Efficient Wavelength Assignment Methods for Distributed Lightpath Restorations in Wavelength-Routed Networks

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Abstract - In distributed lightpath restoration in wavelength-routed networks, different restoration operations may compete for the same wavelength on the same link and get blocked though there are still plenty of idle capacities on the link. In this paper, we propose two different wavelength assignment methods within the same framework for lowering such type of blocking. Simulation results show that the proposed methods significantly outperform the existing ones. Theoretical analysis confirms the optimality of the proposed methods for a special case; while for a few most important more general cases, it is shown that the optimal performance cannot be guaranteed by any distributed wavelength assignment method with a pre-defined wavelength searching sequence. For different cases where the original lightpath establishment has adopted random and first-fit wavelength assignments respectively, we discuss the different concerns in developing efficient distributed restoration schemes.

Index Terms- Wavelength-routed networks, wavelength assignment, distributed lightpath restoration.

I. INTRODUCTION

Wavelength-division multiplexing (WDM) networks have been widely deployed to meet the increasing bandwidth demands. Wavelength-routed networks, which set up transparent *lightpaths* [1, 2] between source-destinations, are becoming today's mainstream solutions. In wavelength-routed networks, each lightpath must occupy the same wavelength along every hop it transverses in the absence of wavelength converters. Such is known as the *wavelength-continuity constraint* [2]. With the large bandwidth provided by optical fibers, network survivability becomes increasingly important: a single link or node failure, if not properly protected, may interrupt a large number of users. In the literature, tremendous efforts have been made to improve network survivability [3]-[18].

Network survivability is generally supported by *protection* or *restoration* schemes [3, 4]. In protection schemes, backup solutions are preplanned and pre-established to ensure full recovery and short reconnection delay (defined as the delay from the moment the failure happens to the moment the transmission is resumed). In restoration schemes, backup resources are searched and identified after the event of failure. Though restoration schemes cannot guarantee full recovery, they lower the network cost by increasing the capacity utilizations.

The protection and restoration may be *link-based* or *path-based* [4]-[7]. In link-based schemes [4], upon a link failure, the affected connections are rerouted around the failed link. In path-based schemes [4], each affected connection is re-allocated to a backup route. Generally speaking, path-based schemes achieve higher capacity efficiency with easier implementations, while link-based schemes achieve shorter recovery time [3]-[7]. In this paper, we study the wavelength assignment problem in path-based network restoration. In link-based restoration, since the backup lightpath usually reuses some wavelength channels of the original lightpath, wavelength assignment generally remains unchanged as that of the original one unless wavelength conversion exists.

Restoration operations can be *centralized*- or *distributed*-controlled. In centralized schemes, a central controller supervises all the restoration operations. Having a single point of decision making helps achieve efficient utilizations of network resources, especially in small networks with highly static traffic where reconnection delay is acceptably short. In large networks with dynamic traffic, however, the centralized control may cause an over-long reconnection delay. Even worse, the central controller itself may become an overloaded and congested point. For such cases, distributed control, where restoration requests are handled by the affected nodes instead of the central controller, becomes a more favorable option [3, 8, 9].

Distributed restoration decisions can be made based on either *global* or *local* information. In global information-based schemes, link-state information is broadcast to all the relevant network nodes so that each node has sufficient information to make its decisions [11]-[18]. Though having more link-state information helps make intelligent decisions, frequent broadcasting may impose heavy control and traffic burdens on the network. In local information-based schemes [4], link-state information exchange is limited and happens only when necessary.

Both global and local information-based distributed schemes can be seriously affected by presence of inaccurate link-state information. Specifically, in global information-based schemes, mainly because of the time delay between broadcasts, some network nodes may make invalid restoration decisions based on stale link-state information [19]-[22]. In local information-based schemes, multiple interrupted connections trigger multiple restoration requests, which may conflict against each other trying to reserve the same wavelength on the same link even when there are still plenty of idle capacities on the link. In this paper, we call such kind of conflicts as *blind contentions*. Fig. 1 shows a simple example where there is a blind contention between two restoration operations.

Several methods have been proposed to solve the blind contention problem. In [4], wavelengths are partitioned into several subsets, each corresponding to an interrupted connection. Each restoration request searches for a wavelength in its own subset. By doing so, blind contentions are eliminated. However, since each restoration request is searching for a free wavelength in its own subset only, it may be blocked when there are still idle capacities in other subsets. Another method was proposed in networks with periodic flooding [17], where one of the affected nodes (e.g., an end node of the failed link) makes all the wavelength assignment decisions based on the flooded information and then notifies all the other nodes. In such a scheme, blind contentions are again eliminated. However, besides the need of frequent link-state updates, the delay caused by decision making and notifications may also be too long, especially when there are a large number of interrupted connections. In [23], a *first-fit-TE* wavelength-assignment scheme is proposed for optical burst switching (OBS) networks which can be adopted in network restoration. The main idea of the method is to let each switch be assigned a *start wavelength*, starting from which a switch can check through all the wavelengths in the first-fit manner and transmit a new burst on the first available wavelength. It is shown that by assigning different routes going through the same link with different start wavelengths, the probability of having blind contentions can be lowered.

In this paper, we propose two new wavelength assignment methods for local link-state information-based distributed lightpath restoration. Similar to the first-fit-TE scheme in [23], they assign different restoration operations with different start wavelengths as well as predefined searching sequences. We call such methods as within the framework of the *Predefined Sequential Search* (PSS) schemes. The main and nontrivial difference between the first-fit-TE method and the proposed methods lies in the searching sequence of each restoration operation: instead of adopting the first-fit manner, we devise different searching sequences for different restoration operations with the objective of minimizing the probability of having blind contentions. Simulation results evidently show that different searching sequences lead to significantly different performances. For the special case where there are only two restoration operations going through the same link and the lightpath establishment in the network has adopted random wavelength assignment, the optimality of the proposed methods among all the local information-based, fixed-routing PSS schemes can be proved. For a few most important more general cases (e.g., the case with random wavelength assignment in lightpath establishment yet three or more interrupted connections going through the same link; or with the first-fit wavelength assignment in lightpath establishment, etc.), we show that the optimality cannot be guaranteed by *any* PSS scheme with only local link-state information.

The rest part of this paper is organized as follows. In Section II, we propose the general framework of the PSS schemes, followed by detailed descriptions of the proposed methods. Theoretical analysis on the proposed methods is proposed in Section III. Extensive simulation results and discussions are presented in Section IV. Section V concludes the paper.

II. THE PROPOSED METHODS

In this section, we present the general framework of the PSS schemes, followed by detailed descriptions of two simple yet efficient PSS methods named *Flagged Search* (FS) and *Periodical Search* (PS) methods respectively.

A. The Framework of the Predefined Sequential Search (PSS) Schemes

In the PSS schemes, each restoration operation searches through all the wavelengths in a predefined sequence and selects the *first* available one among them. If no available wavelength exists along the backup route or if the selected wavelength later turns out to be reserved by another reservation request arrived earlier, the restoration request will be blocked. To focus our discussions solely on wavelength assignment problem, in this paper we consider the case in single-fiber networks where each connection has a single predefined backup route, though the scheme can be extended to apply in multi-fiber networks or networks with multiple or dynamic backup routes as well. We also assume that wavelength conversion is not available in the network.

The framework of the PSS schemes is presented as follows:

Predefined Sequential Search (PSS) Schemes: the Framework

1. *Initialization*: upon a link failure, the end nodes of each interrupted connection are informed.
2. *Link-state information collection*: the link-state information along the backup route is collected.
3. *Wavelength assignment*: based on the collected link-state information, a certain node, usually the source or the destination node of the interrupted connection, decides on the wavelength assignment. The method is to search through all the wavelengths in a pre-defined sequence

and select the first available one among them. If no such wavelength exists, the restoration request is blocked.

4. *Setting up restoration lightpath*: A reservation request is sent out, typically by the source or the destination node, to reserve the selected wavelength along the backup route. Interrupted transmission is resumed once the restoration connection is set up. If the selected wavelength is occupied by another reservation request arrived earlier, however, the restoration request is blocked. □

In the next subsection, we propose two simple yet representative and efficient PSS methods in details. The analysis of their performances and the optimality of them for a special case will be discussed in Section III.

B. The Two Proposed Methods

To simplify the descriptions, without loss of generality, we assume that each restoration request is initialized by the source node of the interrupted connection (Discussions on the signaling scheme for informing the source node upon a link failure can be found in [4].). A restoration request is then sent to the destination node along the backup route, collecting the link-state information along the route. Based on the collected information, the destination node would decide on the wavelength assignment and send a reservation request to reserve the selected wavelength. Communication will be resumed once the reservation request successfully reaches the source node. When a blind contention happens on a certain link, the downstream node of this link (i.e., the end node that is closer to the destination) will send out a *restoration failed* message to both the source and the destination. The reserved capacities meanwhile will be released. Note that the procedure is quite similar to the well-known *destination-initialized reservation* (DIR) method [24].

Two restoration operations going through the same link have a blind contention on a wavelength w if and only if

(i) for each of them, all the wavelengths before w in its searching sequence have been occupied by lightpath establishment on one or multiple links along its backup route; and

(ii) wavelength w is free along both of the two backup routes.

The probability of event (ii) is not affected by searching sequence. To reduce blind contentions, we need to lower the probability of event (i). Specifically, a wavelength at an early position in one searching sequence should be at a late position in the other sequences, so that the chance that the two operations select the same wavelength is lowered. This main idea applies to developing the proposed methods.

Both of the proposed methods are within the PSS framework. The only difference between them lies in their definitions of wavelength-searching sequences. Specifically, assume there are totally K ($K > 1$) interrupted connections, numbered from 1 to K in an increasing order of their *original* wavelength indexes. Denote the number of wavelengths in each fiber as C. The two different methods can be defined as follows.

Flagged Search (FS) method

We let K flags be *evenly* distributed within the interval [1, C], where

$$FLAG_k = (k-1)\cdot\frac{C-1}{K-1}+1, \qquad k = 1,2,...K. \tag{1}$$

Note that each flag is not necessarily of an integer value. Upon a link failure, the k-th interrupted connection will search through all the wavelengths in an increasing order of their *distances* from $FLAG_k$, where the distance between a wavelength w ($1 \le w \le C$) and $FLAG_k$ is defined as

$$d(w, FLAG_k) = \begin{cases} |w - FLAG_k|, & k = 1, K \\ \min\left(|w - FLAG_k|, C - |w - FLAG_k|\right), & \text{otherwise} \end{cases}. \tag{2}$$

If there are two available wavelengths with the same distance from the flag, one of them will be randomly selected. For example, when $C = 8$ and $K = 4$, the four flags would be at 1, $\frac{10}{3}$, $\frac{17}{3}$ and 8 respectively; and the searching sequences of the four restoration operations are

$$\begin{cases} Seq_1 = (1,\ 2,\ 3,\ 4,\ 5,\ 6,\ 7,\ 8) \\ Seq_2 = (3,\ 4,\ 2,\ 5,\ 1,\ 6,\ 8,\ 7) \\ Seq_3 = (6,\ 5,\ 7,\ 4,\ 8,\ 3,\ 1,\ 2) \\ Seq_4 = (8,\ 7,\ 6,\ 5,\ 4,\ 3,\ 2,\ 1) \end{cases}. \tag{3}$$

When $C = 8$ and $K = 2$, the flags would be at 1 and 8; and the searching sequences are

$$\begin{cases} Seq_1 = (1,\ 2,\ 3,\ 4,\ 5,\ 6,\ 7,\ 8) \\ Seq_2 = (8,\ 7,\ 6,\ 5,\ 4,\ 3,\ 2,\ 1) \end{cases} \tag{4}$$

i.e., the two sequences are *reverse permutations* [25] to each other.

Periodically-Search (PS) method

In this method, we divide the wavelength set into K non-overlapping subsets where each subset contains lower- and higher-indexed wavelengths as evenly as possible. Specifically, the k-th subset contains the wavelengths

$$\mathbf{S}_k = \left\{k,\ k+K,\ k+2K,...,k+\lfloor (C-k)/K \rfloor K\right\}, \quad k = 1,2,...K. \tag{5}$$

Here $\lfloor x \rfloor$ denotes the floor function of x, i.e., the largest integer not bigger than x. Upon the link failure, the k-th interrupted connection will search for a free wavelength in $\mathbf{S}_k$. If no feasible solution is found, it proceeds to search $\mathbf{S}_{k+1}$ if $k < K$ and $\mathbf{S}_1$ otherwise. The procedure is repeated until a feasible solution is found or all the wavelengths have been searched. In other words, the subsets are searched sequentially in a round-robin manner. While searching through each subset, an "alternating searching sequence" is adopted. Specifically, it searches $\mathbf{S}_k$ in an increasing order of wavelength indexes, $\mathbf{S}_{k+1}$ ($\mathbf{S}_1$ if $k = K$) in a decreasing order of wavelength indexes, $\mathbf{S}_{k+2}$ ($\mathbf{S}_1$ if $k = K-1$) in an increasing order again, and so on. The alternating searching sequence helps to lower the probability of having blind contentions. For example, when $C = 8$ and $K = 3$, the three subsets are

$$\begin{cases} \mathbf{S}_1 = \{1,\ 4,\ 7\} \\ \mathbf{S}_2 = \{2,\ 5,\ 8\}. \\ \mathbf{S}_3 = \{3,\ 6\} \end{cases} \tag{6}$$

And the three searching sequences are

$$\begin{cases} Seq_1 = (1,\ 4,\ 7,\ 8,\ 5,\ 2,\ 3,\ 6) \\ Seq_2 = (2,\ 5,\ 8,\ 6,\ 3,\ 1,\ 4,\ 7) \\ Seq_3 = (3,\ 6,\ 7,\ 4,\ 1,\ 2,\ 5,\ 8) \end{cases} \tag{7}$$

If the same searching sequence were used in every subset, then we would have

$$\begin{cases} Seq_1 = (1,\ 4,\ 7,\ 2,\ 5,\ 8,\ 3,\ 6) \\ Seq_2 = (2,\ 5,\ 8,\ 3,\ 6,\ 1,\ 4,\ 7). \\ Seq_3 = (3,\ 6,\ 1,\ 4,\ 7,\ 2,\ 5,\ 8) \end{cases} \tag{8}$$

If wavelengths $\{1,\ 4,\ 7\}$ are not available for the first restoration operation, its next five candidate wavelengths $\{2,\ 5,\ 8,\ 3,\ 6\}$ would be in exactly the same order as that of the first five candidate wavelengths of the second restoration operation. Meanwhile, if the third restoration operation cannot be set up on wavelengths $\{3,\ 6\}$, it will have the same searching sequence as that of the first restoration operation in the next six candidate wavelengths. The probability of having blind contentions therefore becomes higher.

When $C = 8$ and $K = 2$, the two subsets are

$$\begin{cases} \mathbf{S_1} = \{1,\ 3,\ 5,\ 7\} \\ \mathbf{S_2} = \{2,\ 4,\ 6,\ 8\} \end{cases}, \tag{9}$$

and

$$\begin{cases} Seq_1 = \left(1,\ 3,\ 5,\ 7,\ 8,\ 6,\ 4,\ 2\right) \\ Seq_2 = (2,\ 4,\ 6,\ 8,\ 7,\ 5,\ 3,\ 1) \end{cases}. \tag{10}$$

Once again the two sequences are reverse permutations to each other.

Remark: Compared to the classic first-fit wavelength assignment method, both of the proposed schemes request only one additional step for calculating the searching sequence. The complexity of this additional step is of a low value at $O(CK)$. □

III. THEORETICAL ANALYSIS

In this section, we propose a general model for analyzing the probability of having blind contentions. Then we prove that both the FS and PS methods achieve the optimality under the special conditions that (i) there are only two restoration requests going through the same link, and (ii) along the same backup route, different wavelengths have the same probability of being available (An example is where we adopt random wavelength assignment in lightpath establishment.). For a few most important more general cases, we show that *no* local information-based fixed-routing PSS scheme can guarantee to achieve the optimal performance.

The following notations are defined:

C the number of wavelengths in each fiber,

K the number of interrupted connections,

k the index of the restoration operation in an increasing order of their original wavelength indexes, $k = 1, 2, \ldots K$,

$\alpha_{k,j}$ the probability that the wavelength λ_j is available along the backup route of the k-th restoration operation, $j = 1, 2, \ldots, C$,

$\boldsymbol{M}^k$ the searching sequence of the k-th restoration operation, $\boldsymbol{M}^k = \left\{M^k_{(1)},\ M^k_{(2)}, \ldots, M^k_{(C)}\right\}$,

$d_k(j)$ the position of λ_j in the searching sequence of the *k*-th restoration request, i.e., $M^k_{(d_k(j))} = j$,

$P_{k,j}$ the probability that the *k*-th restoration request selects the wavelength λ_j.

We have that

$$P_{k,j} = \begin{cases} \alpha_{k,j}, & \text{if } M^k_{(1)} = j \\ \prod_{i=1}^{d_k(j)-1} (1-\alpha_{k,M^k_{(i)}}) \cdot \alpha_{k,j}, & \text{otherwise} \end{cases}. \tag{11}$$

For the special case where $\alpha_{k,1} = \alpha_{k,2} = \cdots = \alpha_{k,C} = \alpha_k$, we have

$$P_{k,j} = \left(1-\alpha_k\right)^{d_k(j)-1} \cdot \alpha_k. \tag{12}$$

From the de Moivre-Jordan Theorem [26], the probability that a restoration request gets blocked, termed as *restoration blocking probability* hereafter, can be calculated as

$$P = \sum_{j=1}^{C} \sum_{k=2}^{K} (-1)^k \cdot (k-1) \cdot S_{k,j}, \tag{13}$$

where

$$S_{k,j} = \sum_{l_1 < \cdots < l_k} \prod_{i=1}^{k} P_{l_i,j}. \tag{14}$$

Theorem 1: Assume that along the same backup route, different wavelengths have the same probability of being available. Also assume there are only two backup routes R_1 and R_2 going through the same link *l*, where the probabilities that each wavelength is available along these two routes equal to α_1 and α_2 respectively. The restoration blocking probability is minimized if and only if the two searching sequences are reverse permutations to each other.

Proof: For such case, from Eqs. (12)-(14), we have that the probability of having a blind contention between the two restoration operations is

$$\begin{aligned} P &= \sum_{j=1}^{C} (1-\alpha_1)^{d_1(j)-1} \cdot \alpha_1 \cdot (1-\alpha_2)^{d_2(j)-1} \cdot \alpha_2 \\ &= (1-\alpha_1)^{-1} \cdot \alpha_1 \cdot (1-\alpha_2)^{-1} \cdot \alpha_2 \cdot \sum_{j=1}^{C} (1-\alpha_1)^{d_1(j)} \cdot (1-\alpha_2)^{d_2(j)}. \end{aligned} \tag{15}$$

Since $\left\{(1-\alpha_i)^1, (1-\alpha_i)^2, \ldots (1-\alpha_i)^C\right\}$, $(i=1,2)$ form into a decreasing series, from the *permutation inequality* [25], we have

$$P \geq (1-\alpha_1)^{-1} \cdot \alpha_1 \cdot (1-\alpha_2)^{-1} \cdot \alpha_2 \sum_{m=1}^{C} (1-\alpha_1)^{d_1(j)} \cdot (1-\alpha_2)^{C+1-d_1(j)}. \qquad (16)$$

The theorem is therefore proved. □

Theorem 1 shows that the proposed FS and PS methods achieve the optimality when there are only two restoration operations going through the same link and the original lightpath establishment has adopted random wavelength assignment. For more general cases where

(i) the assumption remains valid that along the same backup route different wavelengths have the same probability of being available, yet there are three or more restoration requests going through the same link; or

(ii) different wavelengths along the same backup route may have different probabilities of being available,

we observe that

- with three or more restoration operations going through the same link, no predefined searching sequences can guarantee to achieve the best performance even when random wavelength assignment has been adopted in the original lightpath establishment. The best wavelength assignment under such case is link-state dependent; and
- with different wavelengths having different probabilities of being available along each backup route, the reverse permutation wavelength assignment does *not* always minimize the probability of having a blind contention between two restoration operations. The conclusion applies to the special case where the first-fit wavelength assignment has been adopted in lightpath establishment.

Examples demonstrating the above observations are presented in Appendix A. The important conclusion is that, for the most popular cases of adopting random or the first-fit wavelength assignments in lightpath establishment, the optimal performance of lightpath restoration cannot be guaranteed by any PSS schemes without link-state information exchange. On the other hand, as later we will demonstrate in Section IV, though without any such kind of information exchange, the proposed methods nevertheless manage to achieve satisfactory performance under most cases.

IV. NUMERICAL SIMULATIONS AND DISCUSSIONS

To evaluate the performance of the proposed methods, we conduct simulations in three different network models:

- PacNet as illustrated in Fig. 2 [4, 11], where each number next to the link denotes the length of the link in tens of kilometers;
- A 12-node ring network, where the length of each link is 100 km; and
- A 4×4 mesh-torus network, where the length of each link is 100 km.

In each network, we assume that each link is composed of two directional fibers of opposite directions with 64 wavelength channels per fiber (Note that cases with 32 and 128 wavelengths per fiber have also been simulated. All the conclusions we present below appear to hold in these two cases as well.). We also assume that the original lightpath establishment is on the route with the minimum number of hops between source-destination nodes, i.e., the route with the shortest hop length. The backup route is the shortest hop-length path that is link-disjoint to the route of the original lightpath. When there is a tie in route selection (i.e., there are multiple routes with the same hop length), break it randomly. The processing delay for handling each restoration/reservation request on each node is assumed to be equal to 10 microseconds.

For each given traffic load, we let the connection requests be arriving from a Poisson process with an exponentially-distributed duration. The average duration of each connection is one hour. We simulate a large-enough number of connection requests until the network has reached a stable status (i.e., the blocking probability converges). Then we tear down each link in turn and simulate all the restorations. The performance of the different wavelength assignment methods is evaluated by the restoration blocking probability.

We compare several different restoration wavelength assignment methods as follows:

a) *Random* wavelength assignment, where according to the information carried to the destination node by the restoration request, one of the available wavelengths along the backup route is randomly selected.

b) *Partitioning* wavelength assignment as proposed in [4], where wavelengths are partitioned equally among all the restoration operations. This method was discussed for the case with multiple candidate backup routes in [4]. Here for comparison purpose, we assume that there is only a single backup route for each lightpath.

c) The *first-fit-TE* method [23]. As discussed earlier, though the method was not proposed for restoration case, it can be applied to such case without any modification.

d) The *centralized* method where there is a central controller making all the wavelength assignment decisions. Specifically, we sort all the restoration requests in an increasing order of the hop lengths of their backup routes. Then for each of them, we adopt the first-fit wavelength assignment along its backup route. This case provides a benchmark as an "upper bound" of the performance that a distributed wavelength assignment method can reasonably expect to achieve.

e) The proposed FS method.

f) The proposed PS method.

For each case, we repeat the simulations for ten times by using different seeds in random-number generations and then present the average results of these ten rounds of simulations.

We first consider the case where the original lightpath establishment has adopted random wavelength assignment. The simulation results in the three networks are presented in Figs. 3-5 respectively. From the simulation results, we observe that the proposed methods almost always outperform the existing ones; and the improvements tend to become more significant under lower traffic loads with more redundant network resources for wavelength-assignment selections. Under heavy traffic loads, restoration blocking is mainly caused by exhausted network capacities rather than blind contentions. Thus all the different methods perform comparably to each other. In PacNet (Fig. 3) and the ring network (Fig. 4), the performances of the proposed methods can be close to that of the centralized method. In the mesh-torus network (Fig. 5), however, the centralized method performs much better. This is because in the centralized method, the restoration requests are sorted in an increasing order of the hop lengths of their backup routes. As a result, almost all the restoration requests with short backup routes are successfully accepted (at the cost of those restorations with long backup routes), which is not the case in the distributed methods. In sparse networks such as PacNet and ring, the backup routes are generally with quite long hop lengths, leaving the centralized method a less significant winning margin over the distributed methods.

Other important observations include

- In all the three networks, the FS and PS methods always perform comparably to each other.
- The partitioning method performs quite well under low traffic loads. In fact, in all three networks, it outperforms both the random and first-fit TE methods under low traffic loads.

Under high traffic loads, since each partition of wavelengths becomes a small set, some restorations may not be able to find a feasible solution though there are still free wavelengths in other partitions. Consequently the method becomes less attractive. A good method may be developed by adopting the partitioning method only under low traffic loads or only in restoring those lightpaths going through a lightly-loaded link. Detailed discussions on such a method, however, are out of the scope of this paper.

- Under light traffic loads, since the first-fit-TE method adopts the round-robin searching sequence for every restoration request, it is not a surprise that it is outperformed by the proposed methods. This evidently shows the significance of the differences in restoration performance different searching sequences can make. Under heavy traffic loads, as discussed earlier, all the different methods finally perform nearly the same, dominated by the effects of exhausted network capacities.

We then simulate the case where the original lightpath establishment adopts the first-fit wavelength assignment. The results are plotted in Figs. 6-8. As we can see, in all the three networks, the PS method significantly outperforms the FS method under light traffic loads. The reason is easy to understand: in the FS method, a few restoration operations would search through most or even all the lower-indexed wavelengths before starting to search higher-indexed wavelengths. Since lower-indexed wavelengths have been heavily utilized by lightpath establishment, the chance that these restoration operations would compete for the same wavelength becomes rather high. The PS method, on the other hand, searches through higher- and lower-indexed wavelengths in a more balanced manner. As a result, the chance of having blind contentions is significantly lowered. This also explains why even the random restoration wavelength assignment in many cases outperforms most of the existing methods. Also, under such case, the advantages of having global information become more significant. In fact, the PS method appears to be the only distributed wavelength assignment method that can come close to the centralized method even in sparse networks. To summarize, we see that when the first-fit wavelength assignment is adopted in lightpath establishment, a good wavelength assignment scheme for distributed lightpath restoration has to ensure that higher-indexed wavelengths appear reasonably early in each wavelength-searching sequence. Meanwhile, the basic rule remains valid that a wavelength appearing at an early position in one searching sequence should appear at a late position in the others searching sequences as far as such is possible.

V. CONCLUSIONS

In this paper, within the same framework of the PSS schemes we proposed two efficient wavelength assignment methods for lowering the restoration blocking probability. Simulation results showed that under most cases they significantly outperform the existing methods. Theoretical analysis confirmed the optimality of the proposed methods for a special case; while for a few most important more general cases, it was revealed that the optimal performance cannot be guaranteed by any local information-based fixed-routing PSS scheme. We evaluated different cases where lightpath establishment has adopted random and first-fit wavelength assignment methods respectively. It is shown that the latter one imposes additional constraints on the developments of distributed restoration schemes.

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Appendix A: Nonexistence of the Optimal Pre-Defined Searching Sequence

In this appendix, we present examples showing that no pre-defined searching sequence can guarantee to achieve the optimal performance in a few important cases. First, we show that for the case where different wavelengths have different probabilities of being available along each backup route, e.g., where the first-fit wavelength assignment has been adopted in lightpath establishment, the reverse permutation wavelength assignment does not necessarily lead to the lowest probability of having a blind contention between two restoration operations.

Consider the example case where there are two restoration operations in a network with only two wavelengths $\{\lambda_1,\ \lambda_2\}$ on each link. Let the probabilities that the two wavelengths are available on the first backup route be $\{\alpha_{1,1},\ \alpha_{1,2}\} = \{0.01,\ 0.9\}$; and on the second route be $\{\alpha_{2,1},\ \alpha_{2,2}\} = \{0.02,\ 0.8\}$. As shown in Table A.I, the lowest restoration blocking probability is achieved when both restorations adopt the *same* searching sequence $\{1,\ 2\}$.

We then show that with three or more restoration operations going through the same link, the best searching sequences are link-state dependent even when random wavelength assignment has been adopted in lightpath establishment. Specifically, we consider the case with three restoration requests in a network with three wavelengths per fiber. Table A.II shows that for different link states, the optimal solution of searching sequences is different. Therefore no pre-defined search sequences can guarantee to achieve the optimal performance.

Table I. Calculation results for the case with two restoration requests, assuming $\{\alpha_{1,1},\ \alpha_{1,2}\} = \{0.01,\ 0.9\}$ and $\{\alpha_{2,1},\ \alpha_{2,2}\} = \{0.02,\ 0.8\}$

$\{M_{(1)}^{1},\ M_{(2)}^{1}\}$	$\{M_{(1)}^{2},\ M_{(2)}^{2}\}$	P
{1, 2}	{1, 2}	0.698744
{1, 2}	{2, 1}	0.71284
{2, 1}	{1, 2}	0.70562
{2, 1}	{2, 1}	0.720004

Table II. Optimal solutions for example cases with three restoration requests and random wavelength assignment in lightpath establishment

$\{\alpha_1, \alpha_2, \alpha_3\}$	$\{M_{(1)}^{1},\ M_{(2)}^{1},\ M_{(3)}^{1}\}$	$\{M_{(1)}^{2},\ M_{(2)}^{2},\ M_{(3)}^{2}\}$	$\{M_{(1)}^{3},\ M_{(2)}^{3},\ M_{(3)}^{3}\}$	P
{0.1, 0.2, 0.3}	{1, 2, 3}	{1, 2, 3}	{3, 2, 1}	0.195
{0.2, 0.6, 0.3}	{1, 3, 2}	{1, 3, 2}	{2, 3, 1}	0.389
{0.15, 0.45, 0.78}	{1, 2, 3}	{2, 1, 3}	{2, 3, 1}	0.370
{0.21, 0.9, 0.67}	{1, 3, 2}	{3, 1, 2}	{3, 2, 1}	0.383
{0.97, 0.91, 0.98}	{2, 1, 3}	{1, 2, 3}	{1, 3, 2}	0.132

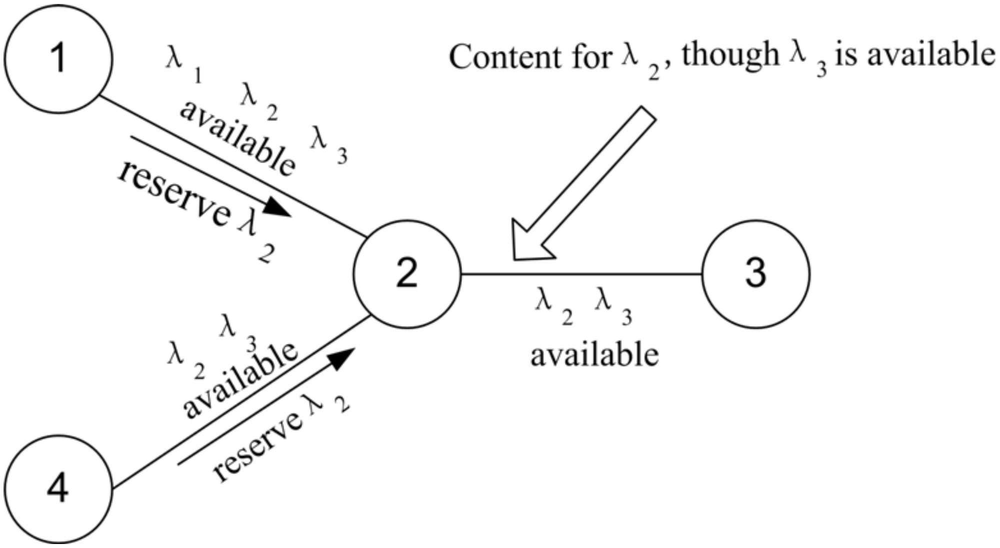

Fig. 1: A simple example of having a blind contention on the link from node 2 to node 3.

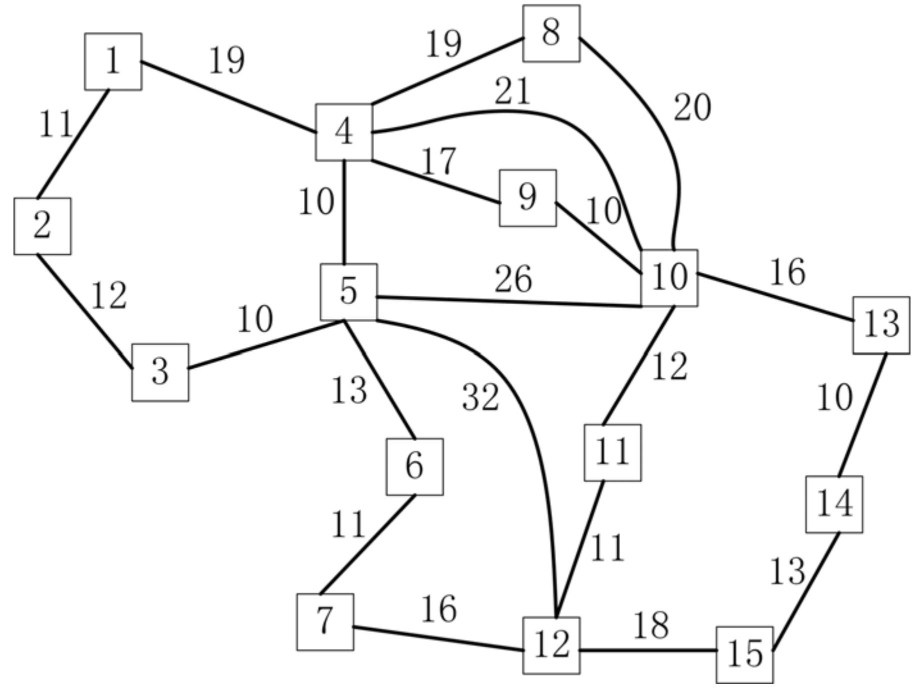

Fig. 2: Network topology of PacNet, where each number next to the link denotes the link length in tens of kilometers.

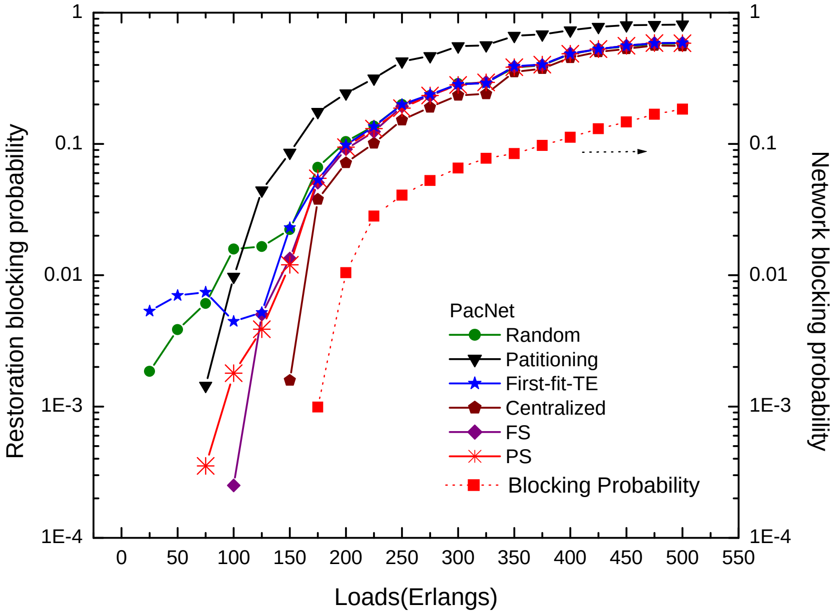

Fig. 3: Restoration blocking probability in PacNet, while the original lightpath establishment has adopted random wavelength assignment.

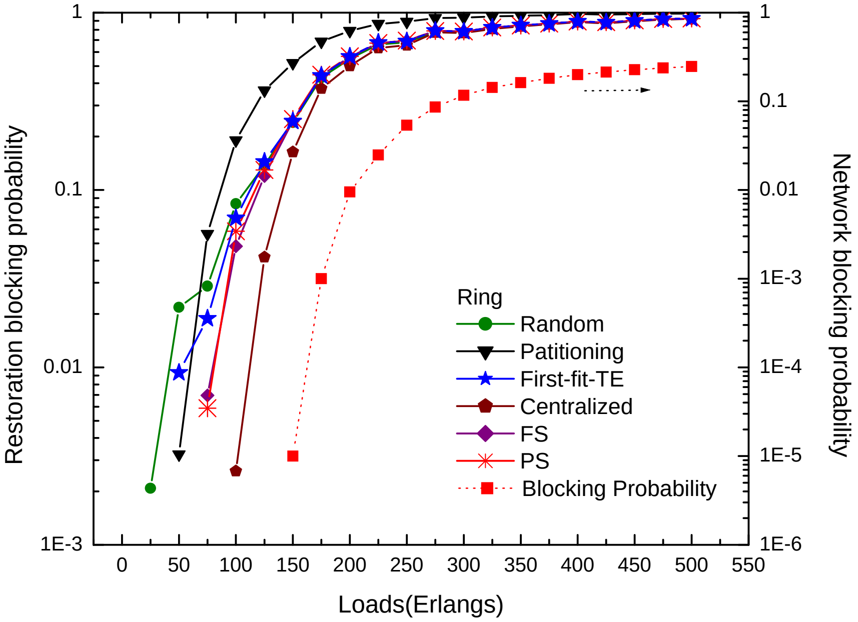

Fig. 4: Restoration blocking probability in the 12-node ring network, while the original lightpath establishment has adopted random wavelength assignment.

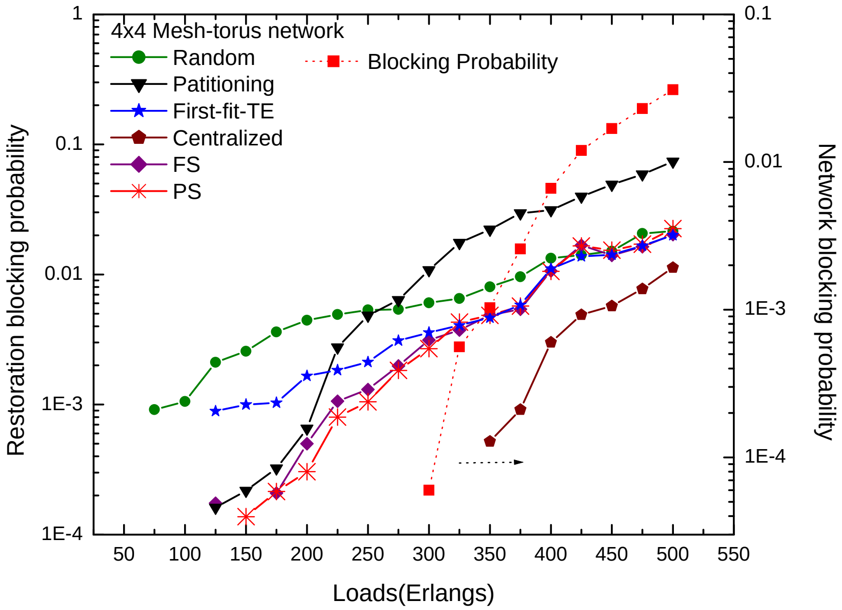

Fig. 5: Restoration blocking probability in the 4×4 mesh-torus network, while the original lightpath establishment has adopted random wavelength assignment.

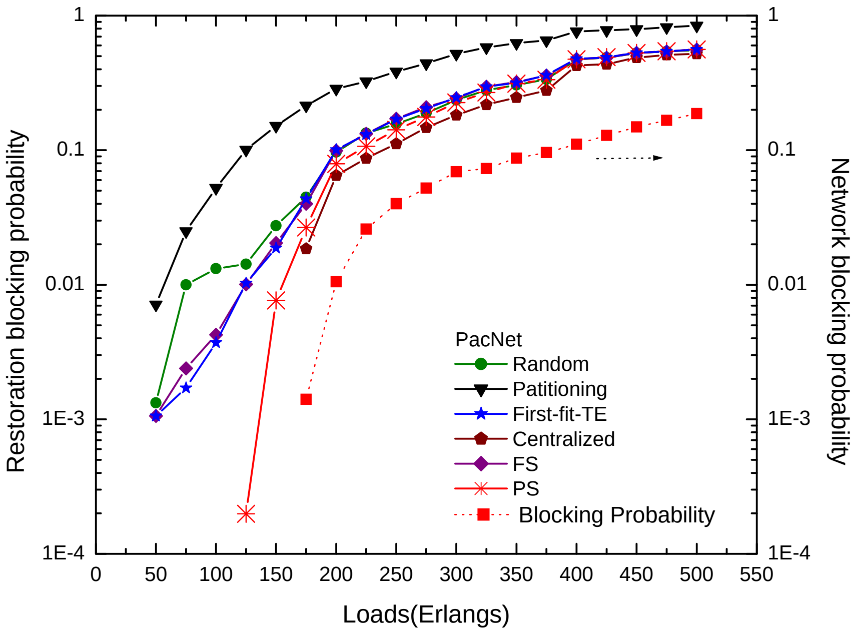

Fig. 6: Restoration blocking probability in PacNet, while the original lightpath establishment has adopted the first-fit wavelength assignment.

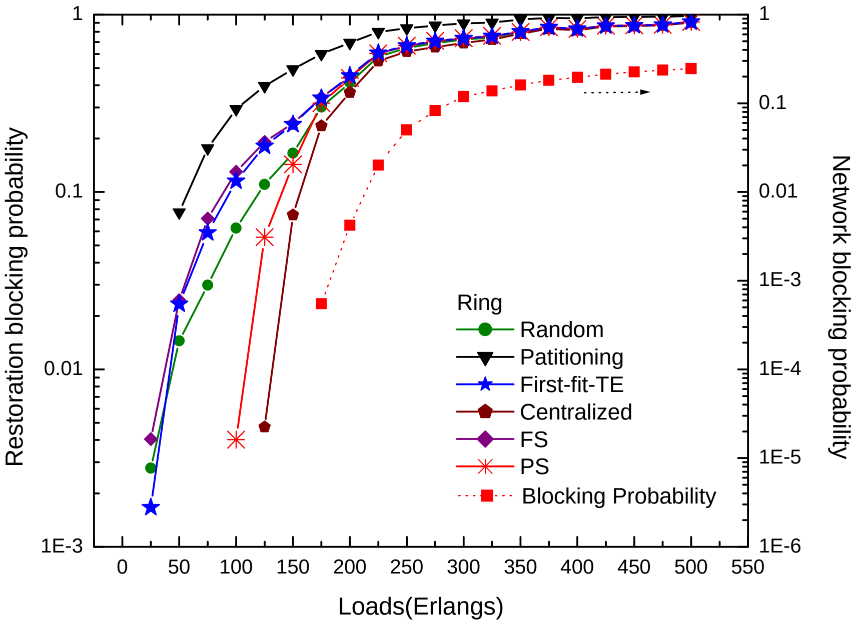

Fig. 7: Restoration blocking probability in the 12-node ring network while the original lightpath establishment has adopted the first-fit wavelength assignment.

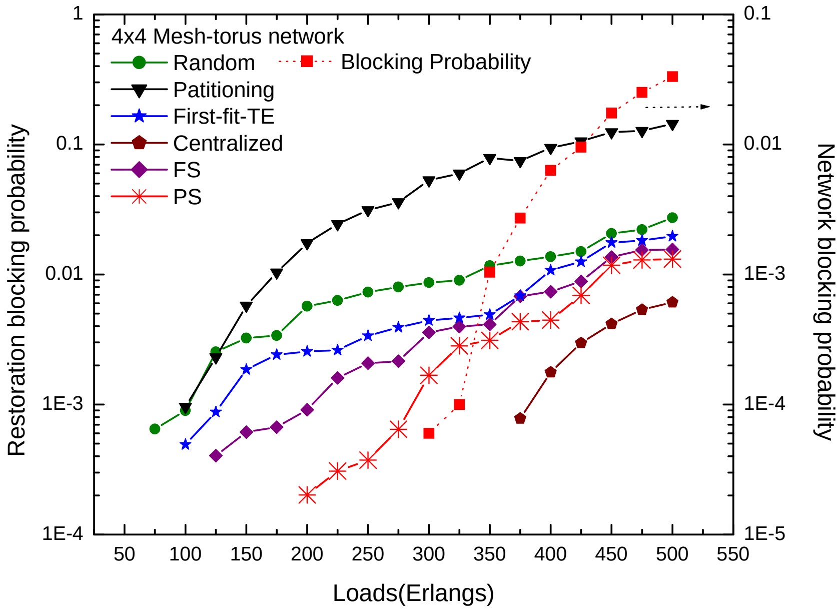

Fig. 8: Restoration blocking probability in the 4×4 mesh-torus network, while the original lightpath establishment has adopted the first-fit wavelength assignment..