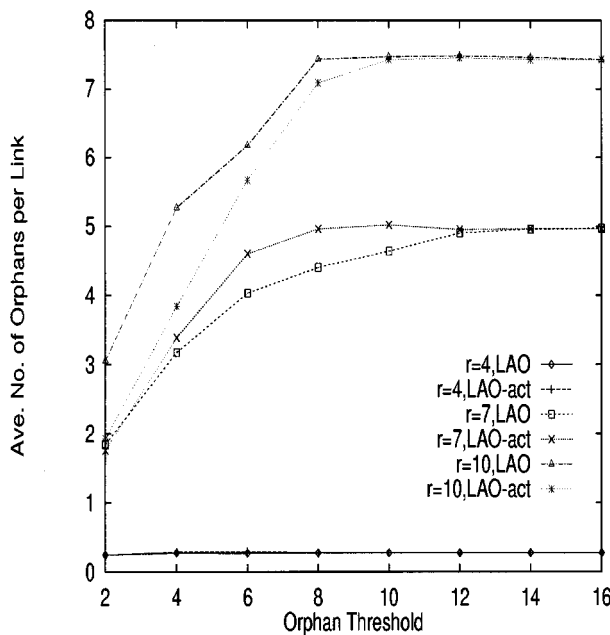


Fig. 13. Average number of orphans created per link by the LAO and LAO-actual algorithms for the Mesh-torus network.

for the ARPA-2 network. The results demonstrate the effectiveness of the proposed algorithms. It can be observed that the performance gain is more for the ARPA-2 network when compared to the mesh-torus network. The reason is as follows. The ARPA-2 is a sparsely connected network. The connections are longer and the number of possible link-disjoint connections for any s - d pair is less. Therefore, the usefulness of a mere backup multiplexing is less. It is highly probable that a connection route encounters at least one pb-channel in such sparsely connected networks. Therefore, for such networks, the primary-backup multiplexing technique is very useful and it will result in increased acceptance of connections.

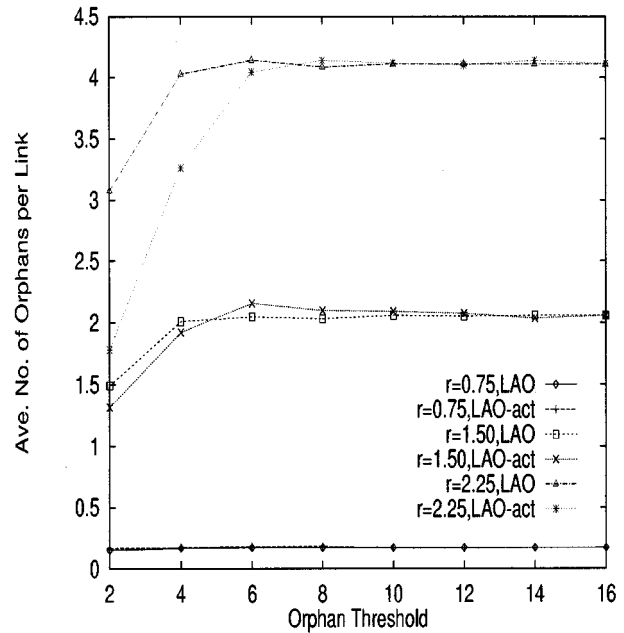


Fig. 14. Average number of orphans created per link by the LAO and LAO-actual algorithms for the ARPA-2 network.

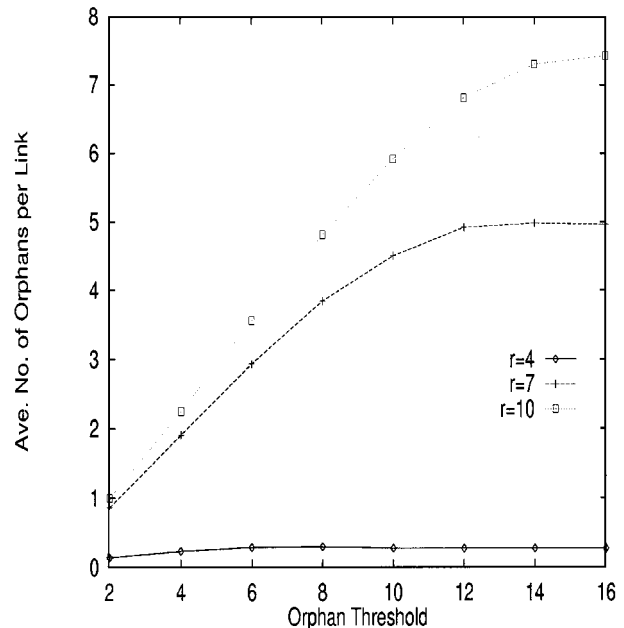


Fig. 15. Average number of orphans created per link by the LO algorithm for the Mesh-torus network.

The performance of the LO algorithm is plotted in Fig. 11 for the mesh-torus network and in Fig. 12 for the ARPA-2 network. It can be observed that the curves change slowly before level off, when compared to that of the LAO algorithm. The reason is as follows. The LO algorithm limits the number of orphans on every link whereas the LAO algorithm limits the average number of orphans on a link. Therefore, the LO algorithm is more restrictive than the other one and hence the rate of change of curves is slower.

Figs. 13 and 14 plot the average number of orphans created per link by the LAO and LAO-actual algorithms as a function

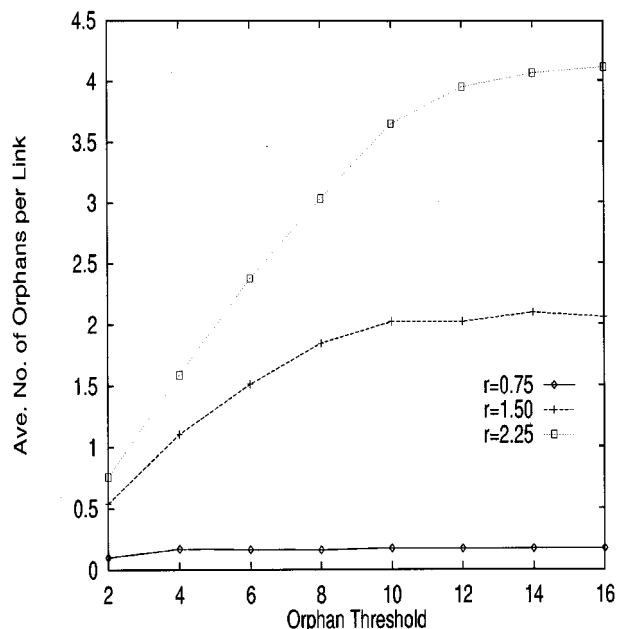


Fig. 16. Average number of orphans created per link by the LO algorithm for the ARPA-2 network.

of orphan threshold parameter (T) for different traffic load conditions, for the mesh-torus and ARPA-2 networks, respectively. Figs. 15 and 16 plot the average number of orphans created per link by the LO algorithm as a function of orphan threshold parameter (T) for different traffic load conditions, for the mesh-torus and ARPA-2 networks, respectively. From the curves, we can observe that when the load is light, the number of orphans created per link is very low and less than one. We can also observe that the curves level off after a certain value of the orphan threshold. The reason is as follows. Although a duplex link has 16 channels, not all are used by primary lightpaths.

VIII. CONCLUSION

In this paper, we addressed the problem of routing dependable connections in WDM networks with dynamic traffic demands. We developed two algorithms which make use of backup multiplexing technique to improve channel utilization. These algorithms differ in their wavelength selection policy, computational complexity, and performance. To further improve channel utilization, we proposed the primary-backup multiplexing technique. We developed different algorithms based on the primary-backup multiplexing technique. The objective of these algorithms is to achieve significant gain in network blocking performance while allowing an acceptable reduction in restoration guarantee. The effectiveness of all the proposed algorithms has been verified using extensive simulation experiments. The primary-backup-multiplexing-based algorithms achieve more than 90% performance gain at the expense of less than 10% reduction in restoration guarantee, under light load conditions. Even under moderate and heavy load conditions, the performance gain is more when compared to the reduction in restoration guarantee.

REFERENCES

- [1] S. Chatterjee and S. Pawlowski, "All-optical networks," *Commun. ACM*, vol. 42, no. 6, pp. 74–83, June 1999.
- [2] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath communications: An approach to high bandwidth optical WANs," *IEEE Trans. Commun.*, vol. 40, pp. 1171–1182, July 1992.
- [3] S. Subramaniam, M. Azizoglu, and A. K. Somani, "All-optical networks with sparse wavelength conversion," *IEEE/ACM Trans. Networking*, vol. 4, pp. 544–557, Aug. 1996.
- [4] L. Li and A. Somani, "Fiber requirement in multifiber WDM networks with alternate-path routing," in *Proc. ICCCN*, Boston, MA, Oct. 1999.
- [5] R. Ramaswami and K. N. Sivarajan, "Routing and wavelength assignment in all-optical networks," *IEEE/ACM Trans. Networking*, vol. 3, pp. 489–500, Oct. 1995.
- [6] D. Banerjee and B. Mukherjee, "A practical approach for routing and wavelength assignment in large wavelength routed optical networks," *IEEE J. Select. Areas Commun.*, vol. 14, pp. 903–908, June 1996.
- [7] A. Mokhtar and M. Azizoglu, "Adaptive wavelength routing in all-optical networks," *IEEE/ACM Trans. Networking*, vol. 6, pp. 197–206, Apr. 1998.
- [8] H. Harai, M. Murata, and H. Miyahara, "Performance of alternate routing methods in all-optical switching networks," in *Proc. IEEE INFOCOM*, vol. 2, 1997, pp. 516–524.
- [9] B. T. Doshi, S. Dravida, P. Harshvardhana, O. Hauser, and Y. Wang, "Optical network design and restoration," *Bell Labs. Tech. J.*, pp. 58–84, Jan.–Mar. 1999.
- [10] E. Karasan and E. Ayanoglu, "Performance of WDM transport networks," *IEEE J. Select. Areas Commun.*, vol. 16, pp. 1081–1096, Sept. 1998.
- [11] J. Anderson, J. S. Manchester, A. Rodriguez-Moral, and M. Veeraraghavan, "Protocols and architectures for IP optical networking," *Bell Labs Tech. J.*, pp. 105–124, Jan.–Mar. 1999.
- [12] S. Ramamurthy and B. Mukherjee, "Survivable WDM mesh networks, Part II—Restoration," in *Proc. ICC*, vol. 3, 1999, pp. 2023–2030.
- [13] C. S. Li and R. Ramaswami, "Automatic fault detection, isolation, and recovery in transparent all-optical networks," *J. Lightwave Technol.*, vol. 15, pp. 1784–1793, Oct. 1997.
- [14] S. Ramamurthy and B. Mukherjee, "Survivable WDM mesh networks, Part I—Protection," in *Proc. IEEE INFOCOM*, 1999, pp. 744–751.
- [15] N. Nagatsu, S. Okamoto, and K. Sato, "Optical path cross-connect system scale evaluation using path accommodation design for restricted wavelength multiplexing," *IEEE J. Select. Areas Commun.*, vol. 14, pp. 893–902, June 1996.
- [16] M. Alanyali and E. Ayanoglu, "Provisioning algorithms for WDM optical networks," *IEEE/ACM Trans. Networking*, vol. 7, pp. 767–778, Oct. 1999.
- [17] S. Baroni, P. Bayvel, R. J. Gibbens, and S. K. Korotky, "Analysis and design of resilient multifiber wavelength-routed optical transport networks," *J. Lightwave Technol.*, vol. 17, pp. 743–758, May 1999.



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