JOURNAL OF COMMUNICATIONS AND NETWORKS, VOL. 10, NO. 3, SEPTEMBER 2008

An Improved Shared-Path Protection Algorithm for Double-Link Failures in Meshed WDM Optical Networks

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Abstract: **In this paper, we investigate survivability in wavelength division multiplexing (WDM) mesh networks and propose a new algorithm called improved shared-path protection (ISPP) to completely tolerate the double-link failures. Compared with previous algorithms for protecting double-link failures, i.e., shared-path protection (SPP) and shared-link protection (SLP), the advantage of ISPP is to allow primary paths and backup paths to share the mixed wavelength-links based on the proposed new rules in which some primary wavelength-links can be changed to mixed wavelength-links, which can be shared by primary paths and backup paths. In addition, some mixed wavelength-links also can be shared by different backup paths for saving resources. Simulation results show that ISPP algorithm performs better in resource utilization ratio and blocking probability than conventional SPP and SLP algorithms.**

Index Terms: **Double-link failures, protection, shared backup resources, survivability, WDM optical networks.**

I. INTRODUCTION

In wavelength division multiplexing (WDM) optical networks, survivability is a very important issue because the fiber link failure may lead to a lot of traffic being dropped since each wavelength channel has the transmission rate over several gigabits per second [1]–[4]. In [5] and [6], the authors investigated the protection for single-link failure and proposed protection algorithms, e.g., link-based protection, path-based protection, segment-based protection, etc.

With the size of optical network keeping enlarging, the probability of multi-link failures becomes much higher. In [7]–[9], the authors proposed the failure dependent protection with the concept of shared-risk link Groups (SRLG) which can be either related to physical network or can be used for modeling purposes to address the multi-failures scenarios. In [7] and [8], the authors considered the single-link failure scenario, which can be modeled SRLG failure with one bi-directional link in each group, and proposed the failure dependent path protection (FDPP) algorithm that has better resource efficiency than the sub-graph protection (SGP) algorithm in [9].

To survive double-link failures, the proposed algorithms mainly include shared-path protection (SPP) and shared-link protection (SLP) [10]–[14]. In these algorithms, SPP has the best resource utilization ratio, which has been simulated and proofed in [10] and [11]. In SPP, each connection request will be assigned to one primary path and two link-disjoint backup paths. In the worst case, if one failed link is on the primary path and another failed link is on the first backup path, there is still one available backup path to transmit the traffic. In SPP, two backup paths can share the common backup wavelength-links if the presented rules in [10] can be satisfied. In SPP, however any backup path and any primary path cannot share the common wavelength-links, so that there may be some redundant wavelength-links.

An illustration is shown in Fig.1, where p_n, b_n^1, and b_n^2 denote the primary path, first backup path, and second backup path for connection request n, respectively. We assume that each connection requires the bandwidth of one wavelength channel, the network node has the full wavelength conversion capacity, and each fiber link is bi-directional. We define three kinds of wavelength-links: 1) Primary wavelength-links that are used by primary paths; 2) backup wavelength-links that are used and shared by backup paths; 3) mixed wavelength-links that are used and shared by primary and backup paths. In SPP, the backup wavelength-link w_2 on link k needs to be assigned to the backup path b_1^2, and the backup wavelength-link w_3 on link j needs to be assigned to the backup path b_1^1. However, the backup wavelength-links w_2 and w_3 are redundant, because b_1^1 can share the primary wavelength-link w_1 on link j used by the primary path p_0, and b_1^2 can share the primary wavelength-link w_0 on link k used by the primary path p_0. The reason for this is that the links traversed by p_1 are all traversed by p_0, so that if p_1 fails p_0 must fail simultaneously. If the cut of links x and j leads to the failures of p_0 and p_1, the primary wavelength-link w_0 on link k used by p_1 can be released, so that w_0 is now free and it can be re-used by b_1^2. Then, the redundant backup wavelength-link w_2 can be saved. Since w_0 can be used (or shared) by primary path p_1 and backup path b_1^2, it can be changed to the mixed wavelength-link. Based on the same principal, the primary wavelength-link w_1 on link j also can be changed to the mixed wavelength-link and can be shared by b_1^1, and then the redundant backup wavelength-link w_3 also can be saved. In this paper, the protection algorithm allowing the primary and backup

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Manuscript received September 07, 2005; approved for publication by Suresh Subramaniam, Division III Editor, April 11, 2008.

This work was supported in part by the National Natural Science Foundation of China (Nos. 60673159, 70671020), the National High-Tech Research and Development Plan of China (No. 2006AA01Z214), the Key Project of Chinese Ministry of Education (No. 108040), the Specialized Research Fund for the Doctoral Program of Higher Education (Nos. 20070145096, 20070145017, 20060145012), the Program for New Century Excellent Talents in University, and the Open Foundation of Key Laboratory of Broadband Optical Fiber Transmission and Communication Networks (UESTC), Ministry of Education, China

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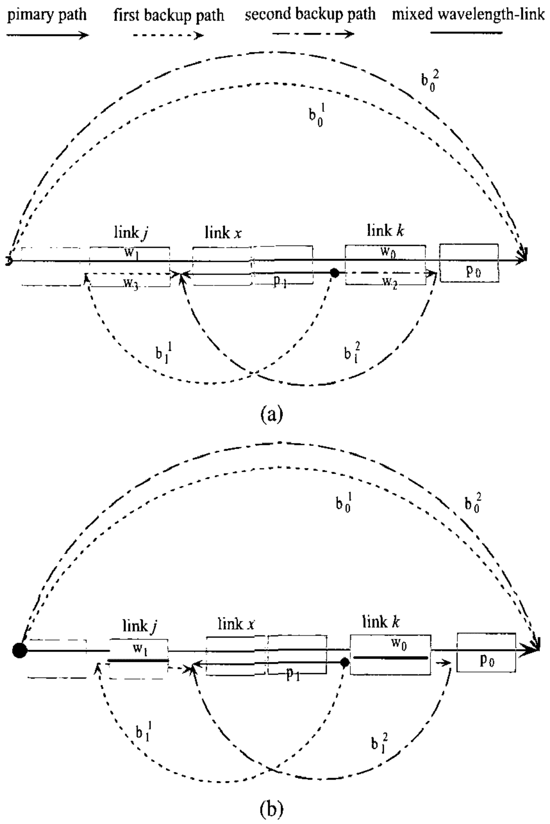

Fig. 1. Illustration of wavelength assignment in (a) SPP and (b) ISPP.

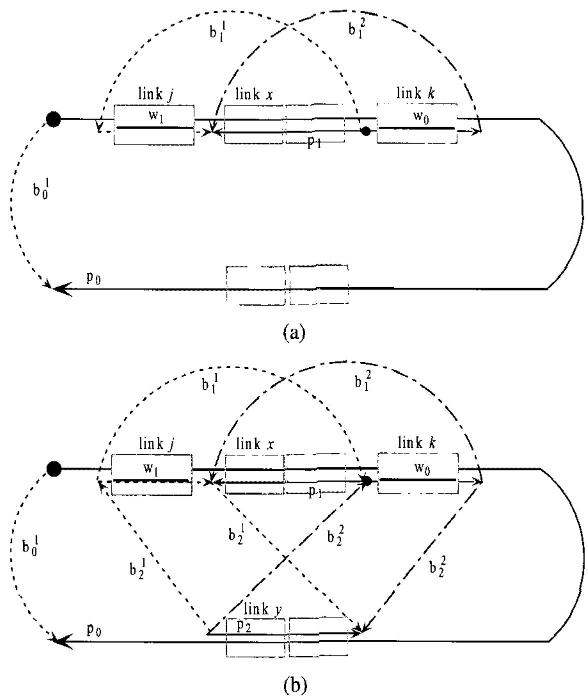

Fig. 2. Illustration of sharing mixed wavelength-links in ISPP.

paths to share the mixed wavelength-link is called improved shared-path protection (ISPP).

In SPP, any two backup paths can share the common backup wavelength-links if the rules of sharing backups presented in [10] can be satisfied. The rules in [10] considered the overlapping relationships between primary and backup paths so that the SPP with the rules has better resource utilization ratio than other protection algorithms (e.g., shared-link protection, shared-segment protection, etc.). In our proposed ISPP, the same rules of sharing backup wavelength-links in SPP are also abided. In addition, the further improvement of ISPP is that any two backup paths may share the common mixed wavelength-links if the constraints presented in Section II can be satisfied. We give an illustration shown in Fig. 2. In Fig. 2(a), there are two mixed wavelength-links w_0 and w_1. Fig. 2(b) shows that (b_1^1, b_2^1) can share w_1 on link j, and (b_1^2, b_2^2) can share w_0 on link k. The reasons of sharing w_1 on link j between b_1^1 and b_2^1 are: 1) p_1 and p_2 both are completely covered by p_0; 2) b_1^1 and b_2^1 both traverse link j; 3) b_1^1 and b_2^1 can share the backup wavelength-links; 4) w_0 on link j used by p_0 is a mixed wavelength-link in Fig. 2(a). For sharing w_0 on link k between b_1^2 and b_2^2, there are similar reasons with sharing w_1 on link j between b_1^1 and b_2^1. In the worst case, if links x and y fail, the traffic on primary paths p_0, p_1, and p_2 can be switched to backup paths b_0^1, b_1^1 and b_2^2, respectively. It is obvious that the protection for double-link failures in the worst case is effective. Although we presented the preliminary idea in [13], lack of considering the direction of sharing mixed wavelength-link may not be practical for real applications. Therefore, the preliminary idea needs to be modified and improved.

In this paper, we focus on protecting the double-link failures in WDM mesh networks and evaluate the performances of resource utilization ratio and connection establishment for ISPP, SPP and SLP. The main contribution of this paper is to propose the new rules of sharing mixed wavelength-links for primary paths and backup paths, which are presented in Section II. In the proposed new rules, some primary wavelength-links can be changed to the mixed wavelength-links which can be shared by primary paths and backup paths, and some mixed wavelength-links also can be shared by different backup paths, so that the consumed wavelength-links can be reduced. Based on the new rules, the proposed ISPP algorithm can obtain better performances than conventional SPP and SLP algorithms.

The rest of this paper is organized as follows. Section II presents the rules of sharing mixed wavelength-links. Section III proposes the heuristic approach. Section IV presents the simulation results. Section V concludes this paper.

II. RULES OF SHARING MIXED WAVELENGTH-LINKS

A. Notations and Assumptions

Assume each connection request arrives at the network orderly, and there is only a connection request arrives at a time. Assume each connection requires the bandwidth of one wavelength channel, each fiber link is bi-directional, and the network has the full wavelength conversion capacity. The following notations are introduced.

- j: Fiber link in the network;
- fw_j: The number of free wavelength-links on link j;
- pw_j: The number of primary wavelength-links on link j.
- bw_j: The number of backup wavelength-links on link j.
- mw_j: The number of mixed wavelength-links on link j.
- cr_n: Connection request n.

- p_n: Primary path for cr_n.
- b_n^1andb_n^2: Backup paths for cr_n.
- mp_n^j: Takes value of 1 if primary path p_n has used a mixed wavelength-link on link j; 0 otherwise.
- $mb_n^{\alpha,j} (\alpha \in \{1,2\})$: Takes value of 1 if backup path b_n^α has used a mixed wavelength-link on link j; 0 otherwise.
- $s_j^{r,b}$: Takes value of 1 if backup paths r and b can share the backup wavelength-links on link j based on the rules in [10]; 0 otherwise.
- $d_j^{p,q}$: Takes value of 1 if paths p and q have the same direction on link j; 0 otherwise.
- $|\Omega|$: The number of elements in set Ω.

B. Mixing Primary Wavelength-Links

The mixed wavelength-links are this kind of wavelengths that can be released by failed primary paths and can be re-used by other backup paths. Assume the connection request cr_n arrives at the network. After finding p_n, b_n^1, and b_n^2, we consider the following two cases:

1) Case 1: A primary wavelength-link on link j used by primary path p_n can be changed to a mixed wavelength-link and can be shared by previous backup path $b_m^\alpha (\alpha \in \{1,2\}, \forall m \le n-1)$, if:

$$\left(\begin{array}{r} (p_n \wedge p_m = p_m) \cap (j \in p_n \wedge b_m^\alpha) \cap (mb_n^{\alpha,j} = 0) \\ \cap (d_j^{p_n, b_m^\alpha} = 1) \cap (bw_j > \theta_j^*) \end{array} \right) \tag{1}$$

where θ_j^* can be written as

$$\theta_j^* = \max \left\{ C(j, v_j^{e,k}) | \forall e, k \in L, e \neq k \neq j \right\}. \tag{2}$$

In (2), $C(j, v_j^{e,k})$ is a function that is presented as follows, in which $v_j^{e,k}$ is written as

$$v_j^{e,k} = \left\{ \begin{array}{r} i | [(j \in b_i^1 \cap mb_i^{1,j} = 0) \cup (j \in b_i^2 \cap mb_i^{2,j} = 0)] \\ \cap (e \in p_i \cup k \in p_i), \forall i \le n-1 \end{array} \right\}. \tag{3}$$

Function: $C(j, v_j^{e,k})$.
Input: Network information, link j, and $v_j^{e,k}$.
Output: Total required backup resources.

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• Setp1: Set $x \leftarrow 0$, $s \leftarrow$ sufficient large number (e.g.,9999),
         $temp_s \leftarrow 0$ and $V \leftarrow v_j^{e,k}$.
• Setp2: Set $i \leftarrow V[x]$, $Y \leftarrow NULL$ and $X \leftarrow NULL$.
• Step3: Compose set $Y$ of all $cr_n (\forall n \in V)$ such that the
         backup paths of $cr_n$ and $cr_i (n \neq i)$ can share spare
         resources on link $j$ according to the rules 1–7 in section II.
• Step4: Compose set $X$ of all $cr_n (\forall n \in Y)$ such that their
         backup paths all can share spare resources each
         other on link $j$ according to the rules 1–7 in section II.
• Step5: Set $X \leftarrow X + i$, $V \leftarrow V - X$ and $temp_s \leftarrow temp_s + 1$;
         If $V \neq NULL$, go back to Step2;
         Else if $temp_s < s$, set $s \leftarrow temp_s$, $x \leftarrow x + 1$ and
         $V \leftarrow v_j^{e,k}$;
         If $V[x] \neq NULL$, set $temp_s \leftarrow 0$ and go back to
         Step2;
         Else return $s$.
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The constraints in (1) can ensure that the primary wavelength-link on link j used by primary path p_n can be changed to a mixed wavelength-link and can be shared by previous backup path b_m^α. In (3), $v_j^{e,k}$ is the set of connections whose primary paths traverse link e or link k and the corresponding backup paths traverse link j. It is obvious that the backup paths of these connections in $v_j^{e,k}$ do not share any mixed wavelength-link since $mb_m^{\alpha,j} = 0$ $(\alpha \in \{1,2\})$. With $C(j, v_j^{e,k})$, we can obtain the backup wavelength-links required on link j when links e and k both fail. Therefore, in (2) we can obtain θ_j^* that denotes the maximal backup wavelength-links required on link j for double-link failures in the worst case. Thus, in order to completely protect the double-link failures in the worst case, the backup wavelength-links on link j should not less than θ_j^*, i.e., $bw_j \ge \theta_j^*$ must be satisfied. If now $bw_j > \theta_j^*$ is satisfied, a primary wavelength-link on link j used by p_n can be changed to a mixed wavelength-link, and then a backup wavelength-link on link j can be saved, i.e., $bw_j \leftarrow bw_j - 1$. At this time, $bw_j \ge \theta_j^*$ can be still satisfied. Therefore, the protection for the double-link failures in the worst case is still effective.

2) Case 2: A primary wavelength-link on link j used by previous primary path p_m $(\forall m \le n-1)$ can be changed to a mixed wavelength-link and can be shared by backup path b_n^α $(\alpha \in \{1,2\}$, if:

$$\left(\begin{array}{r} (p_n \wedge p_m = p_n) \cap (j \in b_n^\alpha \wedge p_m) \cap (mp_m^j = 0) \\ \cap (d_j^{p_m, b_n^\alpha} = 1) \cap (bw_j > \theta_j^*) \end{array} \right). \tag{4}$$

We give an illustration shown in Fig.1. Assume cr_1 arrives after cr_0. After finding p_1, b_1^1 and b_1^2, we can obtain: $p_1 \wedge p_0 = p_1, j \in p_0 \wedge b_1^1, mb_1^{1,j} = 0, d_j^{p_0, b_1^1} = 1$ and $bw_j = 1 > \theta_j^* = 0$. It is obvious that the constraints in (1) can be satisfied, so that the primary wavelength-link w_1 on link j used by primary path p_0 can be changed to a mixed wavelength-link and can be shared by backup path . Then, we can release the backup wavelength-link w_3 on link j reserved for b_1^1 and set $bw_j \leftarrow bwj - 1$, $mw_j \leftarrow mw_j + 1$, $mb_1^{1,j} \leftarrow 1$ and $mp_0^j \leftarrow 1$.

C. Sharing Mixed Wavelength-Links

A mixed wavelength-link on link j used by previous primary path p_k and shared by previous backup path b_i^α $(\alpha \in \{1,\ 2\}, \forall k,\ i \le n-1)$ can be shared by backup path b_n^β $(\beta \in \{1,\ 2\})$, if:

$$\left(\begin{array}{c} (p_i \wedge p_k = p_i) \cap (p_n \wedge p_k = p_n) \cap (j \in p_k, b_i^\alpha, b_n^\beta) \\ \cap (mp_k^j, mb_i^{\alpha,j} = 1) \cap (s_j^{b_i^\alpha, b_n^\beta} = 1) \cap (d_j^{p_k, b_n^\beta} = 1) \end{array} \right). \tag{5}$$

The constraints in (5) can be explained by the illustrations of Fig. 2 in Section I. We assume cr_2 arrives after cr_1 and cr_0. According to (5), we can obtain: b_1^1 and b_2^1 can share the mixed wavelength-link w_1 on link j, and b_1^2 and b_2^2 can share the mixed wavelength-link w_0 on link k.

III. HEURISTIC ALGORITHM

We consider the load-balancing and the resources sharing degree in our proposed heuristic algorithm. We present two path-cost functions that affect the two performances when selecting the primary path and backup paths for each connection request. For each node pair, we pre-compute M different path-groups (PG) by the k-shortest path algorithm from [15] in an off-line manner. For node pair m, the dth PG denoted as $PG_{m,d}(p_{m,d}, b^1_{m,d}, b^2_{m,d})$ includes three link-disjoint paths, i.e., one primary path (i.e., $p_{m,d}$) and two backup paths (i.e., $b^1_{m,d}, b^2_{m,d}$)). In simulation, we set M to 20; that is, we pre-compute 20 different PGs for each node pair.

A. Path-Cost Definition

The network topology is $G(V, L, W)$ for a given WDM mesh network, where V is the set of nodes, L is the set of fiber links, and W is the set of available wavelengths per fiber link. Assume an arrival connection request n is for node pair m.

1) For node pair m, the cost of primary path $p_{m,d}$ is written as:

$$CP_{m,d} = \sum_{\forall j \in p_{m,d}} C_j \tag{6}$$

where the link-cost C_j is written as:

$$C_j = \begin{cases} \infty, & \text{if } fw_j = 0 \\ 1, & \text{else if } fw_j = 1 \\ 0.1[1 - (fw_j - 1)/|W|], & \text{else if } fw_j > 1. \end{cases} \tag{7}$$

It is obvious that the link-cost reduces as the free wavelengths (i.e., fw_j) increase in (7). If we select the minimal cost path as the primary path according to (6), the primary wavelengths will be distributed to all links and the load will be more balance. The load-balancing may lead more wavelengths to be shared [8]. Therefore, the resource utilization ratio can be improved and the blocking probability can be reduced.

2) Before we define the cost for backup paths, we first define the backup wavelengths required on link j as follows:

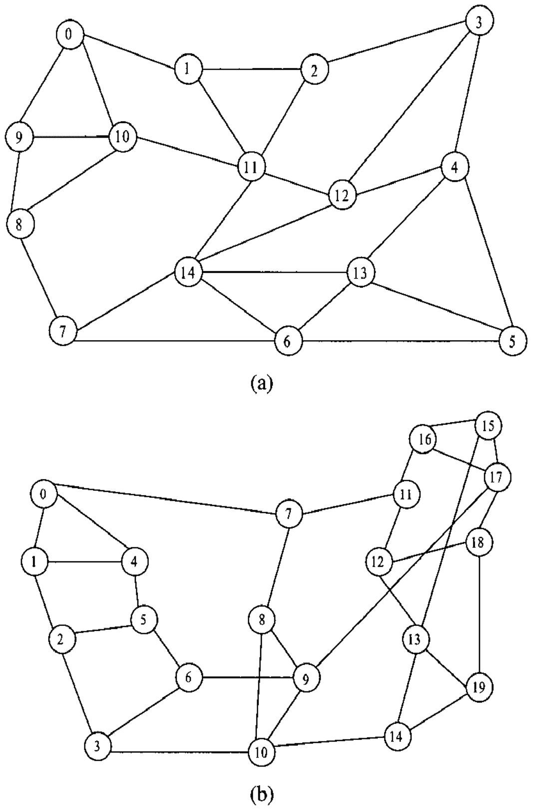
$$\mu^*_j = \max\left\{C(j, \sigma^{e,k}_j) | \forall e, k \in L, (e-k)(e-j)(k-j) \neq 0\right\} \tag{8}$$

where the $\sigma^{e,k}_j$ is written as:

$$\sigma^{e,k}_j = \left\{ \begin{array}{r} i | (e \in p_i \cup k \in p_i) \cap [(j \in b^1_i \cap mb^{1,j}_i = 0) \\ \cup (j \in b^2_i \cap mb^{2,j}_i = 0)], \forall i \leq n \end{array} \right\}. \tag{9}$$

After obtaining the μ^*_j, we can adjust the backup wavelengths on all links based on the rules of sharing mixed wavelengths in Section II. Then, the link-cost C^*_j is written as:

$$C_j = \begin{cases} \infty, & \text{if } fw_j + bw_j < \mu^*_j \\ 1, & \text{else if } fw_j + bw_j \geq \mu^*_j \cap bw_j < \mu^*_j \\ 0.1, & \text{else if } bw_j \geq \mu^*_j. \end{cases} \tag{10}$$



(a)

(b)

Fig. 3. Test networks: (a) US National network and (b) ARPANET.

Therefore, for node pair m the cost of backup paths is written as:

$$CB^{\alpha}_{m,d} = \sum_{\forall j \in (b^1_{m,d}, b^2_{m,d})} C^*_j, \ \alpha = 1, 2. \tag{11}$$

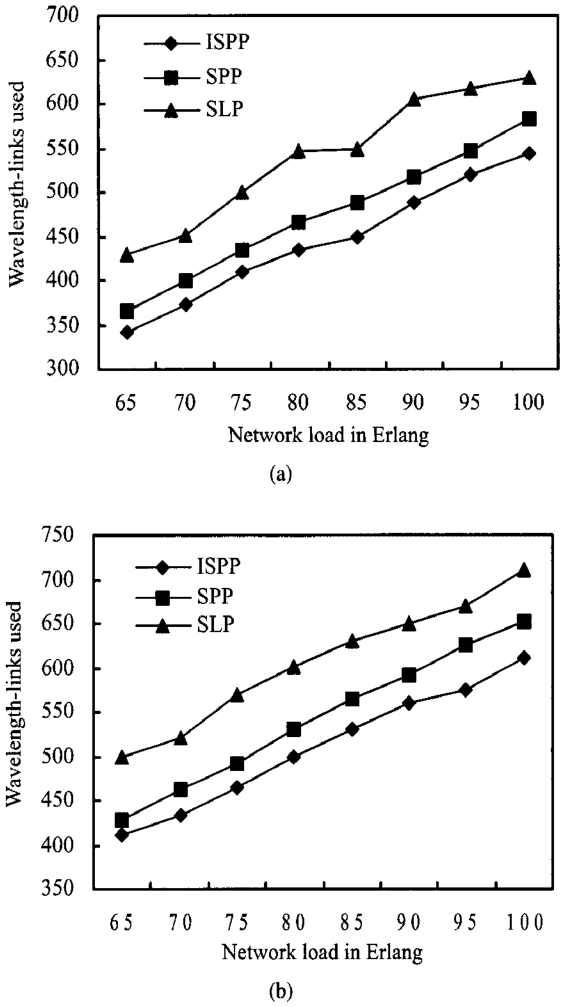
Note that in (10), link j that has enough backup wavelengths (i.e., $bw_j \geq \mu^*_j$) has less link-cost. If we select the minimal cost path as the backup path according to (11), there are minimal new backup wavelengths assigned and the resources utilization ratio can be improved. Higher resources utilization ratio may lead to lower blocking probability because more free resources can be used by the new coming requests.

B. Heuristic Steps

Input: Network information, cr_n for node pair m, PG for node pair m, $d \leftarrow 1$, $r\_used \leftarrow NULL$ and M

Output: Three link-disjoint paths or $NULL$ if no paths are available

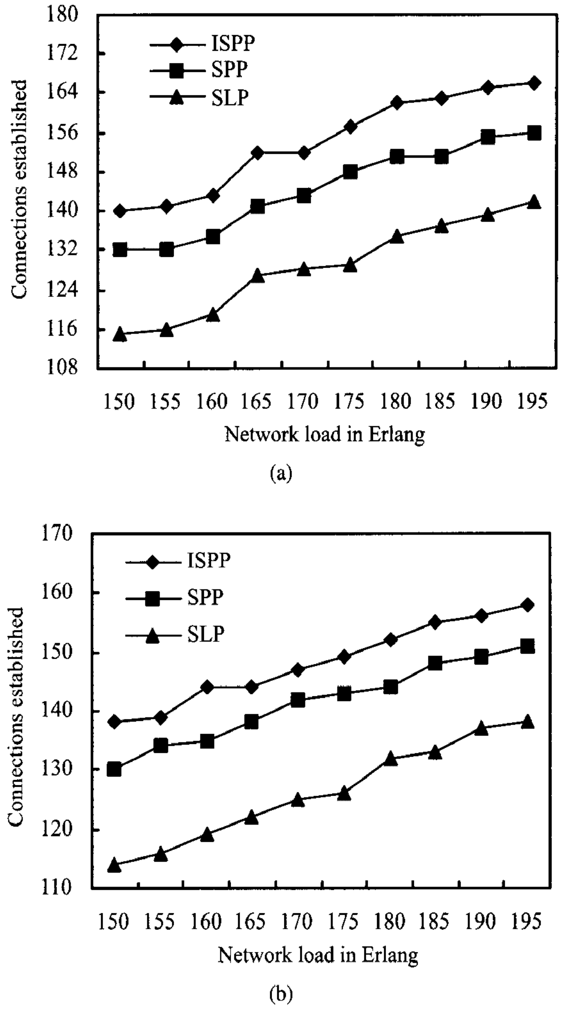
- Step1: Select the $PG_{m,d}$ as potential paths. Calculate the cost for primary path $p_{m,d}$ according to (6).
  If $CP_{m,d} < \infty$, calculate the required backup wavelengths (i.e., μ^*_j) on all links of backup paths according to (8). Based on the rules of sharing mixed wavelengths in Section II, adjust the backup wavelengths (i.e., μ^*_j) on all links. Go to Step2.
  Else, go to Step3.
- Step2: Calculate the cost of backup paths according to (11).
  If $CB^{\alpha}_{m,d} < \infty$, record the total wavelengths used (i.e., $r\_used_{m,d}$) for the selected .
- Step3: Set $d \leftarrow d + 1$.



(a)

(b)

Fig. 4. Wavelength-links used for ISPP, SPP, and SLP in: (a) US National network and (b) ARPANET.



(a)

(b)

Fig. 5. Connections establishment for ISPP, SPP, and SLP in: (a) US National network and (b) ARPANET.

If $PG_{m,d} \neq \emptyset$, go back to Step1;
Else, go to Step4.

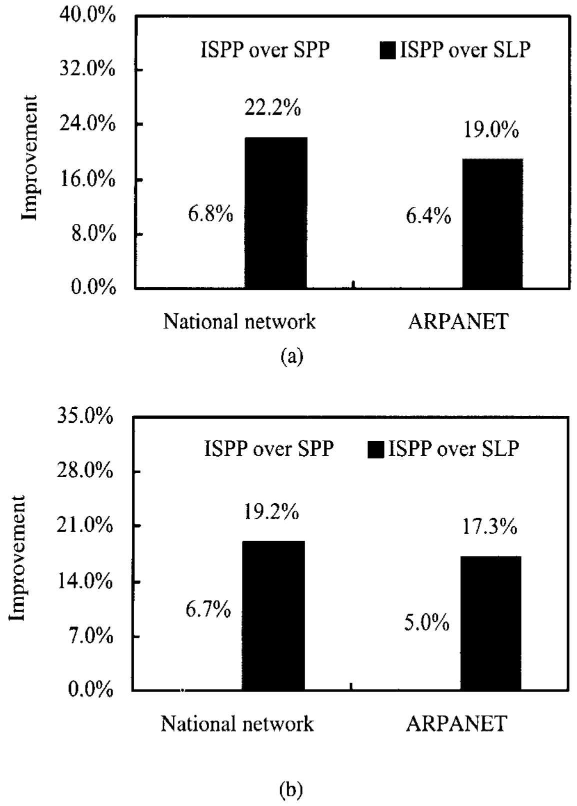
- Step4: Select the $PG_{m,d}\,(1 \leq x \leq M)$ as the final result based on the following rules:
  1) $CP_{m,d} < \infty$ and $CB^{\alpha}_{m,d} < \infty$;
  2) $r\_used_{m,d}$ is the minimal in all $r\_used_{m,y}$ ($\forall y \in [1, M]$);
  3) if $r\_used_{m,d} = r\_used_{m,y}$ ($\forall y \in [1, M]$, $y \neq d$), $CP_{m,d} < CP_{m,y}$ should be satisfied;
  4) if $r\_used_{m,d} = r\_used_{m,y}$ ($\forall y \in [1, M]$, $y \neq d$) and $CP_{m,d} = CP_{m,y}$, $CB^{\alpha}_{m,d} < CB^{\alpha}_{m,y}$ should be satisfied;
  5) if $r\_used_{m,d} = r\_used_{m,y}$ ($\forall y \in [1, M]$, $y \neq d$) and the costs of paths are all equal, the $x < y$ should be satisfied.
- Step5: If find the $PG_{m,d}$, return $PG_{m,d}(p_{m,d}, b^1_{m,d}, b^2_{m,d})$; otherwise, return $NULL$.

IV. SIMULATION AND ANALYSIS

We simulate a dynamic network environment with the assumptions that connection requests arrive according to an independent Poisson process with arrival rate β and that the connections' holding times are negatively exponentially distributed $1/\mu$, i.e., the network load is β/μ Erlang. If the connection fails to be established, it is dropped immediately; i.e., there are no waiting queues. In simulation, we set μ to 1. We test two real-world networks: US National network and ARPANET [14]. The number of wavelengths on each fiber link is set to 32. All test results are averaged by simulating 10^6 connection requests.

Fig. 4 shows that ISPP can save more wavelength-links than SPP and SLP in both National network and ARPANET. The reason of more wavelength-links consumed in SLP than SPP has been explained in [10] and [11]. The reason of more wavelength-links consumed in SPP than ISPP is that: 1) In SPP, the backup paths only can share the backup wavelength-links; 2) in ISPP, if the constraint rules in Section II can be satisfied, the backup paths can share both backup wavelength-links and mixed wavelength-links, and the primary paths and backup paths also can share the mixed wavelength-links. Therefore, ISPP can yield better resource utilization ratio than SPP and SLP.

Fig. 5 shows that ISPP can establish more connection requests than SPP and SLP in both National network and ARPANET. Because ISPP can save more wavelength-links than SPP and SLP, then more free wavelength-links can be utilized by the new coming connection requests, so that more connection requests can be established successfully. Therefore, ISPP can obtain better



(a)

(b)

Fig. 6. Performance improvements of ISPP over SPP and SLP: (a) Resources utilization ratio and (b) connections establishment.

performance of connections establishment than SPP and SLP. Fewer wavelength-links consumed means higher resource utilization ratio, and more connections establishment means lower blocking probability. Therefore, ISPP has better performances in resource utilization ratio and blocking probability than SPP and SLP.

Fig. 6 shows the average performance improvements of resource utilization ratio and connections establishment. For resource utilization ratio: 1) The improvements of ISPP over SPP are up to 6.8% and 6.7% in National network and ARPANET, respectively; 2) the improvements of ISPP over SLP are up to 22.2% and 19.2% in National network and ARPANET, respectively. For connections establishment: first the improvements of ISPP over SPP are up to 6.7% and 5.0% in National network and ARPANET, respectively; second the improvements of ISPP over SLP are up to 19.2% and 17.3% in National network and ARPANET, respectively. Therefore, the improvements of ISPP are promising.

V. CONCLUSION

This paper has studied the protection for double-link failures in WDM mesh networks, and proposed a new algorithm called ISPP. Compared with previous SPP and SLP algorithms, ISPP allows the primary paths and backup paths to share the mixed wavelength-links based on the proposed new rules in which some primary wavelength-links can be changed to mixed wavelength-links which can be shared by primary paths and backup paths and some mixed wavelength-links also can be shared by different backup paths for saving resources. Therefore, ISPP algorithm yields better performances than conventional SPP and SLP algorithms.

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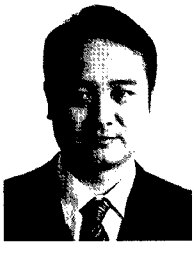

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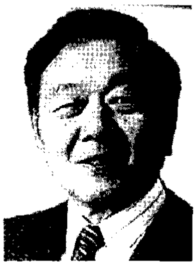

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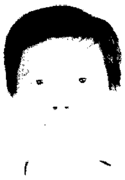

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