Global Versus Essential Post-Disaster Re-Provisioning in Telecom Mesh Networks

Ning-Hai Bao, M. Farhan Habib, Massimo Tornatore, Charles U. Martel, and Biswanath Mukherjee

I. Introduction

As Internet traffic continues to grow rapidly, wavelength-division multiplexing (WDM) optical networks with ultra-high capacity maintain their important role in telecom backbone infrastructures, and are growing in scale and complexity. In such networks, even a single optical fiber cut may lead to a huge amount of traffic disruption and revenue loss, so optical network survivability is a major concern for network operators and attracts a lot of attention from researchers in industry and academia.

In general, technologies for network survivability are classified into two categories: protection [1] and restoration [2]. Protection proactively reserves backup resources to protect service connections against specific types of failures; it can provide fast service recovery time, but it is very resource-intensive. Restoration reactively deploys available resources to recover the disrupted service connections, and it is resource-efficient but time-consuming.

Over the past decade, protection schemes against random single/double-link failures have been the subject of comprehensive research in optical networking [3–5]. However, given the growing importance of network services for our society, in recent years, research has been moving toward new techniques to guarantee some degree of survivability even against large-scale threats, such as natural disasters (earthquake, hurricane, tsunami, etc.) and targeted attacks (weapons of mass destruction). These disasters may simultaneously affect many network components (nodes and/or links) and cause multiple correlated-failure scenarios [6]. Moreover, after a disaster occurs, typically a large amount of traffic carrying urgent communications for rescue operations or pressing inquires about the disaster situations will rapidly emerge in the network. Any connection disruption may cause serious loss of lives and properties. Effectively maintaining the network connectivity and maximizing the traffic flow becomes the most important issue at that time.

Although researchers have proposed many backup-resource-sharing strategies to improve the network resource

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efficiency [7–9], the traditional protection schemes, based on providing backup paths for working paths, sub-paths, or links, cannot handle complex disaster-failure scenarios with reasonable resource costs and a 100% reliability guarantee.

A. Relevant Work

To better protect traffic from large/regional failures in optical networks, the authors of [10] proposed an ellipse-underlay algorithm to increase the "distance" between the working and backup paths by an elliptic isolation region. Compared with node-disjoint path-protection schemes, this region-disjoint path-protection scheme can achieve better survivability of traffic in the case of regional failures. In realistic disaster events, part of the network components may fail with different probabilities (which are usually related to factors such as the disaster's location, distance from the epicenter, and intensity). The authors of [11] defined the concept of the probabilistic shared-risk link group (PSRLG) and proposed mathematical formulations and heuristic algorithms to find working/backup path pairs to minimize their joint failure probability. Unfortunately, even though increasing the space isolation of the two paths can improve the reliability of connections, bypassing a wide high-risk region may yield longer detour paths leading to low resource efficiency. For this concern, the authors of [12] took both the PSRLG model and traffic engineering into account, and proposed a load-balanced path-pair protection scheme to solve the multi-failure scenarios with improved resource efficiency. The authors of [13] developed a probabilistic risk model to evaluate the penalty of possible disasters and proposed a traffic-engineering solution for disaster protection in optical telecom networks.

The approaches [11–13] based on risk-aware routing diversity can be referred to as "risk isolation" strategies. Another possible strategy to combat multi-failure scenarios is "risk dispersion," typically based on multipath routing. Benefiting from virtual concatenation (VCAT) and the link-capacity adjustment scheme (LCAS) [14,15], a connection can be inversely multiplexed onto multiple paths, and the capacity of this connection can be dynamically changed by increasing or decreasing the number of paths. In [16], a region-disjoint self-protecting multipath routing scheme was studied to optimize network traffic throughput under the region-failure scenario. The authors of [17] proposed a novel and effective multipath bandwidth concept to solve the connection availability and traffic-flow maximization problem with adaptability to any number of failures. Intuitively, from a fault-tolerance point of view, provisioning a connection over multiple disjoint paths can decrease the risk of complete disruption of a connection, but it may be hard to provide a 100% protection guarantee, especially if the total bandwidth of the multiple paths has to be equal to or larger than the demanded bandwidth [18]. In such cases protection schemes based on bandwidth degradation (i.e., providing partial bandwidth guarantee) can represent an effective solution.

Another approach, called backup re-provisioning, was proposed to protect the network against multiple sequential failures; i.e., a new failure occurs before a previous failure is repaired [19,20]. In [19], two backup re-provisioning schemes were proposed. The first re-provisions new backup paths for only the connections losing their working paths or backup paths in a previous failure (called essential re-provisioning). The second re-provisions backup paths after a failure for (possibly) all the connections, with the aim of improving resource efficiency (called global re-provisioning). The authors of [20] proposed three different backup re-provisioning policies according to various degrees of SRLG constraints, and the numerical results demonstrated that preferentially re-provisioning the connections whose working paths traverse more SRLGs can achieve higher recovery ratios. However, these backup re-provisioning schemes may still be ineffective in a disaster event as they cannot handle multiple simultaneous failures. In particular, when the network resources become extremely scarce, re-provisioning backup paths for the survived connections might not be possible.

The authors of [21] proposed a novel disaster-recovery-aware multistate multipath provisioning (DREAM-MP) algorithm, which provisions each connection over multiple paths (one of which is reserved as a backup path). As a hybrid of protection and restoration, DREAM-MP protects connections by backup paths for single-link failures and re-provisions affected connections with full or degraded bandwidth for large-scale failure scenarios. However, the unaffected connections always keep their backup paths even during the post-disaster re-provisioning phase. If these backup paths can be released, available network resources will be increased and more disrupted connections may be re-provisioned successfully.

B. Motivation

So far, many survivability schemes have been proposed to combat multi-failure scenarios, and, as discussed above, most are protection schemes. Although these schemes may allow the network to survive in some given multi-failure scenarios, they are unable to solve various disaster-failure scenarios with reasonable resource costs and a complete reliability guarantee. In such cases, i.e., when a protection method cannot properly address some multi-failure scenarios, a restoration scheme that reactively deploys available resources to recover the disrupted connections would be the last-stop solution [22].

In this paper, we investigate novel restoration schemes for optical networks to be used in the post-disaster phase. During this phase, there are generally two major concerns: how to maintain network connectivity and how to maximize traffic flow. For simplicity, we assume that a connection is a single lightpath with a certain amount of bandwidth provided by the optical layer to carry the total traffic flow between a node pair. Also, other issues such as how to assign the connection bandwidth to different classes of services are out of the scope of our research work.

The rest of this paper is organized as follows: in Section II, we introduce two basic re-provisioning methods using simple examples. In Section III, we present mixed integer linear program (MILP) formulations for the no-degradation re-provisioning (NDR) scheme, the degradation-as-needed re-provisioning (DAN) scheme, and the fairness-aware degradation re-provisioning (FAD) scheme. In Section IV, numerical results are presented and analyzed. Section V concludes this paper.

II. Examples of Basic Re-Provisioning Methods

One of the most challenging problems in the post-disaster phase is that re-provisioning the disrupted connections in the residual network may become difficult due to lack of available resources. So, in this section, we illustrate two basic re-provisioning methods, i.e., the rerouting method and the bandwidth degradation method. For both Figs. 1 and 2, we assume a network topology with 6 nodes and 7 links. The bandwidth of each link is 8 units. Hereafter, we mark the connection between node s and node d as $C_{s,d}$, and mark the path a-b-c as $P_{a\text{-}b\text{-}c}$.

In Fig. 1(a), before disaster occurs, there are five connections provisioned in the network, viz. connection $C_{1,4}$ on path $P_{1\text{-}2\text{-}4}$ with 4 W bandwidth, $C_{1,5}$ on $P_{1\text{-}3\text{-}5}$ with 3 W, $C_{2,6}$ on $P_{2\text{-}4\text{-}6}$ with 4 W, $C_{2,5}$ on $P_{2\text{-}5}$ with 5 W, and $C_{3,6}$ on $P_{3\text{-}5\text{-}6}$ with 4 W. Assuming node 4, link 2–4 represents the link between node 2 and node 4, and link 4–6 represents the link between node 4 and node 6 are damaged in a regional disaster; thus $C_{1,4}$ and $C_{2,6}$ are disrupted simultaneously. Obviously, $C_{1,4}$ will be lost permanently due to its destination node failure, but also $C_{2,6}$ cannot be re-provisioned due to a lack of enough available bandwidth on the alternate paths $P_{2\text{-}5\text{-}6}$ and $P_{2\text{-}1\text{-}3\text{-}5\text{-}6}$. But, as shown in Fig. 1(b), if we reroute $C_{1,5}$ along $P_{1\text{-}2\text{-}5}$ and $C_{2,6}$ along $P_{2\text{-}1\text{-}3\text{-}5\text{-}6}$, respectively, both connections can be successfully re-provisioned with full bandwidth. Although $C_{1,5}$ gets temporarily interrupted during the re-provisioning, it may be preferable to have a short interruption for $C_{1,5}$ than to completely lose $C_{2,6}$.

However, rerouting connections might not always be enough to restore connectivity. In Fig. 2(a), five connections are provisioned in the network: connection $C_{1,5}$ on path $P_{1\text{-}3\text{-}5}$ with 4 W bandwidth, $C_{1,6}$ on $P_{1\text{-}2\text{-}4\text{-}6}$ with 5 W, $C_{2,5}$ on $P_{2\text{-}5}$ with 4 W, $C_{2,6}$ on $P_{2\text{-}5\text{-}6}$ with 4 W, and $C_{3,6}$ on $P_{3\text{-}5\text{-}6}$ with 3 W. After the disaster occurs, $C_{1,6}$ is disrupted. Obviously, we cannot re-provision $C_{1,6}$ with full bandwidth. But re-provisioning $C_{1,6}$ along $P_{1\text{-}3\text{-}5\text{-}6}$ with 1 W can represent a desirable solution to maintain at least partial connectivity, as shown in Fig. 2(b). Thus, the bandwidth of $C_{1,6}$ gets degraded by 80%, which is high and would lead to serious reduction of services on this connection. On the other hand, if we globally adjust the bandwidth of connections, as shown in Fig. 2(c), and if the bandwidths of $C_{2,6}$ and $C_{3,6}$ are degraded to 3 W and 2 W, respectively, then $C_{1,6}$ can be re-provisioned along $P_{1\text{-}3\text{-}5\text{-}6}$ with 3 W and its degradation ratio is reduced to 40%, while the connections $C_{1,5}$, $C_{2,6}$, and $C_{3,6}$ lose 25%, 25%, and 33% of their bandwidth, respectively. Although the total traffic in Fig. 2(c) is 5% lower than that in Fig. 2(b), the scheme in Fig. 2(c) can effectively increase the bandwidth available for connection $C_{1,6}$ and balance available bandwidth among connections.

In conclusion, 1) re-provisioning working paths by rerouting and 2) bandwidth degradation are crucial tools to develop post-disaster restoration strategies.

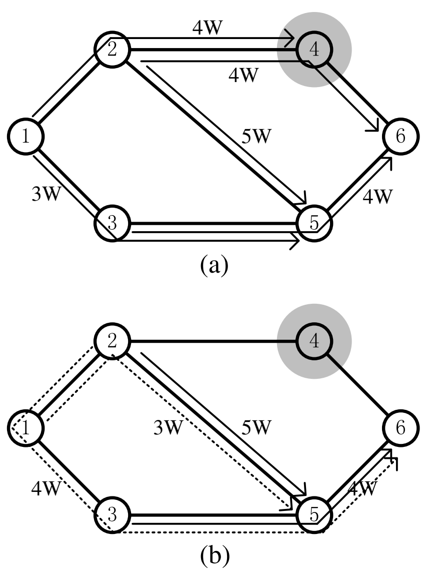

Fig. 1. Example for rerouting method.

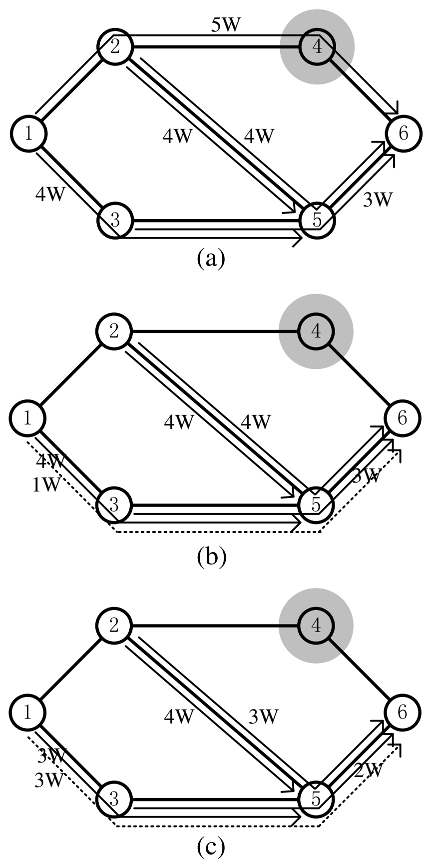

Fig. 2. Example for bandwidth degradation method.

To study the effects of rerouting and bandwidth degradation to maintain network connectivity and maximize traffic flow in the post-disaster optical network, we propose three re-provisioning schemes: 1) NDR, which re-provisions connections but keeps the original full bandwidth; 2) DAN, which re-provisions connections by allowing bandwidth degradation while maximizing the carried flow and the amount of connections; and 3) FAD, which re-provisions connections (as in DAN) by allowing bandwidth degradation but applies a fair redistribution of the bandwidth degradation. We study these post-disaster re-provisioning strategies considering both essential re-provisioning and global re-provisioning [19], and we discuss the pros and cons of the different schemes.

III. Mathematical Formulations

In this section, we provide MILP formulations that can either maximize the number of surviving connections for the post-disaster optical network or maximize the traffic flow of each connection as well.

A. Network Model and Notations

We consider a mesh network represented as a graph $G(N, E)$. N is the set of nodes in which each node has full wavelength conversion capability. E is a set of bidirectional links in which each link has a fixed number of wavelengths. The traffic demand consists of $|C|$ connection requests, and each connection is provisioned with some wavelengths along a single path. Before a disaster occurs, all traffic demands have been provisioned in the network. In the post-disaster phase, the connections whose source node or destination node has been affected by the disaster are disregarded for re-provisioning purposes. The notations employed for our MILP formulations are listed below.

Input parameters:

- E: set of links in the network.
- C: set of connections in the network.
- $S(\subset C)$: set of connections existing/survived during the disaster.
- K_c: set of K pre-computed candidate paths for connection c (after a disaster occurs, the interrupted paths will be removed for this set).
- P_e: set of paths going through link e, $e \in E$.
- W: integer, total number of wavelengths on each link.
- M: integer with big value, such as 10^5.
- b_c: original traffic demand of connection c.
- $y_{c,k}$: binary; it takes the value of 1 if connection c is on path k before the disaster occurs; otherwise 0.
- γ: decimal, upper-bound percentage of rerouted connections in set S.

Output variables:

- λ_c: integer, used to indicate the traffic flow of connection c.
- α_c: decimal, used to indicate the ratio of actual bandwidth over original bandwidth for connection c. Thus, $(1 - \alpha_c)$ is defined as the bandwidth degradation ratio of connection c. It is employed in FAD only.
- $\alpha_{\max}$: maximum value of α_c. It is only employed in FAD.
- $\alpha_{\min}$: minimum value of α_c. It is only employed in FAD.
- β_c: binary; it takes the value of 1 if the bandwidth of connection c is equal to b_c; it takes the value of 0 if the bandwidth of connection c is equal to 0. It is only employed in NDR.
- $r_{c,k}$: integer, used to indicate the bandwidth of connection c on path k.
- $x_{c,k}$: binary; it takes the value of 1 if connection c is on path k after all post-disaster re-provisioning operations; otherwise 0.
- $h_{c,k}$: binary; it takes the value of 1 if $x_{c,k}$ is not equal to $y_{c,k}$; otherwise 0.
- h_c: binary; it takes the value of 1 if connection c, $(c \in S)$ is rerouted during the post-disaster re-provisioning phase; otherwise 0.

B. Mathematical Formulations

1) MILP Formulation for NDR:
Objective Function:

$$\text{Maximize:} \sum_{c \in C} \lambda_c - \frac{1}{M} \cdot \sum_{c \in S} h_c. \tag{1}$$

In objective function (1), the first term maximizes the total traffic flow of connections in the residual network. The second term minimizes the number of rerouted connections, in case there are multiple solutions with the same amount of traffic flows.

Subject to constraints:

$$\lambda_c = \beta_c \cdot b_c, \quad \forall\, c \in C. \tag{2}$$

Constraint (2) guarantees that all re-provisioned connections must be assigned with full bandwidth as demanded. Otherwise, the connections without enough available bandwidth will be discarded.

$$\sum_{k \in K_c} r_{c,k} = \lambda_c, \quad \forall\, c \in C. \tag{3}$$

Constraint (3) ensures that the bandwidth of each connection is consistent with the traffic flow carried on that connection.

$$\sum_{(c,k) \in P_e} r_{c,k} \le W, \quad \forall\, c \in C, \quad k \in K_c, \quad e \in E. \tag{4}$$

Constraint (4) ensures that the total bandwidth consumed on each link will not exceed the bandwidth limitation on that link.

$$x_{c,k} \le r_{c,k}, \quad \forall\, c \in C, \quad k \in K_c, \tag{5}$$

$$x_{c,k} \ge r_{c,k}/M, \quad \forall\, c \in C, \quad k \in K_c. \tag{6}$$

Constraints (5) and (6) are utilized to normalize integer variable $r_{c,k}$ to binary variable $x_{c,k}$.

$$\sum_{k\in K_c} x_{c,k} \le 1, \quad \forall\, c \in C, \quad k \in K_c. \tag{7}$$

Constraint (7) ensures that each connection can only be provisioned on a single path.

$$h_{c,k} \le x_{c,k} + y_{c,k}, \quad \forall\, c \in S, \quad k \in K_c, \tag{8}$$

$$h_{c,k} \ge x_{c,k} - y_{c,k}, \quad \forall\, c \in S, \quad k \in K_c, \tag{9}$$

$$h_{c,k} \ge y_{c,k} - x_{c,k}, \quad \forall\, c \in S, \quad k \in K_c, \tag{10}$$

$$h_{c,k} \le 2 - x_{c,k} - y_{c,k}, \quad \forall\, c \in S, \quad k \in K_c. \tag{11}$$

Constraints (8)–(11) are implemented as an exclusive OR (XOR) operation to check whether a state change of the kth candidate path of connection c ($c \in S$) has occurred due to the re-provisioning by XOR-ing variables $x_{c,k}$ and $y_{c,k}$.

$$h_c \le \sum_{k\in K_c} h_{c,k}, \quad \forall\, c \in S, \tag{12}$$

$$h_c \ge \frac{1}{M} \cdot \sum_{k\in K_c} h_{c,k}, \quad \forall\, c \in S. \tag{13}$$

Constraints (12) and (13) are used to normalize $\sum_{k\in K_c} h_{c,k}$ to h_c. The binary variable h_c records whether the connection c ($c \in S$) is rerouted due to the re-provisioning.

$$\sum_{c\in S} h_c \le \gamma \cdot |S|. \tag{14}$$

Constraint (14) sets an upper bound to restrict the maximum number of survived/existing connections that can be rerouted during the post-disaster re-provisioning phase.

2) MILP Formulation for DAN:
Objective Function:

$$\text{Maximize:} \sum_{c\in C} \lambda_c + \sum_{c\in C, k\in K_c} x_{c,k} - \frac{1}{M} \cdot \sum_{c\in S} h_c. \tag{15}$$

In objective function (15), the first term maximizes the total traffic flow. The second term maximizes the number of connections. And the third term minimizes the number of rerouted connections.

Subject to constraints:

$$0 \le \lambda_c \le b_c, \quad \forall\, c \in C. \tag{16}$$

Constraint (16) indicates the possible bandwidth range of each traffic flow. The bandwidth of each connection can be degraded by an integer number of wavelengths as needed. If the bandwidth is degraded to zero, the connection is discarded. The other constraints of DAN are the same as constraints (3)–(14) of NDR.

3) MILP Formulation for FAD:
Objective Function:

$$\text{Maximize:} \frac{1}{|C|} \cdot \sum_{c\in C} \alpha_c - (\alpha_{\max} - \alpha_{\min}) - \frac{1}{M} \cdot \sum_{c\in S} h_c. \tag{17}$$

In objective function (17), the first term maximizes the average traffic flow of the connections in the network. The second term narrows the gap between the maximum and the minimum degradation ratios, which leads to a fair degradation for all connections. The third term minimizes the number of rerouted connections.

Subject to constraints:

$$\alpha_c = \lambda_c / b_c, \quad \forall\, c \in C, \tag{18}$$

$$\alpha_{\max} \ge \alpha_c, \quad \forall\, c \in C, \tag{19}$$

$$\alpha_{\min} \le \alpha_c, \quad \forall\, c \in C. \tag{20}$$

Constraint (18) calculates the variable α_c. Constraints (19) and (20) define the upper bound and the lower bound of variable α_c, respectively. The other constraints of FAD are the same as constraint (16) of DAN and constraints (3)–(14) of the NDR scheme.

The main terms of complexity of the proposed MILP for NDR, DAN, and FAD are $O(K \cdot |N|^2)$ in terms of the number of variables and $O(K \cdot |N|^2 \cdot |E|)$ in terms of the number of constraints, where K is the number of pre-computed candidate paths for each connection, $|N|$ is the number of nodes, and $|E|$ is the number of links. Note that the average running time of the problem mostly depends on constraint (14), which restricts the maximum number of rerouted existing connections, thus restricting the possible admissible field of the solutions. In fact, in our simulation work (to be presented in Section IV), we observed that the program running time becomes much higher when the variable γ takes larger values. Therefore, we will consider the development of corresponding heuristic algorithms for large-scale networks as future work.

IV. Numerical Results and Analysis

In this section, we apply the MILP models proposed in the previous section to solve the post-disaster re-provisioning problem in typical mesh network topologies, and we present numerical results to illustrate and compare the performance of the NDR, DAN, and FAD schemes.

As shown in Fig. 3, network I has 8 nodes and 13 links, with each link assumed to have 24 wavelengths. Similarly, network II has 9 nodes and 15 links, with each link assumed to have 32 wavelengths. For each source–destination node pair, 10 candidate shortest paths are pre-calculated by Yen's k-shortest path algorithm [23]. The bandwidth demand of each connection is generated

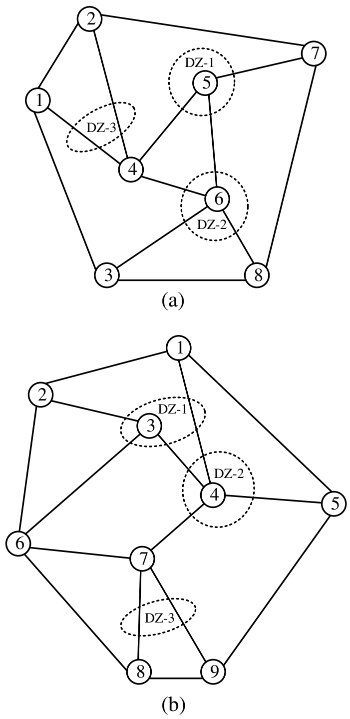

Fig. 3. Test network topologies. (a) Network I. (b) Network II.

randomly between 4 and 8 wavelengths. In this way, for each network, we prepare 30 traffic demand matrices and respectively provision them on the complete network, by which we get 30 sets of pre-disaster network provisioning data. We then identify three sample disaster zones (DZs) for each network, i.e., DZ-1, DZ-2, and DZ-3, assuming that all the network components (nodes and/or links) circled in a disaster zone will be damaged completely and simultaneously during that disaster. The numerical results in Figs. 4–6 are averages over these disaster scenarios.

We consider three performance measures, i.e., the connection loss ratio (CLR), the traffic loss ratio (TLR), and the fairness factor (FF). Note that, in the following definitions of the performance measures, connections whose source nodes or destination nodes are damaged during the disaster are not taken into account. CLR is defined as the number of unrecovered connections divided by the total number of demanded connections in the post-disaster network. TLR is defined as the total amount of degraded bandwidth divided by the total amount of demanded bandwidth in the post-disaster network. FF is defined as the difference between the maximum degradation ratio and the minimum degradation ratio (used only for DAN and FAD).

In the following, we evaluate and compare the performance of the proposed re-provisioning schemes with the measures presented above.

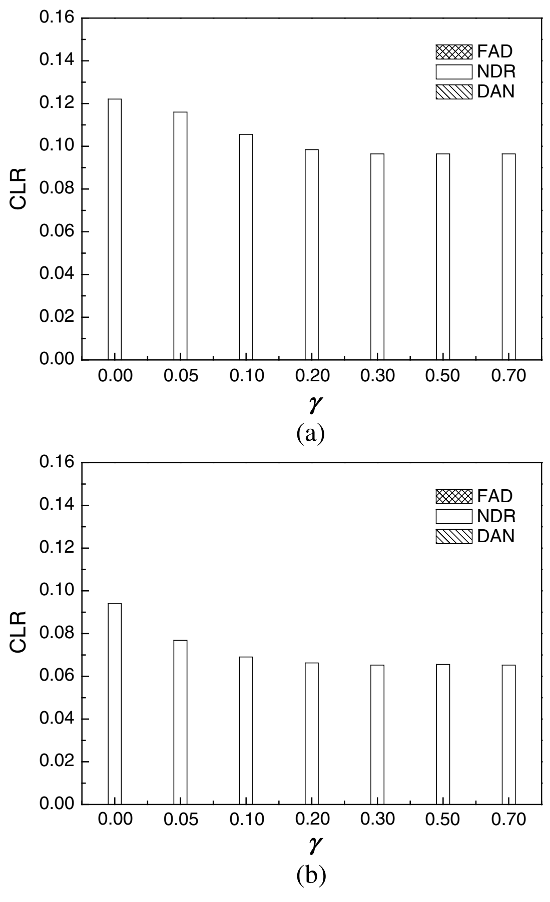

Fig. 4. Effects of γ on connection loss ratio. (a) Network I. (b) Network II.

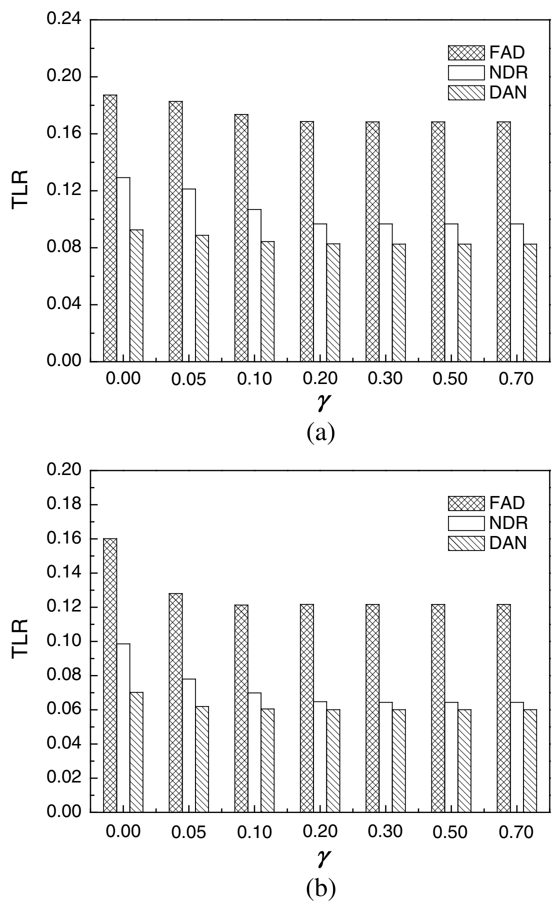

Fig. 5. Effects of γ on traffic loss ratio. (a) Network I. (b) Network II.

In Fig. 4, we see that the CLRs of NDR for networks I and II are 12.2% and 9.4%, respectively, when the parameter γ (upper-bound percentage of rerouted connections) equals 0. As γ increases, the CLRs of NDR gradually reach their best performance. Obviously, for the NDR scheme, rerouting some survived connections can optimize the resource utilization and improve the network connectivity. However, the CLRs of both DAN and FAD are always equal to 0, even if γ is 0, meaning that the bandwidth degradation methods (DAN and FAD) outperform the rerouting method (NDR) in maintaining network connectivity, and in our settings are able to preserve some connectivity for all connections even during a disaster even though the residual network capacity cannot accommodate all connections with full bandwidth.

In Fig. 5, we see that both DAN and NDR perform better than FAD in terms of TLR. The reason is that, as FAD promotes fairness-aware degradation for all connections, long-distance connections will tend to consume more bandwidth resources in the network than short-distance ones. On the contrary, DAN and NDR prefer to assign more bandwidths to short-distance connections for maximizing total traffic flow. We also see that DAN achieves better TLR performance than NDR. This is because, with respect to NDR, DAN can find available bandwidth resources more easily for its adaptive bandwidth degradation. Note that the TLRs of NDR, DAN, and FAD reach their lowest values as soon as γ becomes larger than 20%. This means that rerouting is crucial for resource optimization in all schemes.

In Fig. 6, the FF of DAN is remarkably higher than that of FAD, which means that, under DAN, some connections may lose a large amount of bandwidth and suffer significant reduction of service, while FAD can achieve a fairer distribution of degradation.

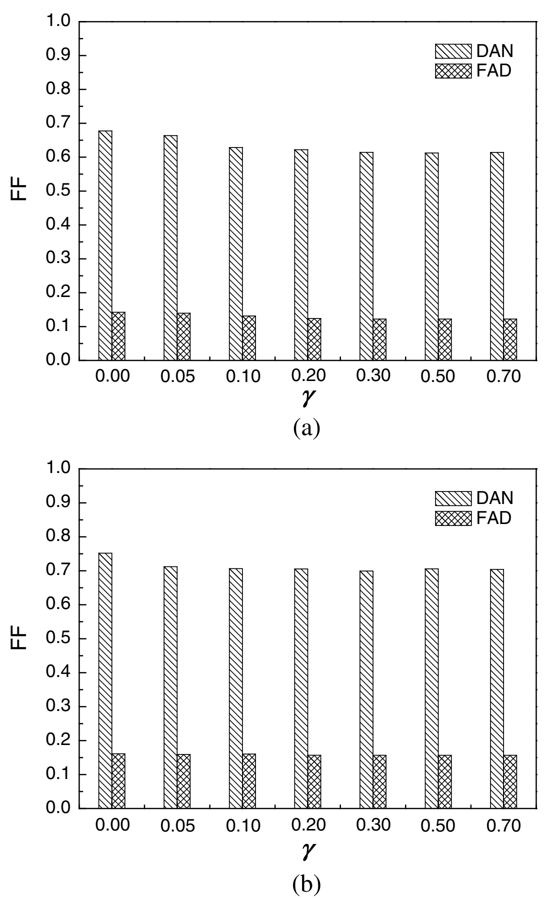

Fig. 6. Effects of γ on fairness factor. (a) Network I. (b) Network II.

V. Conclusion

In this paper, we investigated the survivability technologies against multiple failures in optical networks. Aiming at disaster-failure restoration issues, we studied re-provisioning schemes to maintain network connectivity and maximize the traffic flow in the post-disaster optical network. Based on the rerouting and bandwidth degradation methods, three re-provisioning schemes (named as NDR, DAN, and FAD) were proposed and compared in terms of CLR, TLR, and FF. The corresponding MILP models were developed and applied on two mesh topologies. The numerical results on these topologies show that NDR can effectively improve CLR performance by the rerouting method, but DAN and FAD can achieve optimal CLR performance even without rerouting any survived connections. DAN and NDR outperform FAD on TLR performance. All these schemes can improve the TLR performance by rerouting some survived connections. Compared with DAN, FAD can achieve better performance on FF by sacrificing a certain amount of traffic flow, which can lead to a balanced bandwidth distribution for all connections. Considering the practical complexities of our MILP models, efficient heuristic algorithms for large-scale networks need to be developed in our future work.

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