Restoration Probability Modeling for Active Restoration-Based Optical Networks with Correlation among Backup Routes

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Abstract—Active restoration (AR) is a novel lightpath restoration scheme proposed recently to guarantee a certain degree of survivability in wavelength-division multiplexing (WDM) optical networks with a reasonable trade-off between capacity requirement and restoration time. In this paper, we conduct a comprehensive performance analysis for AR-based optical networks. In particular, we propose a novel analytical framework for modeling the restoration probability of a connection (the probability that the connection can be successfully restored in case of a failure) when the possible correlation among its multiple backup routes is incorporated. Although theoretically, we need to consider all the possible correlations between as many as $\binom{N}{2}$ pairs of backup routes to analyze the restoration probability in a network with N nodes, and this high computation complexity may obscure the practicality of an approach, considering all the possible correlations among backup routes, our analysis in this paper indicates that by considering at most the possible correlations among any three successive backup routes of a connection, we can achieve a very good approximation to the simulated restoration probability of the connection, as verified by extensive simulation results upon two typical network topologies under various workloads. We find that the proposed framework can deeply investigate into the inherent relationship among restoration probability, wavelength channel utilization ratio, number of wavelengths per fiber, routes hop length, and wavelength conversion capability. As a result, the framework significantly contributes to the related areas by providing network designers with a quantitative tool to evaluate the restoration probability and, thus, the survivability of AR-based optical networks.

Index Terms—Network survivability, restoration probability, active restoration, optical networks, path correlation.

1 Introduction

Optical networks based on Wavelength Division Multiplexing (WDM) are promising for serving as the backbone networks of the next-generation Internet due to their potential ability to meet the ever-increasing demands of high bandwidth. The adoption of WDM technology allows hundreds of independent lightpaths multiplexed along a single fiber, which is equivalently an order of terabit per second of effective bandwidth. As WDM networks carry a huge amount of traffic, failure of any part in such networks and the resulting inability to move data around quickly may have tremendous economic impacts on both data and revenue. For this reason, survivability in high-bandwidth WDM networks has become an important research area in recent years.

The approaches to ensuring survivability can be generally classified as proactive protection and reactive restoration. With the former, a backup lightpath is computed for the primary lightpath at the arrival of a connection request, and the switching capacity of each node and the bandwidth of each link along the backup lightpath are reserved during normal operation. The backup path is chosen in such a way that it does not belong to the same Shared Risk Link Groups (SRLGs) [1] as the primary path. This way, both the primary and the backup lightpaths will not have the same risk to fail at the same time, as they are SRLG disjoint. If both primary and backup lightpaths can be found for the corresponding demand, then the demand is accepted. Proactive protection for WDM networks has been subject to extensive research activities [9], [10], [11], [12].

Much of this research work focus on shared mesh protection, which promises significant bandwidth savings. However, most shared mesh protection schemes cannot guarantee that failed traffic will be restored within the 50-ms time frame that Synchronous Optical Network (Sonet) standards specify. Therefore, several techniques have been proposed to provide fast recovery in mesh networks. For example, Ou et al. [13] propose using the subpath protection for survivable lightpath provisioning and fast protection switching in optical WDM mesh networks. The main ideas of this protection strategy are to partition a large optical network into smaller domains and to apply shared-path protection to the optical network while guaranteeing the autonomy of each domain. For shared mesh protection, Grover and Stamatelakis introduce the concept of preconfigured protection cycles (p-cycles) [2], [3], [4] that utilizes the benefits of the speed recovery of ring networks and the efficiency of mesh protection in resource saving. Chou et al. [5] propose a more general protection strategy using the precross-connected trails, which is a structure that is more

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flexible than rings and that adapts readily to both path-based and link-based schemes and to both static and dynamic traffic. Similarly, several protection techniques have been proposed for providing fast recovery in Multi-protocol Label Switched networks. These techniques rely on failure notifications, pre-establishment, or on-demand establishment of backup paths and switching traffic to the backup paths when a failure notification is received [6], [7].

Although a 100 percent restoration for any single failure can be guaranteed, the proactive protection usually results in a high resource redundancy [8] and poor network throughput because the dedicated resources for the protection purpose sit idle even in the absence of failure. With the reactive restoration, on the other hand, a backup lightpath is searched after the primary lightpath is interrupted, which may sacrifice the 100 percent restoration guarantee for all the failed connections. Therefore, Mohan et al. [14] propose an efficient heuristic to estimate the average number of connections per link that do not have backup lightpaths readily available upon a link failure.

Numerous studies [15], [16] have been reported for the reactive restoration scheme. Although efficient in terms of higher capacity utilization and lower blocking probability, reactive restoration may lead to an unacceptable long restoration time due to its global searching for a backup lightpath after a failure happens. To compromise the proactive protection and reactive restoration, the study in [17] proposed a new active restoration scheme, in which a primary lightpath is guarded by multiple backup routes that are predefined but not reserved along the primary path. It is notable that the AR scheme actually works within the SRLG framework in the sense that the multiple backup routes of a connection are also chosen in such a way that they do not belong to the same SRLG as the primary path of the connection. The results in [17] indicate that the AR scheme can reduce blocking probability and capacity requirement significantly while guaranteeing a very high restoration probability (that is, the probability that a connection can be successfully restored in case of a failure). A similar technique [19] has been proposed recently under the protection context. However, in this technique, the backup paths are computed from every intermediate node to the destination.

Many analytical models have been proposed for modeling the blocking probability in WDM networks such as [20], [21], [22], [23], [24], [25], but little has been reported for modeling the restoration probability. A simple analytical model was proposed in [18] to estimate the restoration probability for an AR-based WDM network under the assumption that all the backup paths of a connection are independent. In a real AR-based WDM network, however, the backup paths of a connection are likely correlated, since they may share some common links along their routes, as illustrated in Fig. 1. For the network shown in Fig. 1, consider that the primary path (P) between v_1 and v_3 is $(v_1 - v_2 - v_3)$. Based on the idea of AR [17], its successive backup routes (B1 and B2) are $(v_1 - v_4 - v_2)$ and $(v_1 - v_4 - v_5 - v_3)$, respectively. In this case, although the primary path (P) is link disjoint with the two backup routes (B1 and B2), it is clear that these backup routes are correlated due to sharing a common link (the link between v_1 and v_4).

Therefore, for a connection in AR-based networks with correlation among its backup routes, the model proposed in [18] may result in a significant error in estimating the restoration probability of the connection. However, to consider all the possible correlations among the backup routes of a connection in a network with N nodes, the worst-case computation complexity can be as high as $O(\binom{N}{2} \cdot N)$. This high computation complexity, in practice, is quite cumbersome and may obscure the practicality of an approach, considering all the possible correlations among backup routes.

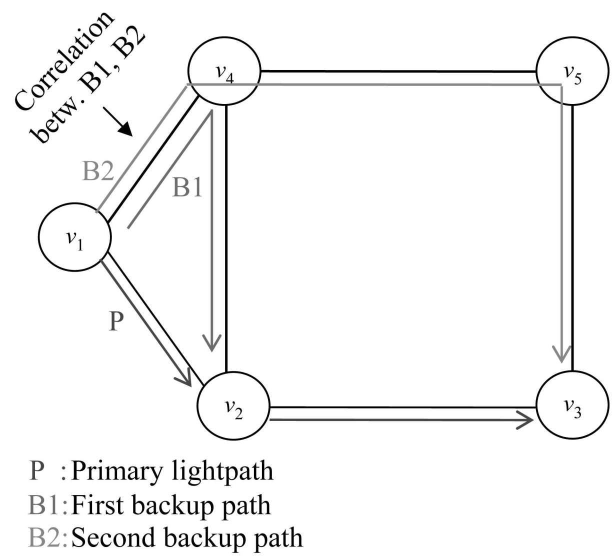


Fig. 1. Illustration of the case where two backup routes are correlated.

As the first step toward the accurate restoration probability analysis for AR-based networks, we propose in this paper an analytical framework to model the restoration probability of a connection in AR-based networks, with the consideration of possible correlation among backup routes of the connection. The main contributions of our work are the following:

- We first develop an analytical model for evaluating the restoration probability of a connection when all the possible correlations between any two successive backup routes of the connection are fully incorporated, for both the cases with full wavelength conversion[1] and without wavelength conversion.
- We then extend the above model to consider all the possible correlations among any three successive backup routes of a connection.
- We conduct extensive simulations to validate our proposed models, and we find that although we do not consider all the possible correlations among all backup routes in our analysis, our two models (especially the second one) can always guarantee a very close approximation to the simulated restoration probability for different network architectures and network workloads.
- We apply our new models to investigate into the inherent relationship among restoration probability, wavelength channel utilization ratio, number of wavelengths per fiber, routes hop length, and wavelength conversion capability.

The rest of this paper is organized as follows: Section 2 presents the preliminaries of this paper. Section 3 introduces briefly the available model for restoration probability. Section 4 provides our new restoration probability model

1. Full wavelength conversion in this paper means that each network node has the full wavelength conversion capability.

when the correlation between any two successive backup routes is considered, and Section 5 introduces our main model for restoration probability, where all the possible correlations among any three successive backup routes is fully incorporated. Section 6 discusses the results of experimental evaluation on different networks to validate the analytical model and, finally, Section 7 concludes the paper.

2 Preliminaries

In this section, we first present the basic assumptions to be adopted in our models. We then introduce briefly the AR scheme and the general framework for restoration probability analysis of AR-based networks.

2.1 Assumptions

A typical framework was developed by Birman [20] to model the blocking probability of WDM networks with and without wavelength conversion, where Lee's standard link independent assumption [26] and the wavelength channels independent assumption of a link were adopted for a steady-state network. These assumptions can be relevant if the networks are densely meshed (that is, the nodal degree is greater than 5), which is the case envisioned for the next-generation optical Internet. In this paper, we extend Birman's framework for blocking probability analysis to model the restoration probability for AR-based optical networks [17], where the scenario of a single lightpath failure in a certain link is concerned. For the correlation among the backup routes of a connection in AR-based networks, we consider three assumptions and develop their corresponding models:

- ***Assumption 1***: no correlation between any pair of backup routes.
- ***Assumption 2***: correlation may only exist between any two successive backup routes.
- ***Assumption 3***: correlation may only exist among any three successive backup routes.

Hereafter, we use model 1, model 2, and model 3 to refer to the models developed based on the above three assumptions, respectively.

2.2 Active Restoration Scheme (AR)

In the AR scheme [17], a primary lightpath is guarded by multiple backup routes that are predefined but not reserved along the primary path, as illustrated in Fig. 1 and Section 1. Upon a failure along the primary path, the node immediate downstream to the failure probes the availability of the predefined backup routes supported by each downstream node of the failure, and the first available backup route will be taken to restore the affected traffic. Under the single lightpath failure scenario in a certain link, the failure may randomly attack one of the links taken by the affected primary path. Therefore, the failure probability $P(f_k)$ for the link k is given by the following for a failed N-hop primary path:

$$P(f_k) = 1/N, \qquad k = 1, 2, \ldots, N. \tag{1}$$

Let $P(r)$ denote the restoration probability (or the probability that a connection can be successfully restored in case of a failure). We have

$$P(r) = \sum_{k=1}^{N} P(f_k) \cdot P(r|f_k), \tag{2}$$

where $P(r|f_k)$ is the restoration probability, given the event that a failure has occurred at the $k\mathrm{th}$ link of the primary path. Formula (2) indicates that we need to calculate the probability $P(r|f_k)$ to get the restoration probability. To calculate $P(r|f_k)$, we need to further specify the restoration process and wavelength conversion capability in a network. In this paper, we consider the WDM networks both with full wavelength conversion and without wavelength conversion and focus on the *node-oriented restoration (NOR)* process proposed in [18]. Given the events that a failure has occurred at the $k\mathrm{th}$ link of an $N\text{-hop}$ primary path, and there are w_k wavelengths that are free on all the downstream hops of the $k\mathrm{th}$ link, the NOR scheme first tries to restore the affected traffic through the immediate node after the failure location based on these w_k wavelengths. If the connection of the primary path can be restored through this node based on any of these w_k wavelengths, then the restoration process is finished. Otherwise, the NOR scheme tries to restore the affected connection through the following nodes along the primary path still based on these w_k free wavelengths. This process continues until we find a node through which the traffic can be restored or where the restoration process fails (that is, the affected connection cannot be restored through any of these downstream nodes of the $k\mathrm{th}$ link along the primary path).

Under the NOR process, we use $P(w_k)$ to denote the probability that there are w_k wavelength planes (including the reserved one), among the total wavelength planes, that are free on all downstream hops of the failed $k\mathrm{th}$ link of the $N\text{-hop}$ primary path, and we use the notation $P(r|f_k, w_k)$ to denote the probability $P(r|f_k)$ when these w_k wavelengths are considered in the NOR process. Let r denote the probability that a wavelength is used on a hop, ω denote the total number of wavelength planes per fiber, and H_i denote the hop count of a backup route initiated from the node i along a primary path. Then, the probability $P(r|f_k)$ can be evaluated as

$$P(r|f_k) = \frac{\sum_{w_k=1}^{\omega} P(w_k) \cdot P(r|f_k, w_k)}{\sum_{w_k=1}^{\omega} P(w_k)} \tag{3}$$

in which

$$P(r|f_k, w_k) = 0 \qquad if \qquad w_k = 0$$

and

$$P(w_k) = \binom{\omega - 1}{w_k - 1} \cdot P_k^{w_k - 1} \cdot (1 - P_k)^{\omega - w_k}. \tag{4}$$

Here, P_k is the probability that a wavelength is free on all downstream hops after the failed $k\mathrm{th}$ link of the $N\text{-hop}$ primary path, and it is given by

$$P_k = (1 - \rho)^{N-k}.$$

For simplicity, hereafter, we use $\bar{r}_i$ to denote the event that the backup route r_i is not available for restoration and simply use r_i to denote the event that the backup route r_i is available for restoration. Note that a failed connection (at failure location k) in AR-based networks can be restored through its $i\mathrm{th}$ backup path $(i \geq k)$ if and only if this backup path is free, and all the preceding backup paths $k, \ldots, i-1$ are not free. Then, we can easily see that, in general, the probability $P(r|f_k, w_k)$ can be calculated as

$$\begin{aligned} P(r|f_k, w_k) &= P(r_k) + P(r_{k+1}, \bar{r}_k) + \cdots + P(r_N, \bar{r}_{N-1}, \ldots, \bar{r}_k) \\ &= P(r_k) + \sum_{i=k+1}^{N} P(r_i, \bar{r}_{i-1}, \ldots, \bar{r}_k). \end{aligned} \tag{5}$$

Hereafter, we will develop analytical models for evaluating $P(r|f_k, w_k)$ for networks with and without wavelength conversion under Assumption 1 (model 1), Assumption 2 (model 2), and Assumption 3 (model 3), respectively.

3 Model 1

To understand the restoration behavior of AR-based networks, a model was proposed in [18] to estimate the restoration probability of a connection request, given the event that the primary path of request is interrupted, where the possible correlation among the backup routes of the connection were ignored. For the calculation of $P(r|f_k, w_k)$ under assumption 1, we have the following theorem [18].

Theorem 1. *For an N-hop primary path, the probability $P(r|f_k, w_k)$ is given by the following when Assumption 1 is adopted:*

$$P(r|f_k, w_k) = \begin{cases} P(r_k) + \sum_{i=k+1}^{N} P(r_i) \cdot \prod_{j=k}^{i-1} P(\bar{r}_j) & 1 \le k \le N-1 \\ P(r_N) & k = N. \end{cases} \tag{6}$$

Note that $P(\bar{r}_j) = 1 - P(r_j)$, so (6) indicates that we only need to determine the probability $P(r_h)$ for $k \le h \le N$ to calculate $P(r|f_k, w_k)$ when assumption 1 is adopted.

The calculation of $P(r_h)$ depends on the wavelength conversion capability, as summarized in the following lemma [18].

Lemma 1. *For an N-hop primary path with w_k free wavelengths (including the reserved wavelength of the failed primary path) along all downstream hops of the kth link, the probability $P(r_h)$, $k \le h \le N$, is given by the following:*

$$P(r_h) = \begin{cases} (1-\rho^{\omega})^{H_h} & \text{with full wavelength conversion} \\ 1 - \left[1 - (1-\rho)^{H_h}\right]^{w_k} & \text{without wavelength conversion.} \end{cases} \tag{7}$$

4 Model 2

In this section, we propose a new model for estimating the restoration probability when Assumption 2 is adopted (that is, we only consider all the possible correlations between any two successive backup routes of a connection).

4.1 Overall Model

For the evaluation of $P(r|f_k, w_k)$ under assumption 2, we have the following theorem.

Theorem 2. *For an N-hop primary path, the probability $P(r|f_k, w_k)$ can be evaluated by the following when Assumption 2 is adopted:*

$$P(r|f_k, w_k) = \begin{cases} P(r_k) + P(r_{k+1}) \cdot P(\bar{r}_k|r_{k+1}) + \\ \quad \sum_{i=k+2}^{N} \Big[P(r_i) \cdot P(\bar{r}_{i-1}|r_i) \\ \quad \cdot \prod_{j=k+1}^{i-1} P(\bar{r}_{j-1}|\bar{r}_j) \Big] & 1 \le k \le N-2 \\ P(r_{N-1}) + P(r_N) \cdot P(\bar{r}_{N-1}|r_N) & k = N-1 \\ P(r_N) & k = N, \end{cases} \tag{8}$$

where

$$\begin{aligned} P(\bar{r}_i|r_j) &= 1 - P(r_i|r_j), \\ P(\bar{r}_i|\bar{r}_j) &= 1 - \frac{P(r_i) \cdot \Big[1 - P(r_j|r_i)\Big]}{1 - P(r_j)}. \end{aligned} \tag{9}$$

Proof. Note that

$$\begin{aligned} P(r_i, \bar{r}_{i-1}, \ldots, \bar{r}_k) &= P(r_i) \cdot P(\bar{r}_{i-1}, \ldots, \bar{r}_k|r_i) \\ &= P(r_i) \cdot P(\bar{r}_{i-1}|r_i) \cdot P(\bar{r}_{i-2}, \ldots, \bar{r}_k|r_i, \bar{r}_{i-1}) \\ &= P(r_i) \cdot P(\bar{r}_{i-1}|r_i) \cdot P(\bar{r}_{i-2}|r_i, \bar{r}_{i-1}) \\ &\quad \cdot P(\bar{r}_{i-3}, \ldots, \bar{r}_k|r_i, \bar{r}_{i-1}, \bar{r}_{i-2}). \end{aligned} \tag{10}$$

By applying the above formula recursively and considering only the correlation between any two successive backup paths (Assumption 2), we can get (8) immediately based on (5).

Since

$$P(\bar{r}_i|r_j) = 1 - P(r_i|r_j), \quad P(\bar{r}_i|\bar{r}_j) = 1 - P(r_i|\bar{r}_j).$$

Thus, we have

$$P(\bar{r}_i|\bar{r}_j) = 1 - P(r_i, \bar{r}_j)/P(\bar{r}_j) = 1 - \frac{P(r_i) \cdot \Big[1 - P(r_j|r_i)\Big]}{1 - P(r_j)}.$$

□

Since the probability $P(r_l)$ for $1 \le l \le N$ can be evaluated by using (7), (8), and (9) indicates that we only need determine the probability $P(r_i|r_j)$ to calculate $P(r|f_k, w_k)$, when Assumption 2 is adopted. Note that the correlation between routes i and j is determined by the overlapped hops between them (hereafter, we use $H_{i,j}$ to denote the number of overlapped hops between routes i and j), so for networks with full wavelength conversion, the $P(r_i|r_j)$ can be simply calculated by using the following:

$$P(r_i|r_j) = (1-\rho^{\omega})^{H_i - H_{i,j}}. \tag{12}$$

For the networks without wavelength conversion (that is, with wavelength continuity constraint), however, the calculation of $P(r_i|r_j)$ is a little complex, as discussed in the following section.

4.1.1 *Calculation of Probability $P(r_i|r_j)$ under the Wavelength Continuity Constraint*

To calculate the probability $P(r_i|r_j)$ under the wavelength continuity constraint (that is, a lightpath must take the same wavelength along its route), we first express it as

$$P(r_i|r_j) = \sum_{w=1}^{w_k} P\Big(r_j^{(w)}|r_j\Big) \cdot P\Big(r_i|r_j^{(w)}, r_j\Big) = P\Big(r_j^{(w)}|r_j\Big) \cdot P\Big(r_i|r_j^{(w)}\Big). \tag{13}$$

Here, $r_j^{(w)}$ denotes the event that w wavelengths among the w_k free wavelengths along the primary path are also free along the backup route r_j, and the probability $P(r_j^{(w)})$ is given by

$$P\Big(r_j^{(w)}\Big) = \binom{w_k}{w} \cdot \Big[(1-\rho)^{H_j}\Big]^w \cdot \Big[1-(1-\rho)^{H_j}\Big]^{w_k-w}. \tag{14}$$

Since we always have $w \geq 1$, the probability $P(r_j^{(w)}|r_j)$ can be evaluated as

$$P\Big(r_j^{(w)}|r_j\Big) = P\Big(r_j^{(w)}\Big) \cdot P\Big(r_j|r_j^{(w)}\Big) \Big/ P(r_j), \tag{15}$$

where the probabilities $P(r_j)$ and $P(r_j^{(w)})$ are given by (7) and (14), respectively.

The problem that remains unsolved is the calculation of probability $P(r_j|r_j^{(w)})$ in (13). To calculate this probability, we need to further express it as

$$P\Big(r_i|r_j^{(w)}\Big) = \sum_{m=w}^{w_k} P\Big(A_{i,j}^{(m)}|r_j^{(w)}\Big) \cdot P\Big(r_i|r_j^{(w)}, A_{i,j}^{(m)}\Big) = \sum_{m=w}^{w_k} P\Big(A_{i,j}^{(m)}|r_j^{(w)}\Big) \cdot P\Big(r_i|A_{i,j}^{(m)}\Big). \tag{16}$$

Here, $A_{i,j}^{(m)}$ denotes the event that m wavelength channels are free on the overlapped hops between the backup routes i and j. Note that given the event $A_{i,j}^{(m)}$, the probability that the backup route i is available for restoration is just the probability that at least one of these m wavelengths is free in the remaining $H_i - H_{i,j}$ hops of the route. Thus, the probability $P(r_i|A_{i,j}^{(m)})$ is given by

$$P(r_i|A_{i,j}^{(m)}) = 1 - \Big[1-(1-\rho)^{H_i-H_{i,j}}\Big]^m. \tag{17}$$

Finally, the probability $P(A_{i,j}^{(m)}|r_j^{(w)})$ in (16) can be evaluated as

$$P\Big(A_{i,j}^{(m)}|r_j^{(w)}\Big) = P\Big(A_{i,j}^{(m)}\Big) \cdot P\Big(r_j^{(w)}|A_{i,j}^{(m)}\Big) \Big/ P\Big(r_j^{(w)}\Big), \tag{18}$$

where $P(r_j^{(w)})$ is given by (14), and probabilities $P(A_{i,j}^{(m)})$ and $P(r_j^{(w)}|A_{i,j}^{(m)})$ are given by the following, respectively:

$$P\Big(A_{i,j}^{(m)}\Big) = \binom{w_k}{m} \cdot \Big[(1-\rho)^{H_{i,j}}\Big]^m \cdot \Big[1-(1-\rho)^{H_{i,j}}\Big]^{w_k-m} \tag{19}$$

$$P\Big(r_j^{(w)}|A_{i,j}^{(m)}\Big) = \binom{m}{w} \cdot \Big[(1-\rho)^{H_j-H_{i,j}}\Big]^w \cdot \Big[1-(1-\rho)^{H_j-H_{i,j}}\Big]^{m-w}. \tag{20}$$

5 Model 3

In this section, we propose a more advanced model for estimating the restoration probability based on Assumption 3 (that is, we consider all the possible correlations among any three successive backup routes of a connection).

5.1 Overall Model

To evaluate the probability $P(r|f_k, w_k)$ when Assumption 3 is considered, we need to establish the following theorem.

Theorem 3. *For an N-hop primary path in a network, the probability $P(r|f_k, w_k)$ can be evaluated by the following when Assumption 3 is adopted:*

$$P(r|f_k,w_k) = \begin{cases} P(r_k) + P(r_{k+1}) \cdot P(\bar{r}_k|r_{k+1}) + P(r_{k+2}) \\ \cdot P(\bar{r}_{k+1}|r_{k+2}) \cdot P(\bar{r}_k|\bar{r}_{k+1}, r_{k+2}) + \\ \sum_{i=k+3}^{N} \Big[P(r_i) \cdot P(\bar{r}_{i-1}|r_i) \cdot P(\bar{r}_{i-2}|\bar{r}_{i-1}, r_i) \\ \cdot \prod_{j=k+2}^{i-1} P(\bar{r}_{j-2}|\bar{r}_{j-1}, \bar{r}_j)\Big], & 1 \leq k \leq N-3 \\ P(r_{N-2}) + P(r_{N-1}) \cdot P(\bar{r}_{N-2}|r_{N-1}) + \\ P(r_N) \cdot P(\bar{r}_{N-1}|r_N) \cdot P(\bar{r}_{N-2}|\bar{r}_{N-1}, r_N), & k = N-2 \\ P(r_{N-1}) + P(r_N) \cdot P(\bar{r}_{N-1}|r_N), & k = N-1 \\ P(r_N), & k = N, \end{cases} \tag{21}$$

where

$$P(\bar{r}_h|\bar{r}_i, \bar{r}_j) = 1 - \frac{P(r_h) \cdot P(\bar{r}_i|r_h) \cdot P(\bar{r}_j|\bar{r}_i, r_h)}{P(\bar{r}_i) \cdot P(\bar{r}_j|\bar{r}_i)},$$
$$P(\bar{r}_j|\bar{r}_i, r_h) = 1 - \frac{P(r_j|r_h) \cdot \Big[1 - P(r_i|r_j, r_h)\Big]}{\Big[1 - P(r_i|r_h)\Big]}. \tag{22}$$

Proof. We can prove this theorem in a similar way as that of Theorem 2 based on (5) and Assumption 3, which considers all the possible correlations between any three successive backup paths of a connection. □

Since the terms $P(r_i)$, $P(\bar{r}_i)$, $P(r_i|r_j)$, $P(\bar{r}_i|r_j)$, and $P(\bar{r}_i|\bar{r}_j)$ can be evaluated by their corresponding formulas provided in models 1 and 2, (22) indicates that we only need to determine the probability $P(r_i|r_j, r_h)$ for the evaluation of restoration probability when assumption 3 is adopted.

Note that the correlation between route i and routes j and h is determined by $H_{i,j}$, $H_{i,h}$, and $H_{i,j,h}$ (the number of overlapped hops among routes i, j, and h), so for networks with full wavelength conversion, the probability $P(r_i|r_j, r_h)$ can be simply calculated by using the following:

$$P(r_i|r_j, r_h) = (1-\rho^{\omega})^{H_i - H_{i,j} - H_{i,h} + H_{i,j,h}}. \tag{23}$$

For the networks without wavelength conversion, however, the calculation of $P(r_i|r_j, r_h)$ is more complex. To calculate the probability $P(r_i|r_j, r_h)$ under the wavelength continuity constraint, we first express it as

$$P(r_i|r_j, r_h) = \sum_{\alpha=1}^{w_k}\sum_{\beta=1}^{w_k} P\Big(r_j^{(\alpha)}, r_h^{(\beta)}\Big|r_j, r_h\Big) \cdot P\Big(r_i\Big|r_j^{(\alpha)}, r_h^{(\beta)}, r_j, r_h\Big) = \sum_{\alpha=1}^{w_k}\sum_{\beta=1}^{w_k} P\Big(r_j^{(\alpha)}, r_h^{(\beta)}\Big|r_j, r_h\Big) \cdot P\Big(r_i\Big|r_j^{(\alpha)}, r_h^{(\beta)}\Big). \tag{24}$$

Equation (24) indicates that we need to evaluate the probabilities $P(r_j^{(\alpha)}, r_h^{(\beta)}|r_j, r_h)$ and $P(r_i|r_j^{(\alpha)}, r_h^{(\beta)})$ to get the probability $P(r_i|r_j, r_h)$. The evaluation of these two probabilities (especially the probability $P(r_i|r_j^{(\alpha)}, r_h^{(\beta)})$) involves a complicated process, as discussed in the Sections 5.2 and 5.3.

5.2 Calculation of $P\left(r_j^{(\alpha)}, r_h^{(\beta)}\middle|r_j, r_h\right)$ under the Wavelength Continuity Constraint

We can easily see that the probability $P(r_j^{(\alpha)}, r_h^{(\beta)}|r_j, r_h)$ can be calculated as

$$P\left(r_j^{(\alpha)}, r_h^{(\beta)}\middle|r_j, r_h\right) = \frac{P\left(r_j^{(\alpha)}, r_h^{(\beta)}\right) \cdot P\left(r_j, r_h\middle|r_j^{(\alpha)}, r_h^{(\beta)}\right)}{P(r_j, r_h)}. \quad (25)$$

Since $1 \leq \alpha$, and $\beta \leq w_k$ (please refer to (24)), we always have $P(r_j, r_h|r_j^{(\alpha)}, r_h^{(\beta)}) = 1$. Thus, the probability $P(r_j^{(\alpha)}, r_h^{(\beta)}|r_j, r_h)$ is given by

$$P(r_j^{(\alpha)}, r_h^{(\beta)}|r_j, r_h) = \frac{P(r_j^{(\alpha)}) \cdot P(r_h^{(\beta)}|r_j^{(\alpha)})}{P(r_j) \cdot P(r_h|r_j)} \quad (26)$$

in which the probabilities $P(r_j)$, $P(r_h|r_j)$, and $P(r_j^{(\alpha)})$ can be evaluated by using (7), (13), and (14), respectively. To calculate the probability $P(r_h^{(\beta)}|r_j^{(\alpha)})$ in (26), we need the following:

$$\begin{aligned} P\left(r_h^{(\beta)}\middle|r_j^{(\alpha)}\right) &= \sum_{\ell=max(\alpha,\beta)}^{w_k} P\left(A_{j,h}^{(\ell)}\middle|r_j^{(\alpha)}\right) \cdot P\left(r_h^{(\beta)}\middle|A_{j,h}^{(\ell)}, r_j^{(\alpha)}\right) \\ &= \sum_{\ell=max(\alpha,\beta)}^{w_k} P\left(A_{j,h}^{(\ell)}\middle|r_j^{(\alpha)}\right) \cdot P\left(r_h^{(\beta)}\middle|A_{j,h}^{(\ell)}\right). \end{aligned} \quad (27)$$

Here, the probabilities $P(A_{j,h}^{(\ell)}|r_j^{(\alpha)})$ and $P(r_h^{(\beta)}|A_{j,h}^{(\ell)})$ can be evaluated by using (18) and (20), respectively.

5.3 Calculation of $P\left(r_i\middle|r_j^{(\alpha)}, r_h^{(\beta)}\right)$ under the Wavelength Continuity Constraint

To calculate the probability $P(r_i|r_j^{(\alpha)}, r_h^{(\beta)})$ in (24), we need to further express it as

$$\begin{aligned} P\left(r_i\middle|r_j^{(\alpha)}, r_h^{(\beta)}\right) &= \sum_{m_\alpha=\alpha}^{w_k} \sum_{m_\beta=\beta}^{w_k} P\left(A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}\middle|r_j^{(\alpha)}, r_h^{(\beta)}\right) \\ &\quad \cdot P\left(r_i\middle|r_j^{(\alpha)}, r_h^{(\beta)}, A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}\right) \\ &= \sum_{m_\alpha=\alpha}^{w_k} \sum_{m_\beta=\beta}^{w_k} P\left(A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}\middle|r_j^{(\alpha)}, r_h^{(\beta)}\right) \\ &\quad \cdot P\left(r_i\middle|A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}\right). \end{aligned} \quad (28)$$

Since both the evaluation of $P(r_i|A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)})$ and of $P(A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}|r_j^{(\alpha)}, r_h^{(\beta)})$ in (28) are quite complex, we present the evaluation of each of them separately hereafter.

5.3.1 Calculation of $P\left(r_i\middle|A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}\right)$

To calculate $P(r_i|A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)})$ in (28) under the wavelength continuity constraint, we need to further define the event $A_{i,j,h}^{(x)}$, which indicates that x wavelengths are free on the common overlapped hops among backup routes i, j, and h. Then, we have

$$\begin{aligned} P\left(r_i\middle|A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}\right) = &\sum_{x=max(m_\alpha,m_\beta)}^{w_k} P\left(A_{i,j,h}^{(x)}\middle|A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}\right) \\ &\cdot P\left(r_i\middle|A_{i,j,h}^{(x)}, A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}\right). \end{aligned} \quad (29)$$

The term $P(A_{i,j,h}^{(x)}|A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)})$ in (29) is given by

$$\begin{aligned} &P\left(A_{i,j,h}^{(x)}\middle|A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}\right) = \\ &\frac{P\left(A_{i,j,h}^{(x)}\right) \cdot P\left(A_{i,j}^{(m_\alpha)}\middle|A_{i,j,h}^{(x)}\right) \cdot P\left(A_{i,h}^{(m_\beta)}\middle|A_{i,j,h}^{(x)}\right)}{P\left(A_{i,j}^{(m_\alpha)}\right) \cdot P\left(A_{i,h}^{(m_\beta)}\middle|A_{i,j}^{(m_\alpha)}\right)}, \end{aligned} \quad (30)$$

where $P(A_{i,j}^{(m_\alpha)})$ is given by (19), and $P(A_{i,j,h}^{(x)})$ is given by

$$P\left(A_{i,j,h}^{(x)}\right) = \binom{w_k}{x} \cdot \left[(1-\rho)^{H_{i,j,h}}\right]^x \cdot \left[1-(1-\rho)^{H_{i,j,h}}\right]^{w_k-x}. \quad (31)$$

Based on the similar idea of (20), we can see that $P(A_{i,h}^{(m_\beta)}|A_{i,j,h}^{(x)})$ is given by

$$\begin{aligned} P\left(A_{i,h}^{(m_\beta)}\middle|A_{i,j,h}^{(x)}\right) = &\binom{x}{m_\beta} \cdot \left[(1-\rho)^{H_{i,h}-H_{i,j,h}}\right]^{m_\beta} \\ &\cdot \left[1-(1-\rho)^{H_{i,h}-H_{i,j,h}}\right]^{x-m_\beta}. \end{aligned} \quad (32)$$

The term $P(A_{i,j}^{(m_\alpha)}|A_{i,j,h}^{(x)})$ in (30) can also be evaluated in a similar way to that in (32). To calculate the probability $P(A_{i,h}^{(m_\beta)}|A_{i,j}^{(m_\alpha)})$ in (30), we need the following:

$$P\left(A_{i,h}^{(m_\beta)}\middle|A_{i,j}^{m_\alpha}\right) = \sum_{e=max(m_\alpha,m_\beta)}^{w_k} P\left(A_{i,j,h}^{(e)}\middle|A_{i,j}^{(m_\alpha)}\right) \cdot P\left(A_{i,h}^{(m_\beta)}\middle|A_{i,j,h}^{(e)}\right) \quad (33)$$

in which $P(A_{i,h}^{(m_\beta)}|A_{i,j,h}^{(e)})$ can be evaluated by using (32), and $P(A_{i,j,h}^{(e)}|A_{i,j}^{(m_\alpha)})$ is given by

$$P\left(A_{i,j,h}^{(e)}\middle|A_{i,j}^{(m_\alpha)}\right) = P\left(A_{i,j,h}^{(e)}\right) \cdot P\left(A_{i,j}^{(m_\alpha)}\middle|A_{i,j,h}^{(e)}\right) \Big/ P\left(A_{i,j}^{(m_\alpha)}\right). \quad (34)$$

Here, the terms $P(A_{i,j,h}^{(e)})$, $P(A_{i,j}^{(m_\alpha)}|A_{i,j,h}^{(e)})$, and $P(A_{i,j}^{(m_\alpha)})$ can be evaluated by using (31), (32), and (19), respectively.

The problem that remains unsolved is the calculation of probability $P(r_i|A_{i,j,h}^{(x)}, A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)})$ in (29). Here, we follow the technique proposed by Subramaniam et al. [27] to calculate this probability. First, we need to define the event $A_{(i,j)\cup(i,h)}^{(y)}$, which indicates that y common wavelengths are free on both the overlapped hops between routes i and j and the overlapped hops between routes i and h. Then, we have

$$\begin{aligned} &P\left(r_i\middle|A_{i,j,h}^{(x)}, A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}\right) = \\ &\sum_{y=max(0,m_\alpha+m_\beta-x)}^{min(m_\alpha,m_\beta)} P\left(A_{(i,j)\cup(i,h)}^{(y)}\middle|A_{i,j,h}^{(x)}, A_{i,j}^{(m_\alpha)}, A_{i,h}^{(m_\beta)}\right) \\ &\cdot P\left(r_i\middle|A_{(i,j)\cup(i,h)}^{(y)}\right), \end{aligned} \quad (35)$$

where the probability $P(r_i|A_{(i,j)\cup(i,h)}^{(y)})$ is given by

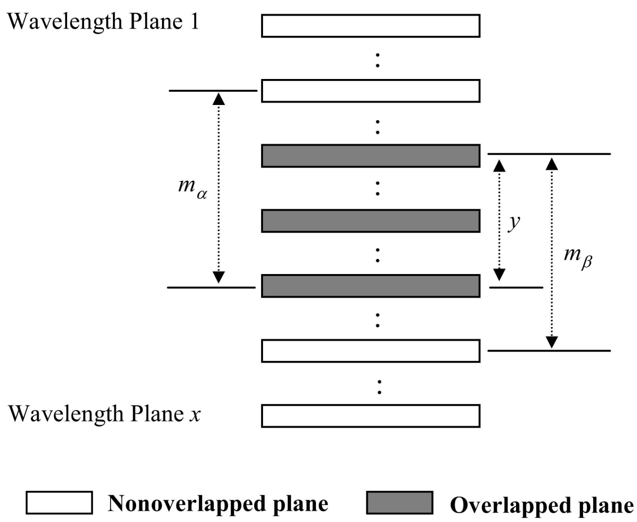


Fig. 2. Given m_α free wavelength planes for $A_{i,j}$, m_β free wavelength planes for $A_{i,h}$, and x free wavelength planes for $A_{i,j,h}$, among them, a total of y free wavelength planes are overlapped between $A_{i,j}$ and $A_{i,h}$.

$$P\Big(r_i \Big| A^{(y)}_{(i,j)\cup(i,h)}\Big) = 1 - \Big[1 - (1-\rho)^{H_i - H_{i,j} - H_{i,h} + H_{i,j,h}}\Big]^y. \quad (36)$$

For the evaluation of $P(A^{(y)}_{(i,j)\cup(i,h)} | A^{(x)}_{i,j,h}, A^{(m_\alpha)}_{i,j}, A^{(m_\beta)}_{i,h})$ in (35), we have the following lemma.

Lemma 2. *Given the events $A^{(x)}_{i,j,h}$, $A^{(m_\alpha)}_{i,j}$, and $A^{(m_\beta)}_{i,h}$, the probability $P(A^{(y)}_{(i,j)\cup(i,h)} | A^{(x)}_{i,j,h}, A^{(m_\alpha)}_{i,j}, A^{(m_\beta)}_{i,h})$ is given by the following under the wavelength continuity constraint:*

$$\begin{aligned} P\Big(A^{(y)}_{(i,j)\cup(i,h)} \Big| A^{(x)}_{i,j,h}, A^{(m_\alpha)}_{i,j}, A^{(m_\beta)}_{i,h}\Big) &= \frac{\binom{m_\alpha}{y}\cdot\binom{x-m_\alpha}{m_\beta - y}}{\binom{x}{m_\beta}} \\ &= \frac{\binom{m_\beta}{y}\cdot\binom{x-m_\beta}{m_\alpha - y}}{\binom{x}{m_\alpha}}. \end{aligned} \quad (37)$$

Proof. Given the events $A^{(x)}_{i,j,h}$, $A^{(m_\alpha)}_{i,j}$, and $A^{(m_\beta)}_{i,h}$ and the assumptions of link independence and wavelength planes independence, the m_α free wavelengths of $A_{i,j}$ and the m_β free wavelengths of $A_{i,h}$ randomly fall within the x free wavelength planes of $A_{i,j,h}$. Thus, we have a total of $\binom{x}{m_\alpha}\cdot\binom{x}{m_\beta}$ ways to select the wavelength planes for both the m_α wavelength of $A_{i,j}$ and the m_β wavelength of $A_{i,h}$, among which a total of y overlapped planes (common free wavelength planes between $A_{i,j}$ and $A_{i,h}$) can be constructed as follows (please refer to Fig. 2).

First, we have $\binom{x}{m_\alpha}$ ways to select m_α wavelength planes out of the total x planes corresponding to the $A_{i,j}$, along with $\binom{m_\alpha}{y}$ ways to select a total of y overlapped wavelength planes that are free in both $A_{i,j}$ and $A_{i,h}$. Then, we have $\binom{x-m_\alpha}{m_\beta-y}$ choices to select $m_\beta - y$ wavelength planes only free in $A_{i,h}$. Therefore, given the events $A^{(x)}_{i,j,h}$, $A^{(m_\alpha)}_{i,j}$, and $A^{(m_\beta)}_{i,h}$, the probability that there are y common free wavelength planes between $A_{i,j}$ and $A_{i,h}$ is given by

$$\frac{\binom{x}{m_\alpha}\cdot\binom{m_\alpha}{y}\cdot\binom{x-m_\alpha}{m_\beta-y}}{\binom{x}{m_\alpha}\cdot\binom{x}{m_\beta}} = \frac{\binom{m_\alpha}{y}\cdot\binom{x-m_\alpha}{m_\beta-y}}{\binom{x}{m_\beta}}.$$

Similarly, we can also prove that this probability is also given by

$$\frac{\binom{m_\alpha}{y}\cdot\binom{x-m_\alpha}{m_\beta-y}}{\binom{x}{m_\beta}}.$$

□

5.3.2 Calculation of $P\Big(A^{(m_\alpha)}_{i,j}, A^{(m_\beta)}_{i,h} \Big| r^{(\alpha)}_j, r^{(\beta)}_h\Big)$

First, we express the probability $P(A^{(m_\alpha)}_{i,j}, A^{(m_\beta)}_{i,h} | r^{(\alpha)}_j, r^{(\beta)}_h)$ in (28) as

$$\begin{aligned} &P\Big(A^{(m_\alpha)}_{i,j}, A^{(m_\beta)}_{i,h} \Big| r^{(\alpha)}_j, r^{(\beta)}_h\Big) = \\ &\frac{P\Big(A^{(m_\alpha)}_{i,j}\Big)\cdot P\Big(A^{(m_\beta)}_{i,h}\Big|A^{(m_\alpha)}_{i,j}\Big)\cdot P\Big(r^{(\alpha)}_j, r^{(\beta)}_h | A^{(m_\alpha)}_{i,j}, A^{(m_\beta)}_{i,h}\Big)}{P\Big(r^{(\alpha)}_j\Big)\cdot P\Big(r^{(\beta)}_h \Big| r^{(\alpha)}_j\Big)}, \end{aligned} \quad (38)$$

where the terms $P(A^{(m_\alpha)}_{i,j})$, $P(A^{(m_\beta)}_{i,h}|A^{(m_\alpha)}_{i,j})$, $P(r^{(\alpha)}_j)$, and $P(r^{(\beta)}_h|r^{(\alpha)}_j)$ can be evaluated by using (19), (33), (14), and (27), respectively.

To evaluate the probability $P(r^{(\alpha)}_j, r^{(\beta)}_h | A^{(m_\alpha)}_{i,j}, A^{(m_\beta)}_{i,h})$ in (38), we need further to express it as

$$\begin{aligned} P\Big(r^{(\alpha)}_j, r^{(\beta)}_h \Big| A^{(m_\alpha)}_{i,j}, A^{(m_\beta)}_{i,h}\Big) &= P\Big(r^{(\alpha)}_j \Big| A^{(m_\alpha)}_{i,j}, A^{(m_\beta)}_{i,h}\Big) \\ &\quad\cdot P\Big(r^{(\beta)}_h \Big| r^{(\alpha)}_j, A^{(m_\alpha)}_{i,j}, A^{(m_\beta)}_{i,h}\Big) \\ &= P\Big(r^{(\alpha)}_j \Big| A^{(m_\alpha)}_{i,j}\Big) \\ &\quad\cdot P\Big(r^{(\beta)}_h \Big| r^{(\alpha)}_j, A^{(m_\beta)}_{i,h}\Big), \end{aligned} \quad (39)$$

where $P(r^{(\alpha)}_j|A^{(m_\alpha)}_{i,j})$ is given by (20), and $P(r^{(\beta)}_h|r^{(\alpha)}_j, A^{(m_\beta)}_{i,h})$ is evaluated as

$$\begin{aligned} P\Big(r^{(\beta)}_h \Big| r^{(\alpha)}_j, A^{(m_\beta)}_{i,h}\Big) &= \sum_{m_\eta = max(\alpha,\beta)}^{w_k} P\Big(A^{(m_\eta)}_{j,h} \Big| r^{(\alpha)}_j, A^{(m_\beta)}_{i,h}\Big) \\ &\quad\cdot P\Big(r^{(\beta)}_h \Big| A^{(m_\eta)}_{j,h}, A^{(m_\beta)}_{i,h}\Big). \end{aligned} \quad (40)$$

The probability $P(A^{(m_\eta)}_{j,h}|r^{(\alpha)}_j, A^{(m_\beta)}_{i,h})$ in (40) is determined as

$$\begin{aligned} P\Big(A^{(m_\eta)}_{j,h} \Big| r^{(\alpha)}_j, A^{(m_\beta)}_{i,h}\Big) &= \frac{P\Big(A^{(m_\eta)}_{j,h}, A^{(m_\beta)}_{i,h}\Big)\cdot P\Big(r^{(\alpha)}_j \Big| A^{(m_\eta)}_{j,h}, A^{(m_\beta)}_{i,h}\Big)}{P\Big(r^{(\alpha)}_j, A^{(m_\beta)}_{i,h}\Big)} \\ &= \frac{P\Big(A^{(m_\eta)}_{j,h}, A^{(m_\beta)}_{i,h}\Big)\cdot P\Big(r^{(\alpha)}_j \Big| A^{(m_\eta)}_{j,h}\Big)}{P\Big(r^{(\alpha)}_j \Big| A^{(m_\beta)}_{i,h}\Big)}. \end{aligned} \quad (41)$$

Here, $P(r^{(\alpha)}_j|A^{(m_\beta)}_{i,h})$ and $P(r^{(\alpha)}_j|A^{(m_\eta)}_{j,h})$ can be calculated based on (33) and (20), respectively. For the evaluation of $P(r^{(\alpha)}_j, A^{(m_\beta)}_{i,h})$ in (41), we have

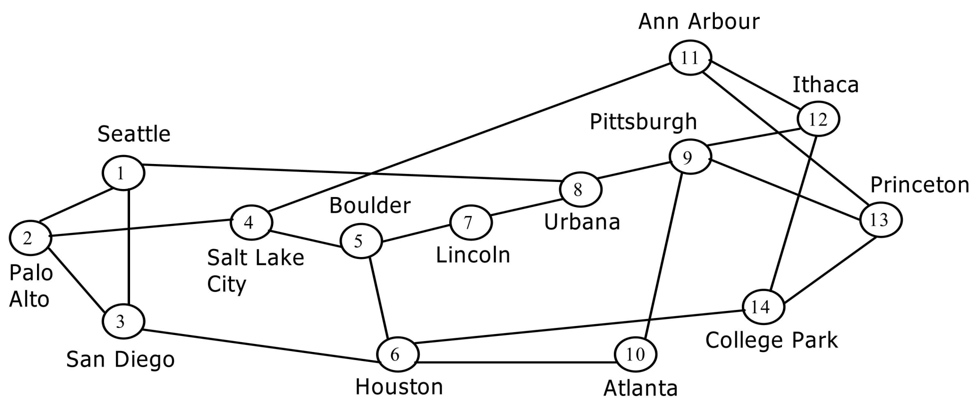


Fig. 3. NSFNET with 14 nodes and 21 links.

$$P\Big(r_j^{(\alpha)}, A_{i,h}^{(m_\beta)}\Big) = \sum_{m_x=m_\beta}^{w_k} P\Big(A_{i,j,h}^{(m_x)}\Big|A_{i,h}^{(m_\beta)}\Big) \cdot P\Big(r_j^{(\alpha)}, A_{i,j,h}^{(m_x)}\Big), \tag{42}$$

where $P(A_{i,j,h}^{(m_x)}|A_{i,h}^{(m_\beta)})$ is given by (34) and $P(r_j^{(\alpha)}, A_{i,j,h}^{(m_x)})$ is given by

$$\begin{aligned} P\Big(r_j^{(\alpha)}, A_{i,j,h}^{(m_x)}\Big) = \binom{m_x}{\alpha} \cdot \Big[(1-\rho)^{H_j - H_{i,j,h}}\Big]^{\alpha} \\ \cdot \Big[1-(1-\rho)^{H_j - H_{i,j,h}}\Big]^{m_x-\alpha}. \end{aligned} \tag{43}$$

The only problem that remains unsolved is the calculation of $P(r_h^{(\beta)}|A_{j,h}^{(m_\eta)}, A_{i,h}^{(m_\beta)})$ in (40). Based on the similar idea of (29) and (35), we have

$$\begin{aligned} P\Big(r_h^{(\beta)}\Big|A_{j,h}^{(m_\eta)}, A_{i,h}^{(m_\beta)}\Big) = \sum_{z=max(m_\eta,m_\beta)}^{w_k} P\Big(A_{i,j,h}^{(z)}\Big|A_{j,h}^{(m_\eta)}, A_{i,h}^{(m_\beta)}\Big) \\ \cdot P\Big(r_h^{(\beta)}\Big|A_{i,j,h}^{(z)}, A_{j,h}^{(m_\eta)}, A_{i,h}^{(m_\beta)}\Big). \end{aligned} \tag{44}$$

Here, $P(A_{i,j,h}^{(z)}|A_{j,h}^{(m_\eta)}, A_{i,h}^{(m_\beta)})$ is given by (30), and $P(r_h^{(\beta)}|A_{i,j,h}^{(z)}, A_{j,h}^{(m_\eta)}, A_{i,h}^{(m_\beta)})$ can be calculated as

$$\begin{aligned} P\Big(r_h^{(\beta)}\Big|A_{i,j,h}^{(z)}, A_{j,h}^{(m_\eta)}, A_{i,h}^{(m_\beta)}\Big) = \\ \sum_{y=max(0,m_\eta+m_\beta-z)}^{min(m_\eta,m_\beta)} P\Big(A_{(i,h)\cup(j,h)}^{(y)}\Big|A_{i,j,h}^{(z)}, A_{j,h}^{(m_\eta)}, A_{i,h}^{(m_{beta})}\Big) \\ \cdot P\Big(r_h^{(\beta)}\Big|A_{(i,h)\cup(j,h)}^{(y)}\Big). \end{aligned} \tag{45}$$

Based on the similar idea of Lemma 2, we can prove that $P(A_{(i,h)\cup(j,h)}^{(y)}|A_{i,j,h}^{(z)}, A_{j,h}^{(m_\eta)}, A_{i,h}^{(m_beta)})$ is given by

$$\begin{aligned} P\Big(A_{(i,h)\cup(j,h)}^{(y)}\Big|A_{i,j,h}^{(z)}, A_{j,h}^{(m_\eta)}, A_{i,h}^{(m_{beta})}\Big) &= \frac{\binom{m_\eta}{y}\cdot\binom{z-m_\eta}{m_\beta-y}}{\binom{z}{m_\beta}} \\ &= \frac{\binom{m_\beta}{y}\cdot\binom{z-m_\beta}{m_\eta-y}}{\binom{z}{m_\eta}}. \end{aligned} \tag{46}$$

Finally, $P(r_h^{(\beta)}|A_{(i,h)\cup(j,h)}^{(y)})$ can be evaluated as

$$\begin{aligned} P\Big(r_h^{(\beta)}\Big|A_{(i,h)\cup(j,h)}^{(y)}\Big) = \binom{y}{\beta} \cdot \Big[(1-\rho)^{H_h - H_{i,h} - H_{j,h} + H_{i,j,h}}\Big]^{\beta} \\ \Big[1-(1-\rho)^{H_h - H_{i,h} - H_{j,h} + H_{i,j,h}}\Big]^{y-\beta}. \end{aligned}$$

6 Experimental Results

To verify our analytical models on restoration probability, a network simulator was developed to simulate the restoration probability of a network under the same conditions used to develop the theoretical models, except that all the possible correlations among all backup routes were incorporated in our simulation, where the correlation among the backup routes is caused by the link sharing among these routes.

6.1 Model Verification

Three network topologies were adopted in our simulation to validate our models. The first network topology (Fig. 3) is the famous NSF network (NSFNET), the second network topology (Fig. 4) is the larger Italian network (ITALIANNET) [28], and the third network topology (Fig. 5) is the typical EON network (EONNET).

For the NSFNET (Fig. 3), we consider a 3-hop connection request from node 2 to node 10 through the primary path

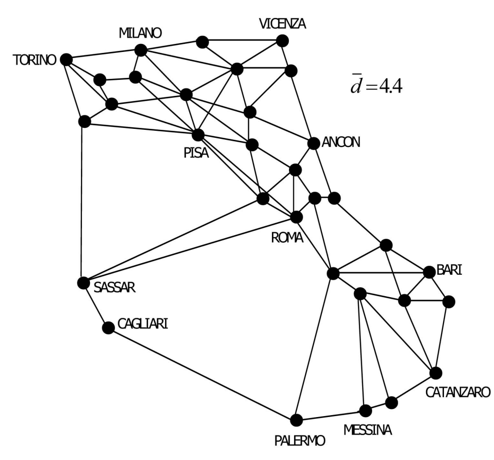


Fig. 4. ITALIANNET with 32 nodes and 70 links.

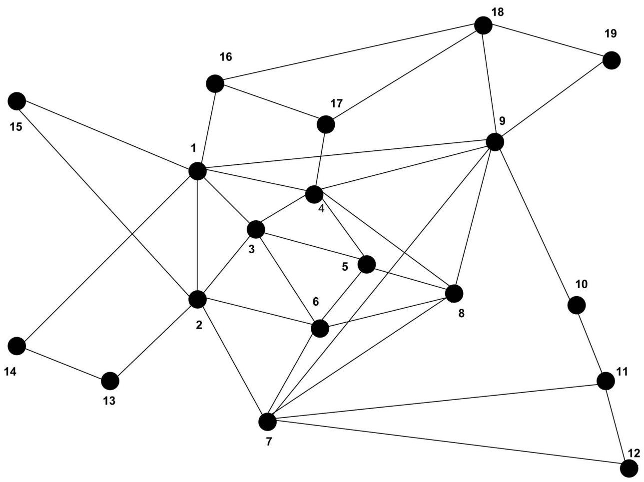


Fig. 5. EONNET with 19 nodes.

(2-3-6-10). Based on the idea of AR, its consecutive backup routes are (2-1-3), (2-4-5-6), and (2-1-8-9-10), respectively. It is clear that the first backup path (2-1-3) and the third backup path (2-1-8-9-10) are sharing a common link (the link between nodes 2 and 1). Therefore, for the 3-hop connection, the correlation only exists between its first and third backup routes, as they share one common link. For the ITALIANNET (Fig. 4), we consider a 5-hop connection request from Milano to Palermo with successive backup routes of hop length 2, 2, 4, 6, and 9, respectively. In the EONNET (Fig. 5), we consider a 4-hop connection request between node 13 and node 19 with the primary path (13-2-1-9-19), where the hop length of its successive backup routes are 4, 2, 4, and 5 hops, respectively. To further investigate the effect on the restoration probability of the primary path's hop length in the next section, we also consider in our study a 2-hop connection request from Milano to Vicenza in ITALIANNET, where each of its successive backup paths has a hop length of 2. To illustrate the correlation patterns of the three connections above, we summarize in Table 1 the number of overlapped hops among the backup routes (correlation pattern) of each connection request that we considered.

Table 1 illustrates clearly the link sharing among the backup routes of each connection. For example, for the 5-hop connection in ITALIANNET, the first two backup routes are link disjoint, the second backup route and the third backup route share two links, whereas the second, third, and fourth backup routes share only one common link. For the 2-hop connection in the same network, its two backup routes share only one link.

6.1.1 Simulation Environment

To simulate the restoration probability of a connection, multiple distinct failure locations are first generated randomly along the primary path of the connection. For a given failure location, the network simulator that we developed was used to estimate the restoration probability corresponding to this failure location. The network simulator consists of two major modules: the wavelength-pattern generator module and the restoration module. Based on the parameter ρ (the occupancy probability of a wavelength channel), the wavelength-pattern generator module randomly generates a pattern of wavelength status (either busy or idle) for all wavelength channels (except the wavelength channels occupied by the primary path of the given connection).

Based on the wavelength pattern and the given failure location, the restoration module seeks the availability of the predefined backup routes supported by each downstream node of the failure, and the first available backup route will be adopted to restore the affected connection. If we can successfully restore the connection request for a given wavelength pattern, then this wavelength pattern is recorded as a successful one. On the other hand, if no free backup routes can be found among all the backup routes supported by the downstream nodes of the failure, then the restoration of this lightpath fails, and this wavelength pattern is recorded as a failed one.

The restoration probability corresponding to the given failure location is then estimated by the ratio of the number of successful wavelength patterns to the total number of wavelength patterns (successful patterns + failed patterns) generated for this failure location. The overall restoration probability of the given connection request is thus estimated by the average of all the restoration probabilities corresponding to the different failure locations that we generated.

6.1.2 Comparison between Theoretical Results and Simulation Results

A comparison between the theoretical results of model 1, model 2, and model 3 and the simulation results is summarized in Tables 2, 3, and 4 for the 3-hop connection of NSFNET, the 5-hop connection of ITALIANNET, and the 4-hop connection of EONNET, respectively. All the three tables indicate clearly that our analytical models (especially

TABLE 1
Number of Overlapped Hops among Backup Routes

	$H_{1,2}$	$H_{1,3}$	$H_{2,3}$	$H_{1,2,3}$	$H_{4,2}$	$H_{4,3}$	$H_{2,3,4}$	$H_{3,5}$	$H_{4,5}$	$H_{3,4,5}$
Connection 1 (3 hops)	0	1	0	0	-	-	-	-	-	-
Connection 2 (5 hops)	0	0	2	0	1	1	1	0	0	0
Connection 3 (2 hops)	1	-	-	-	-	-	-	-	-	-
Connection 4 (4 hops)	2	2	2	2	2	2	2	-	-	-

TABLE 2
Restoration Probability of the 3-Hop Connection in NSFNET, $\omega = 16$

	Without Wavelength conversion				With Full Wavelength conversion			
ρ	Model-1	Model-2	Model-3	Simulation	Model-1	Model-2	Model-3	Simulation
0.2	1.0000	1.0000	0.9999	0.9999	1.0000	1.0000	1.0000	1.0000
0.3	1.0000	1.0000	0.9915	0.9878	1.0000	1.0000	1.0000	1.0000
0.4	0.9827	0.9827	0.9482	0.9472	1.0000	1.0000	1.0000	1.0000
0.5	0.7899	0.7899	0.7640	0.7638	1.0000	1.0000	1.0000	1.0000
0.6	0.4569	0.4569	0.4549	0.4549	0.9996	0.9996	0.9996	0.9996
0.7	0.1813	0.1813	0.1810	0.1810	0.9955	0.9955	0.9942	0.9940
0.8	0.0459	0.0459	0.0459	0.0459	0.9609	0.9609	0.9538	0.9533

TABLE 3
Restoration Probability of the 5-Hop Connection in ITALIANNET, $\omega = 16$

	Without Wavelength conversion				With Full Wavelength conversion			
ρ	Model-1	Model-2	Model-3	Simulation	Model-1	Model-2	Model-3	Simulation
0.2	0.9793	0.9792	0.9691	0.9689	1.0000	1.0000	1.0000	1.0000
0.3	0.8560	0.8519	0.8436	0.8424	1.0000	1.0000	1.0000	1.0000
0.4	0.6183	0.6002	0.5957	0.5941	1.0000	1.0000	1.0000	1.0000
0.5	0.3554	0.3349	0.3308	0.3301	1.0000	1.0000	1.0000	1.0000
0.6	0.1687	0.1580	0.1559	0.1555	0.9995	0.9995	0.9994	0.9993
0.7	0.0710	0.0676	0.0669	0.0667	0.9952	0.9952	0.9940	0.9938
0.8	0.0262	0.0256	0.0256	0.0256	0.9467	0.9454	0.9374	0.9370

TABLE 4
Restoration Probability of the 4-Hop Connection in EONNET, $\omega = 16$

	Without Wavelength conversion				With Full Wavelength conversion			
ρ	Model-1	Model-2	Model-3	Simulation	Model-1	Model-2	Model-3	Simulation
0.2	0.9996	0.9994	0.9993	0.9992	1.0000	1.0000	1.0000	1.0000
0.3	0.9841	0.9773	0.9738	0.9737	0.9999	0.9999	0.9999	0.9999
0.4	0.8775	0.8400	0.8324	0.8323	0.9999	0.9999	0.9999	0.9999
0.5	0.6086	0.5574	0.5535	0.5535	0.9999	0.9999	0.9999	0.9999
0.6	0.3050	0.2760	0.2753	0.2753	0.9996	0.9995	0.9993	0.9993
0.7	0.1131	0.1043	0.1043	0.1042	0.9958	0.9941	0.9925	0.9921
0.8	0.0317	0.0302	0.0302	0.0302	0.9629	0.9480	0.9364	0.9340
0.9	0.0056	0.0055	0.0055	0.0055	0.7030	0.6222	0.5981	0.5933

model 3) are very efficient for estimating the restoration probability of a connection request in AR-based optical networks.

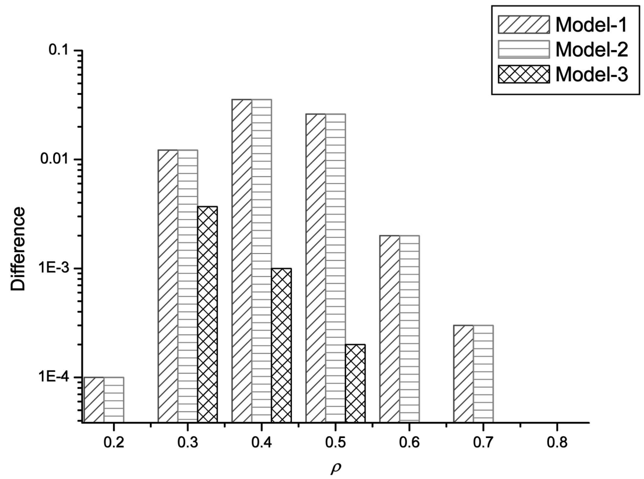
It is notable in Table 2 that for the 3-hop connection in NSFNET, model 3 achieves a very close approximation to the simulation results for both cases with and without wavelength conversion. On the other hand, models 1 and 2 provide an identical estimation, which is significantly higher than that of model 3 and the simulation result. This is due to the fact that for the 3-hop connection under consideration, there are no overlapped hops among its successive backup paths ($H_{1,2} = 0$ and $H_{2,3} = 0$; please refer to Table 1). Thus, model 2, which considers only the possible correlation among any two successive backup routes, provides the same results as that of model 1. The results in Table 2 also show that although models 1 and 2 overestimate the restoration probability of the 3-hop connection for both cases with and without wavelength conversion, the difference between the results of model 1/model 2 and the simulation results is relatively smaller than that when using the wavelength conversion capability. This indicates that the effect of neglecting the possible correlation among the successive backup routes of a connection becomes less significant if the network has a wavelength conversion capability.

The further results in Table 3 indicate that for the 5-hop connection in ITALIANNET, where the correlations exist between successive and nonsuccessive backup routes (please refer to Table 1), both models 2 and 3 provide a close estimation to the simulation results than that of model 1. For example, consider the case without wavelength conversion and $\rho = 0.5$. The percentage of error provided by model 1 is about 2.53 percent, whereas models 2 and 3 provide an error of 0.48 percent and 0.07 percent, respectively. Compared to the corresponding estimation error (2.61 percent) of using model 1 for the 3-hop connection (please refer to Table 2), the above results indicate that the estimation error of adopting model 1 will likely increase with the increase of path hop length. When the network nodes have full wavelength conversion capability, the difference between model 1 and model 2/model 3 becomes significant only when ρ is large. This is due to the fact that when the network nodes have the full wavelength conversion capability, the AR scheme achieves very high restoration probability through the first few (nonoverlapped) backup paths (the first and second backup paths in this case, as $H_{1,2} = 0$) for a large range of ρ. However, when ρ is relatively large, the restoration is likely to be performed through the successive backup routes that are correlated. In this case, neglecting the possible correlation among the backup paths will result in a considerable error in the estimation of the restoration probability.

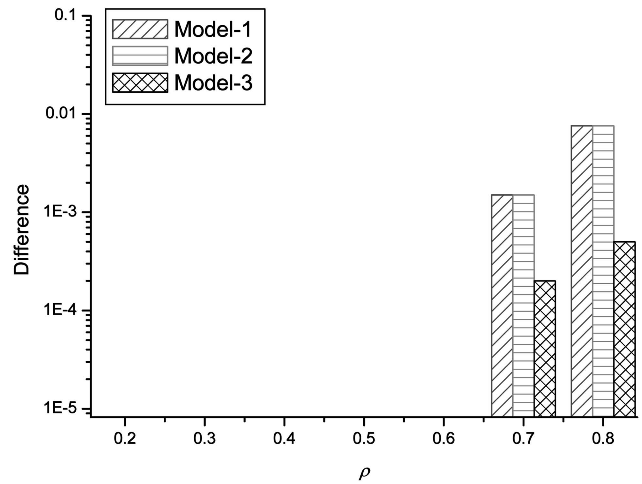
Finally, for the 4-hop connection of EONNET, the results in Table 4 indicate that both models 2 and 3 can provide a very good approximation to the simulated restoration probability for cases with and without wavelength conversion. This is due to the fact that the four backup routes of the 4-hop connection all share two common links (please refer to Table 1), so both models 2 and 3 have the capability to capture such a common correlation.

To show how significant the improvement in the restoration probability computation is as opposed to the increase in complexity between model 1/model 2 and model 3, we plot the error difference in the restoration probability estimation introduced by models 1, 2, and 3 for the 3-hop connection request in the NSFNET for the cases without and with wavelength conversion capability in Figs. 6a and 6b, respectively. The corresponding results for the 4-hop connection of EONNET and the 5-hop connection of ITALIANNET are shown in Figs. 7 and 8, respectively.

The results in Figs. 6a and 6b show that although models 1 and 2 overestimate the restoration probability of the 3-hop connection for both cases without wavelength conversion and with full wavelength conversion, the difference in the restoration probability estimation introduced by model 1/model 2 is relatively smaller than that when using the wavelength conversion capability, which indicates that the effect of neglecting the possible correlation among the successive backup routes of a connection becomes less significant if the network has a wavelength conversion capability. The results in Fig. 7 show clearly that when the backup routes are highly correlated (two common hops in this case; please refer to Table 1), model 1 results in a significant error in the restoration probability estimation. However, this error is reduced to some extent by considering model 2 and, finally, this error is significantly decreased by adopting model 3. The results in Figs. 8a and 8b further indicate clearly that by considering only the possible correlation among any three successive backup routes, our proposed model (model 3) always provides a very close estimation to the restoration probability obtained by simulation.



(a)



(b)

Fig. 6. Restoration probability difference between analytical models and simulation for the 3-hop connection of NSFNET. (a) Without wavelength conversion. (b) With full wavelength conversion.

Hereafter, model 3 will be adopted to investigate into the inherent relationship among restoration probability, wavelength channel utilization ratio, number of wavelengths per fiber, routes hop length, and wavelength conversion capability.

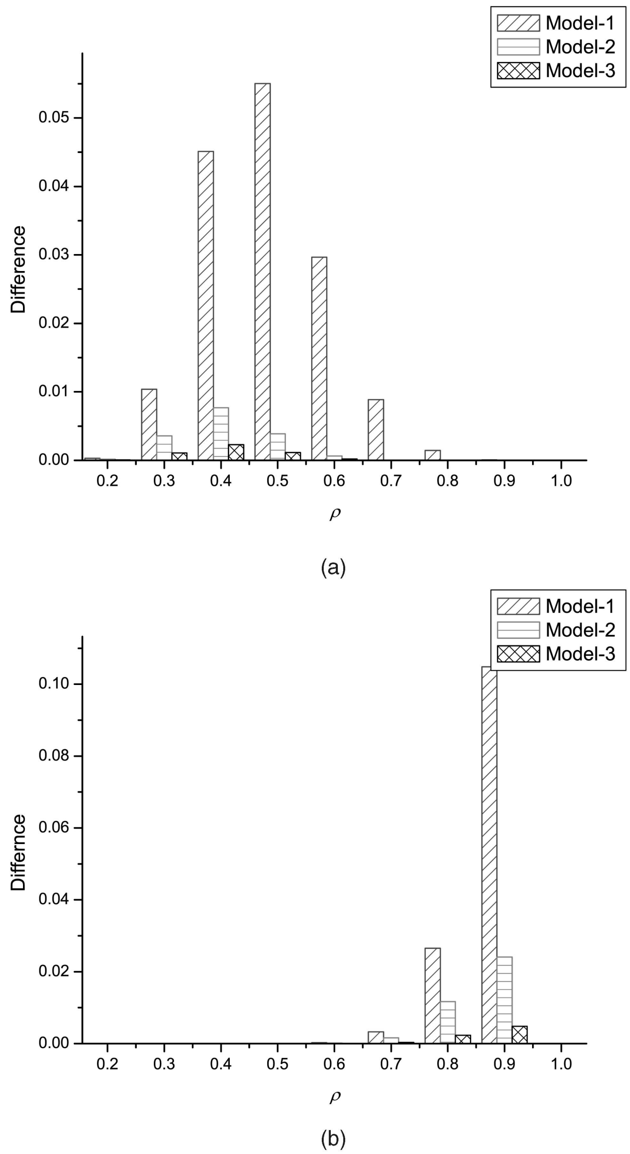


Fig. 7. Restoration probability difference between analytical models and simulation for the 4-hop connection of EONNET. (a) Without wavelength conversion. (b) With full wavelength conversion.

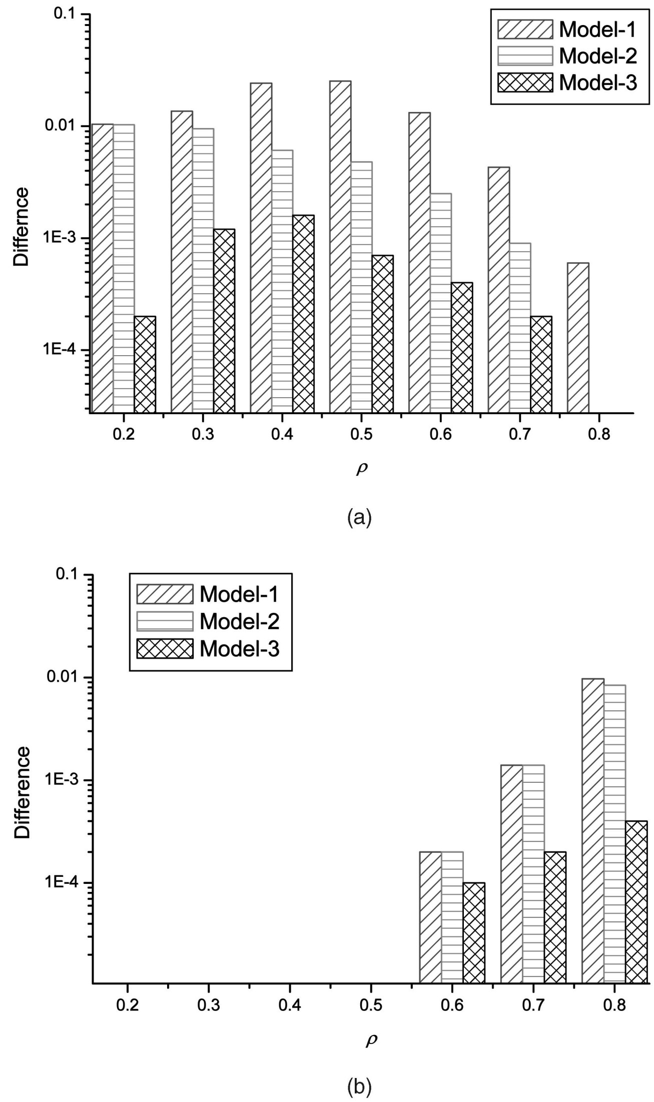


Fig. 8. Restoration probability difference between analytical models and simulation for the 5-hop connection of ITALIANNET. (a) Without wavelength conversion. (b) With full wavelength conversion.

6.2 Discussions

In this section, we investigate the effects of the path hop length, wavelength channel utilization ratio, and number of wavelength channels per fiber and the benefit of using the full wavelength conversion capability upon the restoration probability.

6.2.1 Effects of Path Length, Number of Wavelength Channels per Fiber, and Wavelength Conversion Capability

When ω is in the set 8, 16, and the network nodes have no wavelength conversion capability, a comparison between the restoration probability of the 3-hop connection in the NSFNET and the 2 and 5-hop connections in the ITALIANNET is summarized in Fig. 9. The corresponding comparison for the case of using full wavelength conversion is shown in Fig. 10.

The results in Fig. 9 also show that for a given value of ρ, increasing the number of wavelength channels per fiber from 8 to 16 results in a significant improvement in the restoration behavior of a connection. For example, for the 3-hop connection, when $\rho = 0.4$ and $\omega = 8$, the restoration probability is 0.8013. Doubling the number of wavelength channels supported by the fiber leads to a restoration probability of 0.9482, which is equivalent to an improvement of 15.5 percent in the restoration behavior.

The restoration probability plots depicted in Fig. 10 reveal the fact that setting the network nodes with the full wavelength conversion capabilities improves the network performance significantly. For the 5-hop connection with $\rho = 0.5$, the restoration probabilities are 0.9929 and 1.0 for $\omega = 8$ and $\omega = 16$, respectively. However, the corresponding results for the case without wavelength conversion capabilities (Fig. 9) are 0.2470 and 0.3308, respectively, which is equivalent to improvement of 75.1 percent and 66.9 percent, respectively.

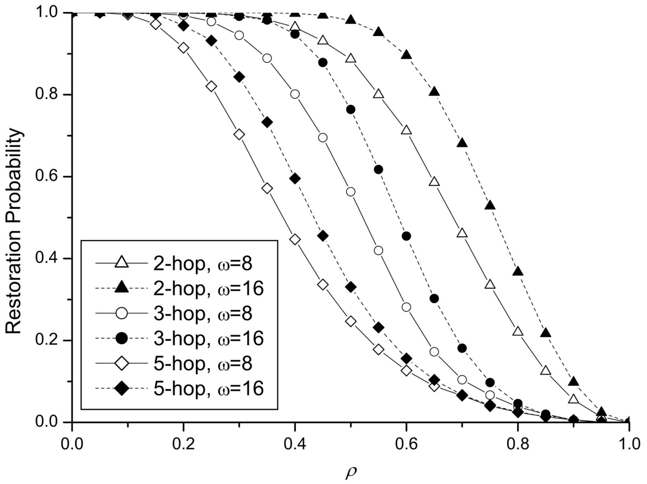


Fig. 9. Restoration probability versus ρ for the case without wavelength conversion.

The comparison in Figs. 9 and 10 all indicate clearly that a connection request with a relatively small number of hops has a higher probability to be restored in the event of failure than that of a connection with a larger hop length. This is because it becomes less likely to find a free wavelength on all hops of a backup path as the number of hops increases. A similar behavior has also been observed for the blocking probability in WDM networks [29].

It also worth noting that for networks with full wavelength conversion, increasing the number of wavelength channels per fiber has less effect than that when the network has no conversion capability. For example, for the 3-hop connection, when $\rho = 0.4$, and $\omega = 8$, increasing the number of wavelength channels by twofold raises the restoration probability from 0.9991 to 1.0, which is equal to an improvement of 0.09 percent. Although the corresponding improvement in the absence of the wavelength conversion capability is 15.5 percent, we cannot say that increasing the number of wavelength channels while using the full wavelength conversion capability has a negligible effect on improving the restoration probability. However, the results in Fig. 10 show that at high values of ρ, doubling

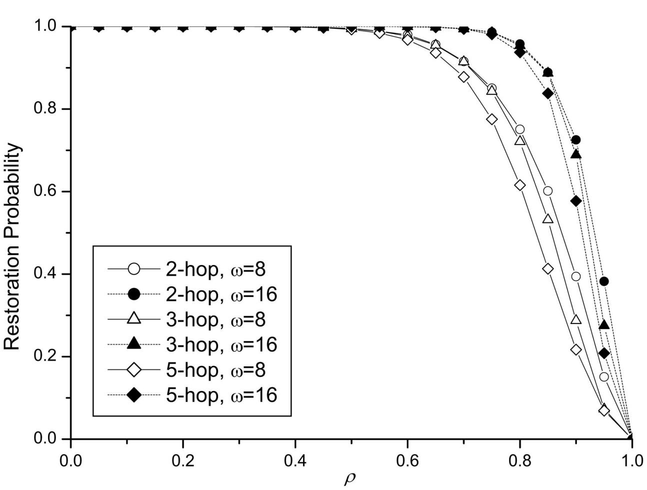


Fig. 10. Restoration probability versus ρ for the case with full wavelength conversion.

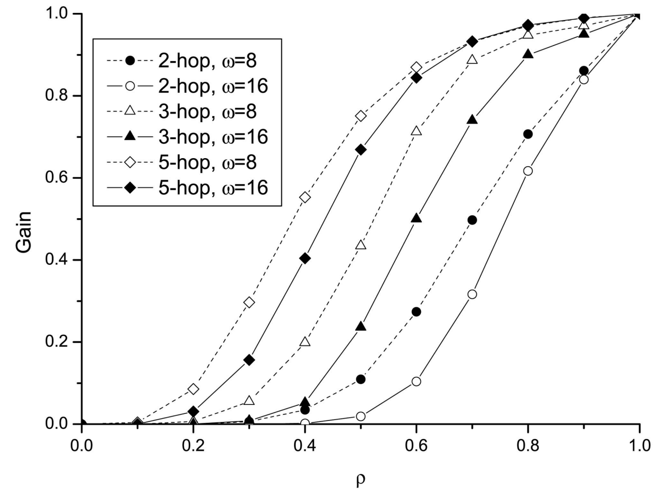


Fig. 11. Gain of using the wavelength conversion.

the number of wavelength channels in the presence of the wavelength conversion capability has a significant improvement on the restoration behavior of a connection.

6.2.2 Gain

To determine qualitatively the benefit of using the wavelength converters, we introduce the gain G of restoration probability, which is defined as follows:

$$G = \frac{P_{WC}(r) - P_{NC}(r)}{P_{WC}(r)},$$

where $P_{WC}(r)$ and $P_{NC}(r)$ are the restoration probabilities with full wavelength conversion and without wavelength conversion, respectively. Fig. 11 illustrates the variations of G with the increase of ρ for NSFNET and ITALIANNET. The results in Fig. 11 indicate that for a small value of ρ, the benefit of using the full wavelength conversion capability in the network is insignificant. However, with increasing the value of ρ, this benefit becomes very significant. The gain plots in Fig. 11 also show that when $\rho = 0.6$, and $\omega = 16$, the benefits of using the full wavelength conversion capabilities are 0.1040 and 0.8440 for the 2-hop and 5-hop connections, respectively. This indicates that although the longer path length has a negative effect on the restoration probability, it results in a better utilization of the wavelength conversion capability.

In summary, the above results indicate clearly that by considering at most the correlation among any three successive backup routes of a connection, model 3 is quite efficient for approximating the restoration probability of a network employing AR. The analysis based on our new model indicates that in an AR-based network, the restoration probability of a connection with a longer path length is lower than that of the connection with a shorter path length, and the restoration probability increases with the increasing of number of supported wavelength channels per fiber, as well as adopting the conversion.

7 Conclusion

In this paper, we studied the restoration behavior of an AR-based optical network by developing the corresponding models for estimating the restoration probability of a connection with the consideration of possible correlation among the backup routes of the connection. The proposed models (especially model 3) can achieve a graceful trade-off between computation complexity and estimation accuracy for analyzing the restoration probability, as demonstrated by both the theoretical analysis and simulation study. The proposed models reveal the inherent relationship among the restoration probability, wavelength channel utilization ratio, number of wavelength channels per fiber, path length, and wavelength conversion capability and, thus, it can be adopted to display the trade-off among them. Our study indicates that the effect of neglecting the inherent correlation among backup routes is not significant for a connection with a short hop length and with the full wavelength conversion capability. However, this effect may cause significant errors in approximating the restoration probability for the network without the wavelength conversion capability, especially for the connections with a longer primary path in terms of the number of hops. In the latter case, our new models should be adopted to provide a much close approximation to the restoration probability. It is expected that the analytical approach developed in this paper will also be helpful for performance modeling of other kinds of survivable optical networks where the routes correlation needs to be considered in the analysis.

Notice that our AR was developed for traffic restoration in case of single lightpath failure in a certain link. Since the fiber cut on a fiber (link) is likely the most common network failure, where all the lightpaths going through this link will be affected instead of only one, one future work is to extend our AR scheme to more general fiber cut scenarios and develop the corresponding analytical models for restoration probability. The analytical models in this paper were developed under Birman's famous analysis framework for blocking probability of optical WDM networks [20], where the standard wavelength channels independent assumption was adopted. Notice that this assumption is not very realistic, especially for optical WDM networks that do not deploy wavelength conversion and, thus, have wavelength continuity constraint. Therefore, another further work is to extend the models in this paper to further incorporate the correlation among wavelength channels on each link (caused by the wavelength continuity constraint), in addition to the correlation among backup paths (caused by the shared links). Notice also that the models in this paper were developed for the networks with full wavelength conversion and the networks without wavelength conversion at all. Since another more general wavelength conversion scenario is the sparse wavelength conversion, where only some network nodes have the wavelength conversion capability. Therefore, the third future work can be the investigation of the impact of sparse wavelength conversion and the placement of wavelength converters on the restoration probability in AR-based optical networks.

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REFERENCES

[1] D. Papadimitriou, F. Poppe, S. Dharanikota, R. Hartani, R. Jain, J. Jones, S. Venkatachalam, and Y. Xue, *Shared Risk Link Groups Inference and Processing*, Internet draft, work in progress, June 2003.

[2] W.D. Grover and D. Stamatelakis, "Cycle-Oriented Distributed Preconfiguration: Ring-Like Speed with Mesh-Like Capacity for Self-Planning Network Restoration," *Proc. IEEE Int'l Conf. Comm. (ICC '98)*, 1998.

[3] W.D. Grover and D. Stamatelakis, "Bridging the Ring-Mesh Dichotomy with P-Cycles," *Proc. Second Int'l Workshop Design of Reliable Comm. Networks (DRCN '00)*, 2000.

[4] D. Stamatelakis and W.D. Grover, "IP Layer Restoration and Network Planning Based on Virtual Protection Cycles," *IEEE J. Selected Areas in Comm.*, vol. 18, Oct. 2000.

[5] T.Y. Chow, F. Chudak, and A.M. Ffrench, "Fast Optical Layer Mesh Protection Using Pre-Cross-Connected Trails," *IEEE/ACM Trans. Networking*, vol. 12, no. 3, pp. 539-548, June 2004.

[6] K. Owens, V. Sharma, S. Makam, C. Huang, and B. Akyol, *Extensions to RSVP-TE for MPLS Path Protection*, Internet draft, work in progress, July 2001.

[7] P. Pan, D.-H. Gan, G. Swallow, J.-P. Vasseur, D. Cooper, A. Atlas, and M. Jork, *Fast Reroute Extensions to RSVP-TE for LSP Tunnels*, Internet draft, work in progress, Jan. 2002.

[8] L. Sahasrabuddhe, S. Ramamurthy, and B. Mukherjee, "Fault Management in IP-over-WDM Networks: WDM Protection versus IP Restoration," *IEEE J. Selected Areas in Comm.*, vol. 20, no. 1, Jan. 2002.

[9] P.-H. Ho and H.T. Mouftah, "A Framework of Service Guaranteed Shared Protection for Optical Networks," *IEEE Comm. Magazine*, pp. 97-103, Feb. 2002.

[10] S. Ramamurthy and B. Mukherjee, "Survivable WDM Mesh Networks, Part I—Protection," *Proc. IEEE INFOCOM '99*, vol. 2, pp. 744-751, 1999.

[11] D. Zhou and S. Subramaniam, "Survivability in Optical Networks," *IEEE Network*, vol. 14, no. 6, pp. 16-23, Nov/Dec. 2000.

[12] G. Maier, S. De Patre, A. Patavina, and M. Martinelli, "Optical Network Survivability: Protection Techniques in the WDM Layer," *Photonic Network Comm.*, vol. 4, nos. 3/4, pp. 251-269, July-Dec. 2002.

[13] C. (Sam) Ou, H. Zang, N.K. Singhal, K. Zhu, L.H. Sahasrabuddhe, R.A. MacDonald, and B. Mukherjee, "Subpath Protection for Scalability and Fast Recovery in Optical WDM Mesh Networks," *IEEE J. Selected Areas in Comm.*, vol. 22, no. 9, Nov. 2004.

[14] G. Mohan, C.S.R. Murthy, and A.K. Somani, "Algorithms for Routing Dependable Connections in WDM Optical Networks," *IEEE/ACM Trans. Networking*, vol. 9, no. 5, pp. 553-566, Oct. 2001.

[15] S. Ramamurthy and B. Mukherjee, "Survivable WDM Mesh Networks, Part II—Restoration," *Proc. IEEE Int'l Conf. Comm. (ICC '99)*, vol. 3, pp. 2023-2030.

[16] G. Mohan and C.S.R. Murthy, "Lightpath Restoration in WDM Optical Networks," *IEEE Network*, vol. 14, no. 6, pp. 24-32, Nov./Dec. 2000.

[17] M.M.A. Azim, X. Jiang, P.-H. Ho, M.M.R. Khandker, and S. Horiguchi, "Active Lightpath Restoration in WDM Networks," *OSA J. Optical Networking*, vol. 3, no. 4, pp. 247-260, Apr. 2004.

[18] M.M.A. Azim, X. Jiang, P.-H. Ho, and S. Horiguchi, "Models of Restoration Probability in WDM Networks Employing Active Restoration," *J. Photonic Network Comm.*, vol. 10, no. 2, pp. 141-153, Sept. 2005.

[19] A. Harjani and S. Ramasubramanian, "DIVERSION: A Trade-Off between Link and Path Protection Strategies in Optical Networks," *Proc. Ninth Conf. Optical Network Design and Modeling (ONDM '05)*, 2005.

[20] A. Birman, "Computing Approximate Blocking Probabilities for a Class of All-Optical Networks," *IEEE J. Selected Areas in Comm.*, vol. 14, no. 5, pp. 853-857, June 1996.

[21] R.A. Barry and P.A. Humblet, "Models of Blocking Probability in All-Optical Networks with and without Wavelength Changers," *IEEE J. Selected Areas in Comm.*, vol. 14, no. 5, pp. 858-867, June 1996.

[22] A. Sridharan and K.N. Sivarajan, "Blocking in All-Optical Networks," *Proc. INFOCOM '00*, pp. 990-999, 2000.

[23] T. Tripathi and K.N. Sivarajan, "Computing Approximate Blocking Probabilities in Wavelength Routed All-Optical Networks with Limited-Range Wavelength Conversion," *IEEE J. Selected Areas in Comm.*, vol. 18, no. 10, pp. 2123-2129, Oct. 2000.

[24] L. Li and A.K. Somani, "A New Analytical Model for Multifiber WDM Networks," *IEEE J. Selected Areas in Comm.*, vol. 18, no. 10, pp. 2138-2145, June 1996.
[25] K. Lu, G. Xiao, and I. Chlamtac, "Blocking Analysis of Dynamic Lightpath Establishment in Wavelength-Routed Networks," *Proc. IEEE Int'l Conf. Comm. (ICC '02)*, vol. 5, pp. 2912-2916, 2002.
[26] C. Lee, "Analysis of Switching Networks," *Bell System Technical J.*, vol. 34, pp. 1287-1315, Nov. 1955.
[27] S. Subramaniam, M. Azizoglu, and A.K. Somani, "All-Optical Networks with Sparse Wavelength Conversion," *IEEE/ACM Trans. Networking*, vol. 4, no. 4, pp. 544-557, Aug. 1996.
[28] W. Grover, J. Doucette, M. Clouqueur, D. Leung, and D. Stamatelakis, "New Options and Insights for Survivable Transport Networks," *IEEE Comm. Magazine*, vol. 40, no. 1, pp. 34-41, Jan. 2002.
[29] R. Ramaswami and K.N. Sivarajan, "Routing and Wavelength Assignment in All-Optical Networks," technical report, IBM T.J. Watson Research Center, 1993.

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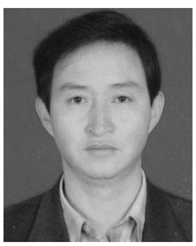

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