Segment shared protection for survivable meshed WDM optical networks

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Abstract

In this paper, we investigate the protection design for survivable meshed WDM optical networks, and propose a novel heuristic algorithm, which is called segment shared protection (SSP), to completely protect the dual-link failures. For each connection request, first SSP computes a least-cost working path, second SSP divides the working path into several un-overlapped segment paths according to a parameter $M$, and finally SSP computes two least-cost and link-disjoint backup paths for each segment path. If two segment paths do not traverse the same fiber links, then their corresponding backup paths can shared the common reserved backup wavelengths. When computing the paths, we suggest two dynamic link-cost functions to adjust the resource sharing degree according to the current state of the network, and then our routing algorithm, which computes the least-cost paths, has higher resource utilization ratio and lower blocking ratio than those routing algorithms that merely compute the shortest paths. We describe our scheme of dividing the segment path and the method of assigning the reserved backup wavelengths. We also study the procedure of the protection switching time, which had not been studied by previous algorithms, for the dual-link failures, and calculate the formulas of the protection switching time. Under dynamic traffic with different load, the simulation results show that: SSP provides 100% reliable protection for the dual-link failures; with respect to the previous algorithm, SSP, adds a valuable elasticity between the resource utilization and the protection switching time, and is able to perform higher resource utilization ratio, lower blocking ratio, and faster protection switching time.

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1. Introduction

In Wavelength-division-multiplexing (WDM) optical networks, the protection design is very important, because a wavelength channel has the transmission rate of over gigabits per second; if the fiber links fail, a lot of traffics would be dropped. Most papers have investigated the single-link failure [1–4], which is dominant in WDM optical networks. The amount of users increasing heavily leads to the size of networks keeping enlarging, and many heterogeneous networks interconnecting leads to more complicated structure of the networks. Then, the probability of risks become much higher, and the dual-link failures must be considered for protection design in survivable WDM optical networks [5–7].

Recently, some papers investigate the dual-link failures and propose their protection algorithms [8–10]. The algorithm in [8] is for the static network flows, and it uses ILP method that has high complexity to compute the paths. Although the algorithm in [9] is for the dynamic network flows, it cannot provide 100% reliable protection for the dual-link failures. A representative dynamic algorithm, which is called path shared protection (PSP) [10], searches a working path and two link-disjoint backup paths for each connection request. In the worst case, if the working path traverses a failed link and the first backup path traverses another failed link, the second backup path can transmit the traffics of the connection request. It is obvious that the PSP can provide 100% reliable protection for the dual-link failures. But, when computing the paths, the PSP does not consider the resource sharing degree according to the current state of the network, and then the working and backup paths of the PSP are merely the shortest routes. Therefore, the resources would not be effectively used, and the resource utilization ratio would not be high and the blocking ratio would not be low [11–14]. So, in this paper, in order to completely protect the dual-link failures and improve the resource utilization ratio, we shall describe a novel scheme of assigning the reserved backup wavelength, and suggest two dynamic link-cost functions to adjust the resource sharing degree according to the current state of the network. In Section 4, we shall see our heuristic algorithm, called segment shared protection (SSP) that computes a least-cost working path and two least-cost backup paths for each segment path, not only provides 100% reliable protection for the dual-link failures but also performs higher resource utilization ratio and lower blocking ratio than PSP.

Those algorithms [8–10] all did not study the procedure of the protection switching time for the dual-link failures, but the protection switching time is an important performance parameter and should not be ignored in the heuristic algorithms, because a smaller protection switching time means faster recovery after the failures. So, in this paper, we shall first study the detailed protection switching procedure for the dual-link failures and calculate the formulas of the protection switching time.

In order to achieve a fast recovery after the failures and an appropriate resource utilization ratio, we consider dividing the working path of each connection request into several un-overlapped segment paths according to a parameter $M$ that denotes the length of each segment path, because different segment division can determine different protection switching time and resource utilization [2,15–17]. In Section 2.2, we shall detail describe our division scheme of segment path. In Section 4, from simulation results, we shall see that, by configuring parameter $M$, the SSP has faster protection switching time than the PSP; and different parameter $M$ means different segment division that will make the appropriate trade-offs between the resource utilization ratio and the protection switching time.

If we extend the link-disjoint to the shared-risk link group (SRLG) disjoint, those algorithms [1–4] for protecting the single-link failure can easily be extended to protect the single-SRLG failure [18,19]; and those algorithms [8–10] and our proposed algorithm for protecting the dual-link failures can easily be extended to protect the dual-SRLG failures [20].

The rest of the paper is organized as follows. Section 2 formally states the network model, the scheme of dividing the segment path, the method of assigning the reserved backup wavelengths, the link-cost assignment, and the protection switching time. Section 3 presents the procedures.
of our proposed algorithm and the performance parameters. Section 4 evaluates the performance of our algorithm via simulations. Section 5 is for conclusions.

2. Problem statement

2.1. Network model

The network topology is \( G(N, L, W) \) for a given survivable meshed WDM optical network, where \( N \) is the set of nodes, \( L \) is the set of bi-directional links, and \( W \) is the set of available wavelengths per fiber link. \(|N|, |L| \) and \(|W|\) denote the node number, the link number and the wavelength number, respectively. Connection request arrives at the network dynamically, and there is only a connection request arrives at a time, defined by \( r(s, d) \), where \( s, d \in N \) denote the source node and destination node. We assume a requested bandwidth is a wavelength and allow full wavelength conversion. A least-cost path algorithm, Dijkstra’s algorithm, applies to compute the routes. The following notations are introduced.

\( l \in L \) is a bi-directional fiber link in \( G \).

\( c_l \) is the basic cost of the link \( l \), and it is determined by many factors, such as the physical length of the fiber link, installation cost of the fiber link, and so on; \( c_l \) is the dynamic cost of the link \( l \), and it is determined by the current state of the network.

\( WP_n \) is the working path for the connection request \( n \); \( SP^k_n \) is the \( k \)th segment path of \( WP_n \); \( BP^1_n \) and \( BP^2_n \) are the first and the second backup paths for \( SP^k_n \), respectively.

\( W_l, F_l, R_l, TFR_l \) and \( TSR_l \) are illustrated in Fig. 1. \( W_l \) is the total wavelengths consumed by the segment paths traversing link \( l \); \( F_l \) is the total free wavelengths on link \( l \); \( R_l \) is the total reserved backup wavelengths on link \( l \); \( TFR_l \) and \( TSR_l \) are two temporary records of reserved backup wavelengths on link \( l \) (\( TFR_l \geqslant TSR_l \)); \( TFR_l \) and \( TSR_l \) are the sets of IDs of the segment paths whose reserved backup capacities affect the \( TFR_l \) and \( TSR_l \), respectively.

\( v_l \) is the set of IDs of the segment paths that traverse link \( e \) and are protected by link \( l \) (their backup paths traverse \( l \)).

\(|S|\) is the number of elements in set \( S \).

2.2. Segment paths division

We define a parameter \( M \) to adjust the segment paths division, where \( M \) denotes the length of each segment path. We give an illustration in Fig. 2.

In Fig. 2, there already exists a working path a–b–c–d–e–f–g. If \( M = 1 \), the working path will be divided into six equal length segments; if \( M = 2 \), the working paths will be divided into three equal length segments; and if \( M = 6 \), which is the full length of the working path, the segment is equivalent to the working path. After accomplishing the segment paths division, we shall compute two link-disjoint backup paths for each segment. It is obvious that, when \( M = 1 \), our algorithm is equivalent to link protection; when \( M \) is equal to the full length of the working path, our algorithm is equivalent to the path protection.

In our concept, all segment paths are independent, whether or not they are included by the same working path; that is, if two segment paths are link-disjoint, then their corresponding backup paths can share the common reserved backup wavelengths. We give an illustration in Fig. 3.

Fig. 1. An illustration of wavelengths distribution for link \( l \).
In Fig. 3, there already exists a working path g–h–i–j–d and three segments (segment 1 g–h–i, segment 2 i–j, and segment 3 j–d), which all are included by the same working path. We can see that, the first backup path of segment 2 has an overlapped path (link) with segment 1, and the first backup path of segment 3 has an overlapped path (link) with segment 2; the second backup paths of the segment 1 and segment 2 share a common reserved backup wavelength on link b–i, because segments 1 and 2 are link-disjoint; that is, although the two segments are included by the same working path, they can share the common reserved wavelengths and their corresponding backup paths can traverse the same path (link) with other segments.

We can see from Figs. 2 and 3 that, as the length of the segment decreasing, more revered backup wavelengths will need to be assigned; that is, the segment shared protection has lower resource utilization ratio than the path shared protection (see the simulation results in Section 4.2). It is obvious that, as the length of the segment decreasing, the lengths of the paths (segment paths and backup paths) for the segment shared protection will be shorter, and then segment shared protection has a smaller protection switching time and faster recovery than path shared protection after the failures (see the analysis in Section 2.5).

2.3. Reserved backup wavelengths

Assuming a connection request \( n \) arrives at a given time. For arbitrary link \( l \), first we let \(\text{TFR}_l = \max\{v^*_l\} \) (\( \forall e \in L, e \neq l \) \( \text{TRFR}_l = v^*_l \)), second we let \(\text{TSR}_l = \max\{|v^*_l - v^*_j \cap \text{TRFR}_l|\} \) (\( \forall t \in L, t \neq l \) \( \text{TRSR}_l = v^*_l - v^*_j \cap \text{TRFR}_l \)). We give an illustration in Fig. 4, and shall compute the reserved backup wavelengths \( R_l \) for link \( l \).

In Fig. 4, we can see that there are six segments whose second backup paths all traverse the link \( l \). First, we find that \( v^*_l = \{0, 1, 2\} \), \( v^*_j = \{3, 4\} \), and \( v^*_l = \{5\} \). Second, we get \(\text{TFR}_l = |v^*_l| = 3 \) and \(\text{TRFR}_l = v^*_l = \{0, 1, 2\} \). Finally, we get \(\text{TSR}_l = |v^*_l - v^*_j \cap \text{TRFR}_l| = 2 \) and \(\text{TRSR}_l = v^*_l - v^*_j \cap \text{TRFR}_l = \{3, 4\} \). Then, the total reserved backup wavelengths \( R_l \) is equal to five.
In the worst case, in Fig. 4, if links \( x \) and \( y \) fail simultaneously, then the segments 0–4 and their first backup paths all fail, because the first backup paths of segments 0–2 traverse link \( y \) and the first backup paths of segments 3 and 4 traverse link \( x \). The traffics of those segments can be switched to their second backup paths that all traverse link \( l \), and five reserved backup wavelengths on link \( l \) are enough to transmit the switched traffics of the failed segments. Thus, those connection traffics would not be dropped.

2.4. Link-cost assignment

Assuming connection request \( n \) arrives at a given time. First, we adjust the link-cost according to Eq. (1) and compute a least-cost working path

\[
c'_i = \begin{cases} 
\infty & \text{if } (s_i \cap U = \emptyset) \cup (F_i + R_i < TFR_i + TSR_i), \\
-c_i & \text{if } R_i \geq TFR_i + TSR_i, \\
c_i & \text{otherwise,}
\end{cases}
\]

(1)

If the working path \( WP_n \) has been found, then we divide the working path into several un-overlapped segments. After adjusting the link-cost according to Eq. (2), we compute the first link-disjoint and least-cost backup path for the \( k \)th segment \( SP_k^n \). In Eq. (2), \( \varepsilon \) is a positive constant considering the resource sharing degree \((\varepsilon |W| + c_i \text{ should be greater than zero})\) and \( U = \{l; l \in SP_k^n\} \). After finding the first backup path \( BP_n^{k,1} \), we adjust the link-cost according to Eq. (3) and compute the second link-disjoint and least-cost backup path, where \( Q = U + \{l; l \in BP_n^{k,1}\} \).

\[
c'_i = \begin{cases} 
\infty & \text{if } (s_i \cap U = \emptyset) \cup (F_i + R_i < TFR_i + TSR_i), \\
-c_i & \text{if } R_i \geq TFR_i + TSR_i, \\
c_i & \text{otherwise,}
\end{cases}
\]

(2)

\[
c'_i = \begin{cases} 
\infty & \text{if } (l \cap Q = \emptyset) \cup (F_i + R_i < TFR_i + TSR_i), \\
-c_i & \text{if } R_i \geq TFR_i + TSR_i, \\
c_i & \text{otherwise.}
\end{cases}
\]

(3)

We can see from Eqs. (2) and (3) that, these links, which already have enough reserved wavelengths (that is, \( R_i \geq TFR_i + TSR_i \)) have less link-cost. If the backup paths traverse these links, then we need not reserve new backup wavelengths. Thus, the resource utilization ratio will be improved. We give an illustration in Fig. 5.

In Fig. 5(b), there already exist two reserved wavelengths on link \( f-a-b \). For segment \( e-c \), (1) if we use the shortest routing algorithm, then we can find the two backup paths \( e-f-b-c \) and \( e-d-c \) in Fig. 5(c), and five backup wavelengths need to be assigned; (2) if we use the least-cost routing algorithm that considers the resource sharing degree according to Eqs. (2) and (3), we can find the two backup paths \( e-f-a-b-c \) and \( e-d-c \) in Fig. 5(d), and only four backup wavelengths need to be assigned, because the two reserved wavelengths on link \( f-a-b \) can be shared. It is obvious that the algorithm with the resource sharing degree can save more wavelengths, and more free wavelengths can be used by the following connection requests, and then fewer connection requests would be blocked and the blocking ratio would be decreased.

![Fig. 5. Illustration of sharing reserved wavelengths; (a) a network topology, (b) there already exist two reserved wavelengths on links \( f-a \) and \( a-b \), (b) wavelength assignment of the shortest routing for segment \( e-c \), and (d) wavelength assignment of the least-cost routing for segment \( e-c \).](image-url)
2.5. Protection switching time

Previous papers [9–11] did not study the protection switching time for the dual-link failures, so our presentation at here is the first investigation for the dual-link failures.

The protection switching time is defined as the time between the failure of the segment path and the time that the corresponding backup path begins to work. The following notations are introduced according with [2]:

- \( D \) is the message processing time at a node is assumed to be 10 µs, corresponding to 1-GHz CPU time.
- \( P \) is the propagation delay on the link is assumed to be 400 µs.
- \( X \) is the time to configure, test, and set up an OXC (Optical Cross-Connect) is assumed to be 10 µs.
- \( F \) is the time to detect the link failure is assumed to be 10 µs.
- \( l_1 \) and \( l_2 \), the two failed fiber links.

There are three protection switched cases of the segment shared for the dual-link failures:

**Case 1:** In Fig. 6(a), we assume segment \( q \) traverses the failed links \( l_1 \) and \( l_2 \), the number of hops from the link source of \( l_1 \) to the segment source is \( n_1 \), and the number of hops of the first backup path is \( m \).

Now, we illustrate the steps in the protection switching procedure for segment shared protection in Fig. 6(a). When link \( l_1 \) fails, the end nodes of \( l_1 \) that are the link source and the link destination send failure messages to the segment source and the segment destination, respectively. Then the segment source sends a setup message to the segment destination along the first backup path and configures the OXCs at each intermediate node along the first backup path. As the setup message arrives at the link source of \( l_2 \), the link source of \( l_2 \) sends a failure message back to the segment source along the first backup path and releases the OXCs that have just been configured by the setup message at each intermediate node along the first backup path. Then the segment source sends a confirmation message back to the segment source along the second backup path, thus completing the recovery procedure. Then the protection switching time \( t_q \) for segment \( q \) is calculated as

\[
 t_q = F + n_1 \times P + (n_1 + 1) \times D + 2 \times m \times P \\
+ 2 \times (m + 1) \times X + 2 \times (n_2 + 1) \times D + 2 \\
\times m \times P + 2 \times (m + 1) \times X + 2 \times (n_2 + 1) \times D + 2 \\
\times m \times P + 2 \times (m + 1) \times X.
\]  

(Case 2: In Fig. 6(b), we assume the segment traverses the failed link \( l_1 \) and the first backup path traverses the failed link \( l_2 \), the number of hops from the link source of \( l_1 \) to the segment source is \( n_1 \), the number of hops of the link source of \( l_2 \) to the segment source is \( n_2 \), and the number of hops of the second backup path is \( m \).

When link \( l_1 \) fails, the end nodes of \( l_1 \) that are the link source and the link destination send failure messages to the segment source and the segment destination, respectively. Then the segment source sends a setup message to the segment destination along the first backup path and configures the OXCs at each intermediate node along the first backup path. As the setup message arrives at the link source of \( l_2 \), the link source of \( l_2 \) sends a failure message back to the segment source along the first backup path and releases the OXCs that have just been configured by the setup message at each intermediate node along the first backup path. Then the segment source sends a setup message to the segment destination along the second backup path and configures the OXCs at each intermediate node along the second backup path. After receiving the setup message, the segment destination sends a confirmation message back to the segment source along the second backup path, thus completing the recovery procedure. Then the protection switching time \( t_q \) is calculated as

\[
 t_q = F + n_1 \times P + (n_1 + 1) \times D + 2 \times n_2 \times P \\
+ 2 \times (n_2 + 1) \times X + 2 \times (n_2 + 1) \times D + 2 \\
\times m \times P + 2 \times (m + 1) \times D + (m + 1) \times X.
\]  

(Case 3: In Fig. 6(c), if the first backup path does not traverse the failed link \( l_2 \), then the protection switching procedure is same to Case 1, and the protection switching time \( t_q \) is also calculated as Eq. (4).

It is obvious that, shorter lengths of segments and backup paths mean smaller \( n_1 \), \( n_2 \) and \( m \) (see Section 2.2), and this will lead to smaller \( t_q \) and faster recovery after the failures.
3. Proposed algorithm

3.1. Procedure and complexity of the algorithm

In this subsection, we shall present the procedure of our heuristic algorithm, called Segment Shared Protection (SSP).

**Step 1:** Wait for a connection request arrival. If a connection request arrives, go to Step 2. Else, update the network’s state and go back to Step 1.

**Step 2:** Adjust the link-cost according to Eq. (1), and compute a least-cost working path.

If succeed to find the working path, then divide the working path into several segments according to $M$ and go to Step 3.

Else, block the connection request, update the network’s state, and go back to Step 1.

**Step 3:** If the $k$th segment has not been assigned the backup paths, then go to Step 4.

Else, if all segments have been assigned the backup paths successfully, then update the temporary records and the network’s state, and go back to Step 1.

**Step 4:** Adjust the link-cost according to Eq. (2), and compute the first backup path for segment $k$.

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Fig. 6. Protection switching time illustrated for segment shared protection with dual-link failures: (a) the working path traverses the two failed links; (b) the working path traverses a failed link and the first backup path traverses another failed link; (c) the working path traverses a failed link and the first backup path does not traverse failed link.
If succeed to find the first backup path, then go to Step 5.
Else, block the connection request, update the network’s state, and go back to Step 1.

Step 5: Adjust the link-cost according to Eq. (3), and compute the second backup path for segment $k$.
If succeed to find the second backup path, record the finding paths and the reserved wavelengths, update the network’s state, let $k ← k + 1$, and go back to Step 3.
Else, block the connection request, update the network’s state, and go back to Step 1.

Above procedure of the SSP shows that if only a segment fails to establish the backup paths, the connection request will be blocked. The complexity of the SSP mostly depends on running the times of Dijkstra’s algorithm whose complexity is $O(|N|^2 \log |N|)$. Analyzing the process of the algorithm, SSP will run one time of Dijkstra’s algorithm for computing a working path, and run two times of Dijkstra’s algorithm for computing two backup paths of a segment. For $k$ segments of a working path of a connection request, the complexity of the SSP is approximately $O(|N|^2 + 2k|N|^2)$.

3.2. Performance parameters

The resource utilization ratio (RUR) is calculated as

$$\text{RUR} = \frac{\sum_{l \in L} R_l}{\sum_{l \in L} W_l}.$$  \hfill (6)

It is obvious that a smaller value of the RUR means that we need to assign fewer wavelengths and also means a smaller backup wavelengths reserve on all the backup paths and a higher degree of reserved wavelengths sharing; that is, a higher resource utilization ratio. Higher resource utilization ratio will lead to lower traffic blocking because more free wavelengths can be used in the following traffic routing.

The requests blocking ratio (BR) is the ratio of $|R|$ to $|V|$, where $R$ is the set of connection requests that are being abandoned by the network and $V$ is the set of all connection requests that have arrived at the network. In the case of dynamic traffics, the BR can approximately reflect the effectiveness of resource utilization, and a smaller BR means a higher resource utilization ratio.

The average protection switching time (APST) is calculated as

$$\text{APST} = \sum_{q \in M} t_q/|M|,$$  \hfill (7)

where $M$ is the set of segments that traverse the failed links. A smaller APST means faster recovery after the failures.

The dropping ratio (DR) is the ratio of $|C|$ to $|H|$, where $C$ is the set of unprotected connections as the failures occur and $H$ is the set of connections that are holding on the network. It is obvious that value of DR is equal to zero means that the algorithm provides 100% reliable protection.

4. Simulation results and analysis

4.1. Testing model

We simulate a dynamic network environment with the assumptions that connection requests arrive according to an independent Poisson process with arrival rate $\beta$ and that the connections’ holding times are negatively exponentially distributed, $1/\mu$; that is, the network load is $\beta/\mu$ erlang. We assume that $\mu = 1$ and each requested bandwidth is a wavelength. If the connection fails to be established, the network abandons it immediately; i.e., there are no waiting queues. The test network is shown in Fig. 7, where nodes, which have full wavelength conversion capacities (assume Optical-Electric-Optical conversion), are interconnected by bi-directional fiber links whose basic link-cost are a constant assumed to be 50. The number of wavelengths per fiber is assumed to be ten.

The $M$, which denotes the length of the segment, can be equal to 1, 2, 3, and FL (full length of the working path), respectively. We shall compare the performances of the SSP with the previous algorithm PSP [10] that computes a shortest working path and two shortest backup paths for each connection request. All simulation results are averaged by simulation of $10^6$ connection requests.
4.2. Results analysis

Fig. 8(a) shows that, with a same $M$, the RUR of the SSP is big for $\varepsilon = 0$, and reduces and gradually becomes invariable as $\varepsilon$ increases. Because there is no consideration about the resource sharing degree as $\varepsilon = 0$ according to Eqs. (2) and (3), and the paths are merely the shortest routes; as $\varepsilon$ increases, the links, which already have enough reserved wavelengths, have less link-cost. Then, the backup paths would be favorable for traversing these links, that is, they are favorable for selecting the least additional reserved backup wavelengths as the paths. Thus, the resource utilization ratio would be improved (see the illustration in Fig. 5). Based on this simulation result, we choose $\varepsilon = 4$ for the SSP to
compare with the PSP. In fact, PSP is a special case for SSP as $\varepsilon = 0$ and $M = FL$.

Fig. 8(a) also shows that, as the $M$ increasing, the RUR of the SSP will reduce, and this means that the resource utilization ratio has been improved as the $M$ increasing. Because the $M$ is bigger, the resource utilization ratio of the SSP will be higher. The reason for this has been analyzed in Section 2.2.

Fig. 8(b) shows that, when two random links fail, the DRs of the SSP and the PSP both are equal to zero, and this means that the SSP and PSP can completely protect the dual-link failures, namely, they provide 100% reliable protection.

We can see in Fig. 8(c) that, the RUR of the SSP ($M = FL$) is lower than the PSP, because the SSP ($M = FL$) can improve the resource sharing degree and are favorable for selecting the least additional reserved backup wavelengths as the paths, but the PSP only compute the shortest paths that do not consider the resource sharing degree. Therefore, the SSP ($M = FL$) has higher resource utilization ratio than the PSP, and this will lead more free wavelengths can be used by the following connection requests, and then SSP ($M = FL$) has a lower blocking ratio than PSP, which has been shown in Fig. 8(d).

Fig. 8(c) also shows that, when the $M$ increasing, the RUR of the SSP will reduce, and this denotes that bigger $M$ means higher resource utilization ratio (the reason for this has been analyzed in Section 2.2). Thus, bigger $M$ will lead to lower blocking ratio, which has been shown in Fig. 8(d), because more free wavelengths can be used by the following connection requests.

It is shown that, in Fig. 8(e), the APST of the SSP ($M = FL$) is bigger than the PSP, and this means that the SSP ($M = FL$) has a slower recovery than the PSP after the failures. Because the paths of the PSP are the shortest routes, but the paths of SSP ($M = FL$) are the least-cost routes. Generally, the lengths of the paths with least-cost are bigger (e.g., in order to share more reserved wavelengths, the paths may traverse more link hops), and this will lead $n_1$, $n_2$ and $m$ in Eqs. (4) and (5) increase, and then the APST becomes bigger. We also see that, as the $M$ increasing, the APST of the SSP will increases, and this means that longer segment will lead to longer protection switching time. The reason for this is that (see Section 2.2), as the lengths of the paths (segment paths and backup paths) increasing, the $n_1$, $n_2$ and $m$ in Eqs. (4) and (5) will increase, and then the APST will become bigger.

We can thus conclude that: (1) the SSP can provide 100% reliable protection for the dual-link failures; (2) when $M = FL$, the SSP has higher resource utilization ratio and lower blocking ratio than the PSP; (3) when $M$ is less than the FL, the SSP has faster protection switching time than the PSP; (4) by configuring different $M$, the SSP is able to determine the appropriate trade-offs between the resource utilization ratio (blocking ratio) and the protection switching time.

5. Conclusions

In this paper, we investigate the protection design for the dual-link failures in survivable meshed WDM optical networks, and propose a novel heuristic algorithm, which is called segment shared protection (SSP) that can adjust the resource sharing degree according to the current state of the network. We describe our scheme of dividing the segment and the method of assigning the reserved backup wavelengths. We also study the protection switching time, which had not been studied by previous algorithms, for the dual-link failures, and calculate the formulas of the protection switching time. The simulation results show that: SSP provides 100% reliable protection for the dual-link failures; with respect to the previous algorithms, SSP, adds a valuable elasticity between the resource utilization and the protection switching time, and is able to perform higher resource utilization ratio, lower blocking ratio, and faster protection switching time.

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