Enhanced Dynamic Segment Protection in WDM Optical Networks under Reliability Constraints

Lei Guo, Jin Cao, Hongfang Yu, and Lemin Li

ABSTRACT—*In this letter, we study the protection problem in wavelength division multiplexing (WDM) optical networks, and propose a novel dynamic heuristic algorithm called differentiated reliable segment protection (DRSP). Differing from previous work, DRSP can effectively avoid the trap problem and is able to find a feasible solution for each connection request. Therefore, DRSP outperforms the previous work. Simulation results have shown to be promising.*

Keywords—*WDM optical networks, path protection, segment protection, differentiated reliability.*

I. Introduction

In wavelength division multiplexing (WDM) optical networks, fiber link failure may lead to a lot of traffics being blocked, as a wavelength channel has a transmission rate of over gigabits per second [1]. Therefore, survivability has become an important issue in WDM optical networks. In an optical layer, previous works have proposed many protection methods to tolerate failures [2]-[7]. Although these algorithms, called path protection (PP) [2], [3], which assign a primary path and a link-disjoint backup path for each connection, are able to provide complete survivability for single-link failure, they do not consider the issue of differentiated reliability [5], [6]. In actual situations, users may need different connection reliability (for example, 99, 98, or 96%). Therefore, the performances of the resource utilization ratio and blocking probability for PP may not be promising. In order to satisfy the differentiated reliabilities required by users and improve the performances of the resource utilization ratio and blocking probability, previous works [5], [6] have proposed their protection algorithms called differentiated reliable path protection (DRPP). DRPP first computes a primary path for each connection request, and follows to check the reliability provided by the primary path. If the reliability provided by the primary path satisfies the reliability required by users, a backup path is not needed; otherwise, a backup path is required. With simulation results in [5], [6], we observe that DRPP yields a higher resource utilization ratio and lower blocking probability than PP.

Although DRPP obtains better performances than PP, it has a main flaw that may lead to the *trap* problem and increase the blocking probability, as the solution cannot be found in the trap topology even though the solution exists [3], [7]. In this letter, we study the flaw of DRPP and propose our solution approach to overcome the trap problem under differentiated reliability constraints. Therefore, our approach can outperform DRPP.

II. Problem Definition

The network topology is $G(N, L, W)$ for a given WDM network, where N is the set of nodes, L is the set of fiber links, and W is the set of available wavelengths per fiber link. Numbers $|N|$, $|L|$, and $|W|$ denote the node number, the link number, and the wavelength number, respectively. Connection requests arrive at the network dynamically, and there is only one connection request that arrives at a time. Assume each connection requires the bandwidth of a wavelength channel and that the network has full wavelength conversion capacity (that is, optical-electrical-optical). A shortest-path algorithm, Dijkstra's algorithm, is applied to compute the routes. The following are some important notations:

j: fiber link in G; $cost_j$: dynamic cost for link j, determined by

Manuscript received July 12, 2005; revised Sept. 21, 2005.

This work was supported in part by the National Natural Science Foundation of China under grant 60302010.

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the current network state; cr_n: connection request n; p_n: primary path for cr_n; b_n: backup path for p_n; sp_n: segment path required to be protected on p_n; bs_n: backup path for sp_n; pw_j, fw_j, sw_j: number of primary wavelengths, number of free wavelengths, and number of spare wavelengths on link j, respectively; r_j: reliability of link j; $r(q)$: reliability of path q; $r(q_1, q_2)$: joint reliability of paths q_1 and q_2; $r(cr_n)$: reliability of connection n; and ru: reliability required by users.

1. Differentiated Reliable Path Protection

According to previous works [5], [6], the idea of DRPP that is based on dedicated protection can be presented as follows:

The reliability of primary path p_n is written as

$$r(p_n) = \prod\nolimits_{\forall j \in p_n} r_j. \tag{1}$$

The reliability of backup path b_n is written as

$$r(b_n) = \prod\nolimits_{\forall j \in b_n} r_j. \tag{2}$$

The joint reliability of p_n and b_n is written as

$$r(p_n, b_n) = r(p_n) + (1 - r(p_n)) \times r(b_n). \tag{3}$$

With DRPP, the reliability $r(cr_n)$ is equal to $r(p_n, b_n)$. The main procedures of DRPP are as follows:

Step 1. Compute a maximal reliable primary path p_n. If p_n has been found and $r(p_n) \geq ru$, establish connection. Else, if p_n has been found, go to step 2; if p_n has not been found, block the request.
Step 2. Delete the links that have no free capacities and are traversed by p_n. In the residual graph, compute the maximal reliable backup path. If b_n has been found and $r(p_n,b_n) \geq ru$, establish connection; otherwise, block the request.

Although DRPP outperforms PP, it has a main flaw that may lead to the trap problem and increase the blocking probability. The trap problem includes two cases shown as follows.

Case 1 (a link disjoint caused trap) is shown in Fig. 1(a). For connection request cr_n with source node 1 and destination node 5, DRPP first finds the maximal reliable primary path 1-2-3-4-5. According to (1), we obtain $r(p_n)$=0.96 < ru=0.97, so that a backup path is needed. However, DRPP cannot find a link-disjoint backup path from source node 1 to destination node 5 because deleting the links traversed by p_n will disconnect the source node and the destination node. Therefore, the connection request will be blocked.

Case 2 (a resource constraint caused trap) is shown in Fig. 1(b). For connection request cr_m with source node 2 and destination node 4, DRPP first finds the maximal reliable primary path 2-5-4. According to (1), we obtain $r(p_n)$=0.97 < ru =0.98, so that a backup path is needed. Note that the potential backup paths are 2-1-4 or 2-3-4. However, links 2-1 and 2-3 cannot be used if their free capacities are equal to zero. Therefore, cr_n will be blocked.

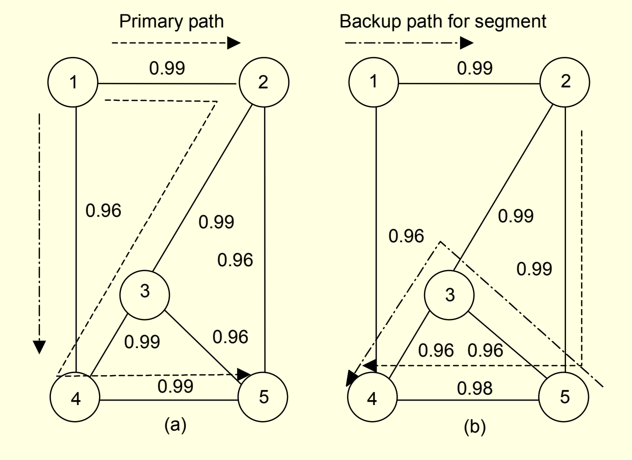

Fig. 1. Routing assignment for DRPP and DRSP; the number labeled beside the link is the link reliability; (a) ru = 0.97 and (b) ru = 0.98.

2. Differentiated Reliable Segment Protection

In order to avoid the trap problem induced by DRPP, we consider computing a backup path only for a segment path on the primary path based on differentiated reliability. We propose a solution approach called differentiated reliable segment protection (DRSP), which is also based on dedicated protection. We assume that the segment path sp_n on p_n needs to be protected and its corresponding backup path bs_n also exits.

The reliability of segment path sp_n is written as

$$r(sp_n) = \prod\nolimits_{\forall j \in sp_n} r_j. \tag{4}$$

The reliability of backup path bs_n is written as

$$r(bs_n) = \prod\nolimits_{\forall j \in bs_n} r_j. \tag{5}$$

The joint reliability of sp_n and bs_n is written as

$$r(sp_n, bs_n) = r(sp_n) + (1 - r(sp_n)) \times r(bs_n). \tag{6}$$

The reliability of cr_n is written as

$$r(cr_n) = \left(\prod\nolimits_{\forall j \in (p_n - sp_n)} r_j\right) \times r(sp_n, bs_n). \tag{7}$$

Based on these equations, DRSP first assigns a maximal reliable primary path p_n for cr_n. If p_n has been found and $r(p_n) \geq ru$, a backup path is not needed; otherwise, DRSP selects a segment sp_n and assigns a maximal reliable bs_n to it.

Compared to DRPP, DRSP can yield a higher resource utilization ratio. Because DPSS assigns a backup path only to a segment path, while DRPP assigns a backup path to the full primary path, and the backup path for a segment path may traverse fewer links and consume fewer resources than the backup path for the full primary path [4], DRSP consumes fewer resources than DRPP; that is, DRSP has a higher resource utilization ratio. Then, DRSP will also have lower blocking probability than DRPP for the following reasons: First, more free resources saved by DRSP can be utilized by the following connection requests; and second, DRSP can avoid the trap problem and reduce the blocking probability, while DRPP cannot avoid the trap problem in Fig. 1.

In Fig. 1(a), with DRPP the connection request cr_n will be blocked. However, with DRSP, if we choose segment path 1-2-3-4 to be protected, we obtain the corresponding backup path 1-4 and $r(cr_n) = 0.988 \geq ru = 0.97$. Therefore, cr_n can be established successfully. In Fig. 1(b), with DRPP, the cr_m will be blocked. However, with DRSP, if we choose segment path 5-4 to be protected, we obtain the backup path 5-3-4 and $r(cr_m) = 0.988 \geq ru = 0.98$. Then, cr_m can be established successfully.

III. Proposed Heuristic Approach

1. Link-Cost for Computing Primary Path

We assume connection request cr_n arrives at a given time. Before computing the minimal cost primary path, we adjust the link-cost according to (8). Therefore, the minimal cost path will be the maximal reliable route.

$$cost_{\forall j \in L} = \begin{cases} +\infty & \text{if } (fw_j = 0), \\ \log r_j & \text{otherwise}. \end{cases} \quad (8)$$

For poof, if we compute the logarithm of both sides of (1), then we obtain

$$\log r(p_n) = \log r_1 + \log r_2 + \ldots + \log r_j \geq \log ru. \quad (9)$$

Since $r_j(\forall j \in L)$ and ru both are between 0 and 1, $\log r_j$ and $\log ru$ have negative values. Multiplying both sides by -1 in (9), we obtain

$$-\log r(p_n) = -\log r_1 - \log r_2 - \ldots - \log r_j \leq -\log ru. \quad (10)$$

It is obvious that if link cost $cost_j$ is defined as such a function of its reliability (that is, $\log r_j$), the cost is additive and the path with minimal cost will be the path with maximal reliability. Therefore, the standard shortest-path algorithm (that is, Dijkstra) can be applied to compute the minimal cost path. If the maximal reliable primary path has been found and the reliability of the primary path is not smaller than ru, we know that the backup path is not needed. Therefore, more resources can be saved and the resource utilization ratio can be improved.

2. Link-Cost for Computing Backup Path

If the reliability of the primary path is smaller than ru, the backup path is needed. Before computing the backup path for a segment path, we adjust the link-cost according to (11).

$$cost_{\forall j \in L} = \begin{cases} +\infty & \text{if } (j \in p_n) \cup (fw_j = 0), \\ -\log r_j & \text{otherwise}. \end{cases} \quad (11)$$

If p_n and bs_n have been both found and $r(cr_n)$ is not smaller than ru, the reliability required by users has been satisfied.

3. Procedure of DRSP

Differentiated Reliable Segment Protection (*DRSP*)
Input: $G = \{N, L, W\}$; a connection requests n; *source node* and *destination node*$\in N$; ru
Output: p_n or (p_n, sp_n, b_n), or NULL if no satisfying paths
Step 1. Adjust the link-costs according to (8), and compute a minimal cost primary path. If p_n has been found and $r(p_n) \geq ru$, establish a connection, update the network state, and return p_n. Otherwise, if p_n has been found, go to step 2; if p_n has not been found, block the connection, update the network state, and return NULL.
Step 2. Choose a segment path sp_n such that the node degrees for segment source and segment destination both are greater than one after deleting these links that have no free capacities and are traversed by p_n. Go to step 3.
Step 3. Adjust the link-costs according to (11) and compute a minimal cost backup path bs_n for sp_n. If bs_n has been found and $r(cr_n) \geq ru$, establish a connection, update the network state, and return (p_n, sp_n, bs_n); Otherwise, choose a new segment path. If all potential segment paths have been selected, block the request, update the network state, and return NULL; otherwise, go back to step 3.

The time complexity of DRSP mostly depends on the running times of Dijkstra's algorithm, whose time complexity is $O(|N|^2)$. In the worst case, for each connection request, DRSP will run Dijkstra's algorithm one time to compute a primary path and run Dijkstra's algorithm k times to compute the backup path for a segment, where k is the number of potential segment paths on the primary path. Therefore, the time complexity of DRSP is approximately $O((k+1)|N|^2)$.

IV. Simulation Results and Analysis

We simulate a dynamic network environment with the assumptions that the connection requests arrive according to an independent Poisson process with arrival rate β, and the connection holding time is negative, exponentially distributed 1/μ, namely, the network load is β/μ Erlang. We assume $\mu = 1$, and that each required bandwidth is a wavelength. The test network is shown in [5]. The number of wavelengths on each fiber link is set to 16. Assume the network nodes have full wavelength conversion capacity. According to [6], the reliability of each link is randomly distributed between 0.96 and 1, and the reliability required by users is randomly distributed between 0.95 and 0.99. We compare the performances of DRSP and DRPP. The resource utilization (RU) and the blocking probability (BP) both can be defined according to [5].

Figure 2(a) shows that DRSP yields a higher resource utilization ratio than DRPP. Because DRSP assigns a backup path only to a segment path but DRPP assigns a backup path to the full primary path, and the backup path for a segment path may consume fewer resources than the backup path for the full primary path, DRSP obtains a higher resource utilization ratio than DRPP. Figure 2(b) shows that DRSP yields a lower blocking probability than DRPP. There are two reasons for this: First, DRSP has a higher resource utilization ratio, and more free resources saved by DRSP can then be utilized by the following connection requests, which results in the blocking probability being lower; and second, DRSP can effectively avoid the trap problem, and more connections can then be established so that the blocking probability of DRSP will be lower. Figure 3 shows the average performance improvement of DRSP over DRPP, and the improvements for the resource utilization ratio and blocking probability are on average up to 5.7 and 13.1%, respectively. Therefore, DRSP obtains better solutions than DRPP.

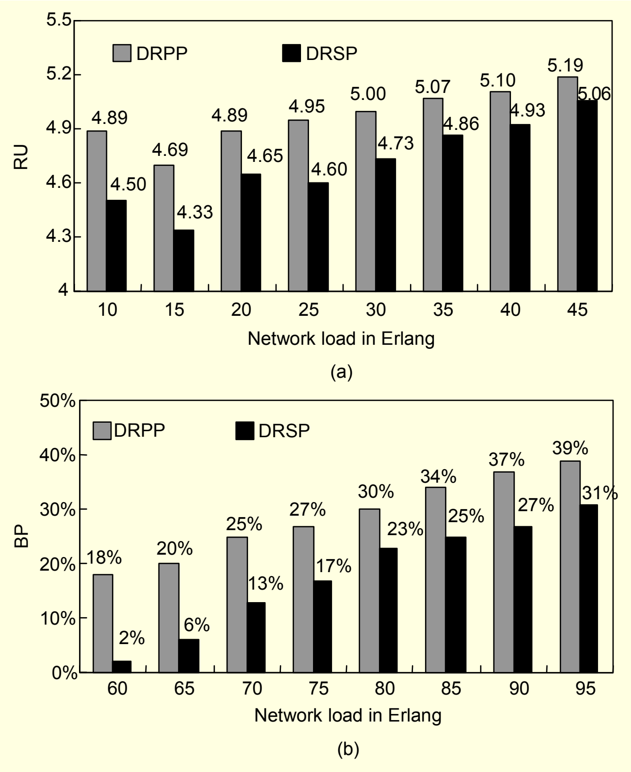

Fig. 2. The performances for (a) RU and (b) BP as network load increases.

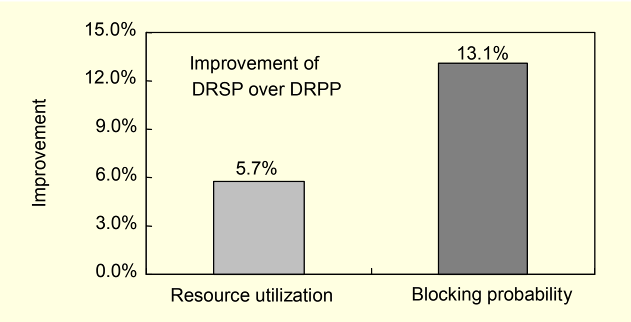

Fig. 3. Average performance improvement for DRSP over DRPP.

V. Conclusions

In this letter, we studied differentiated reliable protection in WDM optical networks, and proposed a novel dynamic protection algorithm called DRSP. Simulation results show that DRSP yields better solutions than previous DRPP.

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