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Efficient path protection in bi-directional WDM systems

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Abstract

Bi-directional WDM transmission is a technique that allows data to be transmitted simultaneously in both directions of a fiber, with different sets of wavelength channels for each direction. Compared with unidirectional WDM systems, it not only saves the cost of deploying extra fibers, but also allows more flexible bandwidth provisioning. To exploit this flexibility, we investigate path protection schemes for bi-directional WDM transmission systems in this paper. With path protection, a call is accepted if and only if an active data path together with a disjointed backup path can be found in the network. With bi-directional WDM, backup resource sharing in both directions of a fiber is possible. Based on a set of judiciously designed link cost functions, two original path protection schemes are proposed in this paper, BiPro and BiProLP. BiProLP aims at further economizing the hardware cost incurred by BiPro. In contrast to the traditional unidirectional schemes, we show that both BiPro and BiProLP can yield noticeably lower call blocking probability, higher system capacity and shorter active/backup path length.

Keywords: Bi-directional WDM; Two-step routing; Path protection

1. Introduction

Wavelength-division multiplexing (WDM) [1] is a promising technology to construct optical mesh networks. Exploiting the large bandwidth of optical fibers, WDM couples multiple wavelengths onto a single fiber. In circuit-switched WDM mesh networks, a concatenation of wavelengths on different fibers provides an all-optical end-to-end connection called lightpath. Notably, the data carried by a lightpath remains in the optical domain while traversing through the intermediate nodes.

To deliver reliable services in high-speed networks such as WDM networks, efficient recovery schemes are required to protect the traffic carried on data paths. Many schemes have been proposed and studied in the literature [2–10,21,23–25,29,32]. (Please refer to Section 2 for details.). In this paper, we consider path protection for its high bandwidth efficiency [10]. With path protection, a call is accepted if and only if an end-to-end active path (AP) together with a disjointed backup path (BP)

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can be found in the network. The traffic on the AP is protected by switching data onto BP if any failure occurs on the AP. The resources reserved by BPs can be shared for protecting multiple APs, provided that those APs are disjointed. Different routing algorithms have been proposed for path protection. The routing algorithms in [2,7,10,21] are based on integer linear programming (ILP) formulation, aiming at minimizing the cost consumed by the pair of disjointed AP and BP.

An alternative approach adopts the notion of two-step routing [6], where it first finds the widest–shortest path for AP and then the shortest–widest path for BP. The adoption of two different routing algorithms is motivated by the fact that an AP is dedicated to a particular call and is occupied for the whole call duration, whereas a BP is shared and will not be occupied unless there is a fault in the APs under its protection. In [6], the widest–shortest path (WSP) algorithm is adopted for AP routing in order to minimize the resources occupied by an AP. Note that minimizing the AP length also helps to minimize undesirable service interruptions at recovery [31]. On the other hand, due to bandwidth sharing, load balancing is considered more important than minimizing network resources in BP routing. Shortest–widest path (SWP) routing is thus preferred. Results in [6] showed that two-step routing outperforms the ILP-based schemes.

In the context of WDM networks, both AP and BP are lightpaths. In a conventional WDM network, at least two fibers are required for providing direct duplex transmission between two nodes. This is because the direction of data transmission is fiber-based. We refer to such a WDM network as unidirectional. With the recent advances in WDM technology, bi-directional WDM transmission [1,8,14–17,35–39] becomes mature and widely available. A bi-directional WDM system allows data to be transmitted simultaneously in both directions of a fiber, with different sets of wavelength channels for each direction, or the direction of data transmission becomes wavelength-based. This allows a much flexible bandwidth provisioning because any combinations of wavelengths can be assigned to either direction of a single fiber.

To exploit this flexibility, we focus on designing efficient path protection schemes in bi-directional WDM networks in this paper. Two original bi-directional path protection schemes, BiPro and BiProLP, are proposed. They both follow the approach of two-step routing in determining active paths and backup paths, where BiProLP aims at further economizing the hardware cost incurred by BiPro. Comparing with the existing schemes based on unidirectional WDM transmission, we show that both BiPro and BiProLP yield noticeably lower call blocking probability, higher system capacity and shorter active/backup path length.

The rest of the paper is organized as follows. Section 2 reviews the existing work on optical WDM network protection. Section 3 introduces the bi-directional WDM transmission technology, and presents our basic bi-directional path protection scheme (BiPro). Aiming at further economizing the hardware cost incurred by BiPro, Section 4 extends BiPro to BiProLP. The performance of BiPro and BiProLP is then compared with unidirectional scheme (UniPro) in Section 5. We conclude the paper in Section 6.

2. Related work

In recent years, recovery schemes and techniques for optical WDM mesh networks have been intensely studied [2–10,21,23–25,29,32]. They differ from each other in the speed of recovery, the amount of resources that must be pre-allocated (if any) to backup paths, the increased complexity of configuration and signaling, and the change in the length of data paths.

Depending on how backup paths/lightpaths are established, recovery schemes can be classified into two models [10]: dynamic restoration or preplanned protection. Using dynamic restoration, backup paths are created after detecting a fault on active paths (defined as the established lightpaths carrying traffic under the normal situation). Dynamic restoration has more efficient resources utilization, since it does not need to allocate resources for backup in advance. But the associated recovery time is relatively long due to the signaling and processing overhead in establishing backup paths on demand. More importantly, the network may not have enough available spare resources to accommodate the new backup paths, and thus the dynamic restoration cannot guarantee 100% recovery, even for single element failure. Considering high capacity of data carrying by fibers, preplanned protection is much more attractive for protection in optical networks.

Depending on the sharability of the resources along the backup paths, preplanned protection can be further categorized as dedicated protection [30] and shared protection [10,32]. The former refers to the simple preplanned protection in which the resources pre-allocated along the backup path are only dedicated for one connection. In contrast, shared protection has received much more attention [2–4,6–10,24,25] because of its high resource efficiency. The reasoning behind shared protection is that since concurring failures are not expected in a network, two backup paths whose active paths are disjointed must not be activated simultaneously. Hence, to take this advantage, we allow that the resources reserved along a backup path can be shared to another backup path as long as their active paths are disjointed. This is so-called backup resource sharing. Compared to dedicated protection, shared protection is cost-effective and pervasive, but it may have a slower recovery speed because it may need time to configure some optical switches en route when activating a backup path.

In terms of protected unit, protection schemes can alternatively be further classified into path protection, link protection and segment (sub-path) protection. Path protection [3,6,7,23,24] uses an end-to-end disjointed backup path to protect the active path. Any node or link failure on active path triggers traffic switchover to backup path at the source node. Compared with link or segment protection, path protection is more popular because it has more efficient bandwidth utilization [10,32] and lower end-to-end propagation delay for the recovered route [30].

With link protection [23], each link on an active path is protected by a backup path that can reroute traffic around that link. If a failure occurs at a protected link, the upstream node adjacent to the fault will respond to redirect the affected traffic flow onto the corresponding backup path. So the recovery can be completed locally and thus quickly. But, it incurs high overhead while setting up backup paths, as well as high resource costs.

Segment (sub-path) protection [25,29] is a compromise between path protection and link protection, attempting to achieve both cost-efficiency and fast restoration simultaneously. Specifically, segment protection divides the active path into several segments and provides a backup path to each of them. But how to partition an active path into segments is still an open question. Besides, we have to mention that in an optical network without wavelength conversion, segment protection or link protection requires that all links along the active and backup paths of a connection must reserve the same wavelength, whereas path protection allows the backup path to use different wavelengths from the active path uses. So provisioning a protected connection under segment protection or link protection is generally more difficult than under path protection.

In this paper, we focus on shared path protection schemes that provide 100% survivability for any single-link failure.

3. Bi-directional path protection (BiPro)

3.1. Bi-directional WDM and bi-directional backup sharing

Bi-directional WDM transmission technology can provide uplink and downlink in a single fiber for FTTH access networks [36]. It can also be employed to construct bi-directional self-healing ring (SHR) network with two fibers instead of four [35]. Besides, bi-directional WDM adapts well to asymmetric traffic demands. With the exponential growth of IP traffic carried by optical backbone networks, asymmetric nature of IP traffic has sometimes caused one direction of some links fully congested and the other direction underutilized [34]. The study in [33] based on European backbone optical network tells us that allowing asymmetric capacity on different directions can reduce network cost dramatically. Due to the flexibility of bi-directional WDM transmission, we can allow adjustable sets of wavelength channels for each direction of a fiber. In this paper, we focus on designing efficient network protection schemes using bi-directional WDM transmission.

In a bi-directional WDM network, the wavelengths in a fiber are divided into two non-overlapped sets for carrying traffic in both directions. Bi-directional WDM transmission can be implemented using bi-directional add/drop multiplexers (BADMs) or bi-directional optical cross-connects (BOXCs) at each end of the fiber. Although bi-directional WDM transmission suffers from relative intensity noises caused by Rayleigh backscattering (RB), optical reflection and crosstalk [8,35], many new techniques have been invented for constructing BADMs or BOXCs, such as arrayed-waveguide grating (AWG), circulator and tunable fiber Bragg grating (FBG) [14–17,35–39]. In [14,35], a new bi-directional WDM ring network with BOXC based on a single arrayed-waveguide grating (AWG) is designed, where RB noise can be eliminated at a cost of a high insertion loss due to using AWG. A cost-effective BADM using multi-port circulators and fiber Bragg gratings (FBG) is proposed in

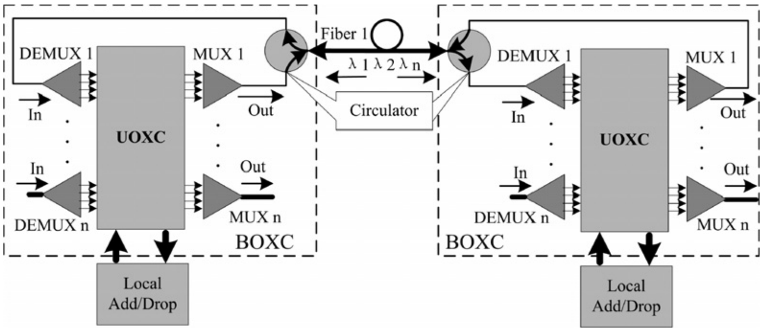

Fig. 1. A bi-directional WDM system implemented using unidirectional optical cross-connect and circulators.

[16,38]. Two identical sets of wavelengths in opposite direction, along with optical edge filters, to eliminate RB crosstalk in bi-directional WDM networks are demonstrated in [36]. Since our proposed path protection schemes can be applied relatively independent of the BOXC implementation, without loss of generality, we adopt the independently switchable bi-directional optical cross connect (IS-BOXC) [17] model in our subsequent discussion.

An IS-BOXC consists of a conventional unidirectional optical cross-connect (OXC) and a set of circulators. Fig. 1 shows that two nodes, equipped with IS-BOXC, are connected by a single fiber. Notably, the circulators, which are responsible for properly separating/isolating the wavelengths running in the opposite directions of a fiber, play a key role in such a system. A circulator [1,8] is a multi-port device that allows signals to propagate in certain directions based on the port that the signals come from and block all transmission in other directions. In Fig. 1, wavelengths arriving at the circulators from the fiber can only be transmitted toward the input ports of the switch, while other wavelengths leaving the switch are guided onto the fiber. Note that a circulator is flexible in provisioning asymmetric traffic flows, *i.e.* an arbitrary number of wavelengths in each direction of the fiber.

If two nodes in a WDM network are connected, we say there is a link (or cable) between them. All the links in the network constitute a link set $\boldsymbol{E}$. Link l consists of f_l parallel fibers and each fiber can simultaneously carry up to W wavelengths, where W is called the capacity of a single fiber. The total capacity on link l is thus $f_l \cdot W$ wavelengths, which carry the bi-directional traffic flows between the two connected nodes. With conventional unidirectional WDM, wavelengths inside the same fiber must follow the same direction. Therefore, the wavelengths allocated to the two directions of the link are of the format $(xW, (f_l{-}x)W)$, *i.e.* xW wavelengths in one direction and the rest in the other direction. The value x is pre-determined and cannot be (easily) changed. If bi-directional WDM is adopted, a more flexible bandwidth allocation of $(i,\ f_lW - i)$ can be obtained on each fiber. More importantly, the value of i, ranged from 0 to f_lW, can be dynamically adjusted on a call-by-call basis.

Under the assumption that a single link[1] failure occurs at a time, two link-disjointed active paths (APs) will not be affected by the same link failure, and so their backup paths (BPs) can share the same wavelength resources. For unidirectional WDM systems, the backup resource sharing is also unidirectional. That means a wavelength can only be used to carry those BPs running in the same direction as the fiber it resides in. But in bi-directional WDM systems, the reserved backup wavelength can be used to carry the rerouted data traffic in either direction of the link. So two BPs running in the opposite direction can share the same wavelength inside a link – we call this bi-directional backup sharing. Refer to the example in Fig. 2. There are two APs, $1 \to 2 \to 5 \to 7$ and $7 \to 6 \to 3 \to 1$. Each of them requires one wavelength in every traversed link. With unidirectional WDM, the two corresponding backup paths (BP1 and BP2) are carried by four unidirectional fibers, $1 \to 4$, $4 \to 7$, $7 \to 4$ and $4 \to 1$. So four units of bandwidth, or four wavelength-links, must be reserved. With bi-directional WDM, only two wavelength-links are needed, in bi-directional fibers $1 \leftrightarrow 4$ and $4 \leftrightarrow 7$, respectively.

[1] This can be easily extended to the case of node failure. In practice, node failure can be effectively suppressed by placing redundant switching components at each node.

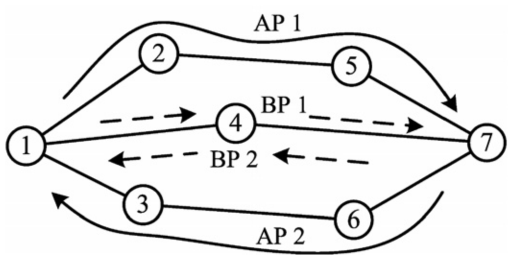

Fig. 2. An example to illustrate bi-directional backup sharing. In unidirectional sharing, four wavelength-links along BP1 and BP2 should be reserved. With bi-directional sharing, only two wavelength-links are required.

3.2. Bi-directional path protection (BiPro)

Consider a bi-directional WDM network using three-port circulator (Fig. 1). Assume each node has unlimited local wavelength add/drop and full wavelength conversion capability. In order to provide flexible bandwidth allocation, the switch fabric at each node must provide W input ports and W output ports for each connected fiber. Since cable/link cut is the most common cause for link failure and generally all the fibers in a link span the same cable, we assume that all fibers in a link share the same risk of failure. Following the common practice [2,6,7], we consider single link failure at a time.

Let each connection request be characterized by a tuple (s, d, w), where s and d are the source and destination nodes, and w is the number of wavelengths requested. Without loss of generality, Fig. 3 shows a snapshot of the bandwidth usage on link l. We can see that among the total $f_l W$ wavelengths, A_l wavelengths are occupied by active paths (APs) (running in both directions), B_l wavelengths are taken by backup paths (BPs), and the remaining $R_l = f_l W - (A_l + B_l)$ wavelengths are idle (called residual wavelengths). We use $\boldsymbol{A}_l$, $\boldsymbol{B}_l$ and $\boldsymbol{R}_l$ to denote the corresponding sets of wavelengths. Note that wavelengths in $\boldsymbol{B}_l$ can be shared to protect multiple APs, and the wavelengths in sets $\boldsymbol{B}_l$ and $\boldsymbol{R}_l$ can be used to carry calls along either direction of the link.

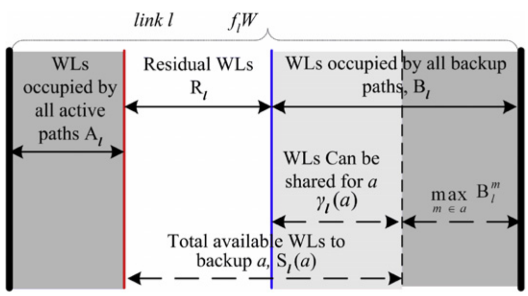

Fig. 3. Channel usage on a bi-directional link l. (WL = wavelength.)

A call is admitted if two link-disjointed AP and BP paths are found. To carry an AP via link l, we must have $R_l \geqslant w$. If $R_l < w$, link l must reject the call due to insufficient bandwidth. The associated link cost is defined as

$$\text{link cost (active)} = \begin{cases} w & \text{if} \quad R_l \geqslant w \\ \infty & \text{otherwise} \end{cases}. \tag{1}$$

The total cost of setting up an AP, or its path cost, is the sum of the costs induced at individual links along the selected path. Path cost is minimized if the hop-distance between nodes s and d is minimized.

Assume AP a is found. Then we need to determine the backup path for a. To carry the BP via link l, a must be disjointed with l and l must have sufficient bandwidth to provide the protection. Let $\boldsymbol{S}_l(\boldsymbol{a})$ be the set of available wavelengths on l for carrying the BP of a. As shown in Fig. 3, $\boldsymbol{S}_l(\boldsymbol{a})$ consists of two components, the residual wavelengths $\boldsymbol{R}_l$ and $\boldsymbol{\gamma}_l(\boldsymbol{a})$, a subset of $\boldsymbol{B}_l$ that can be shared to carry the current BP. If we use $S_l(a)$ to denote the size of $\boldsymbol{S}_l(\boldsymbol{a})$, we have

$$S_l(a) = \gamma_l(a) + R_l. \tag{2}$$

If $S_l(a) \geqslant w$, the BP can be set up on link l. To encourage backup resources sharing, the associated link cost is defined as follows:

$$\text{link cost (backup)} = \begin{cases} 0 & \text{if} \quad \gamma_l(a) \geqslant w, \ l \notin a \\ w - \gamma_l(a) & \text{if} \quad 0 \leqslant \gamma_l(a) < w, \ l \notin a\,. \\ \infty & \text{if} \quad S_l(a) < w, \ \text{or } l \in a \end{cases} \tag{3}$$

Unlike APs, the path cost of a longer BP may be less than that of a shorter one, because of backup sharing.

Next we derive $\boldsymbol{\gamma}_l(\boldsymbol{a})$ and its size $\gamma_l(a)$. Assume m is a link traversed by AP a. Let $\boldsymbol{\Omega}^m$ be the set of active paths carried on m (in both directions). Let $\boldsymbol{\Omega}_l^m$ be a subset of $\boldsymbol{\Omega}^m$ that have their BPs passing through link l. So from link l's point of view, APs in $\boldsymbol{\Omega}_l^m$ are not disjointed and thus their BPs on l cannot mutually share the same set of reserved wavelengths. Assume the number of wavelengths taken up by APs in $\boldsymbol{\Omega}_l^m$ is B_l^m. We have

$$\gamma_l(a) = B_l - \max_{m \in a} B_l^m. \tag{4}$$

The term $\max_{m\in a} B_l^m$ is to take the maximum of B_l^m over all links along AP a, that are protected by the BPs on link l.

Note that we must have

$$B_l = \max_{\forall m \in E} B_l^m. \tag{5}$$

Accordingly, $\gamma_l(a) \geqslant 0$. The above Eq. (5) can be understood by the fact that the total number of reserved wavelengths on link l, *i.e.* B_l, must be sufficient for carrying the rerouted traffic on APs that are affected by any single link failure. Therefore B_l must take the maximum of B_l^m over all possible links in the network.

When a call arrives, based on the cost functions defined in Eqs. (1)–(3), we adopt the two-step routing algorithm [6] for finding the best pair of link-disjointed AP and BP. The pseudo code of our proposed BiPro path protection scheme is summarized in Fig. 4. Specifically, the widest–shortest path algorithm [12] is used to find the AP with the widest residual bottleneck capacity (R_l) among all the shortest paths between the source (s) and the destination (d). If an AP is found, then the shortest–widest path algorithm [13] is activated to find the shortest backup path among all the widest paths (which have the same widest bottleneck backup cost of $S_l(a)$ in Eq. (2)).

It is worth to note the interesting work on the "trap topology" problem in [26–28]. A trap refers to a specific topology such that although link-/node-disjoint path pairs exist, routing algorithms operating in two steps (including our two-step routing) may fail to find such path pairs, *i.e.* to fully avoid traps. In fact, finding two link-disjoint paths with minimum bandwidth cost in a shared path protection network is NP-complete [23]. (Note that if the shared risk link group (SRLG) constraints [27,31] are imposed, finding a risk-disjoint path pair even without considering minimization of bandwidth cost is NP-complete [22].) Since the occurrence of trap topology in real networks is fairly rare [4,24], we thus focus on studying the impacts of bi-directional WDM transmission system rather than routing algorithms for trap-avoiding.

```
Algorithm BiPro:
/*Input: wavelength consumption information and connection
 *request (s, d, w).
 *Output: A pair of link disjointed AP and BP.*/
Call widest-shortest path algorithm based on residual
bandwidth R_l to find a path a from s to d;
if (the path cost of path a is infinite)
   return (FAILURE);              // the call is blocked.
else
{
      Compute γ_l(a) and S_l(a) using Eqns. (4) and (2) for any
   link l∈E;
      Call shortest-widest path algorithm to find path b;
      if (the path cost of path b is infinite)
          return (FAILURE);       // the call is blocked.
      else
          return a as AP and b as BP; //successfully found!
}
```

Fig. 4. Pseudo code of BiPro routing algorithm.

4. Bi-directional path protection with limited port (BiProLP)

4.1. Bi-directional path protection with limited port number

In BiPro, we have assumed that there are $2W$ ports (W inputs and W outputs) for each fiber at each node (Fig. 1). This ensures that there are always enough ports at a node to support any patterns of bandwidth allocation. Therefore, in BiPro a call is blocked only due to insufficient wavelengths to carry the call. The blocking due to insufficient ports will never occur. This high degree of bandwidth flexibility is, however, at the expenses of high port counts/costs. It is obvious that each engaged wavelength (by AP or BP) only takes up two ports, one at each end (node) of the fiber. That means on the average, each node needs only W ports ($W/2$ for inputs and $W/2$ for outputs) for each fiber, whereas $2W$ ports are provisioned by BiPro.

In this section, aiming at reducing the port counts and minimizing the blocking due to insufficient ports, we propose a new scheme called bi-directional path protection with limited port (BiProLP). Let K be the number of input ports or output ports assigned to each fiber. For a link with f_l bi-directional fibers, $f_l K \times f_l K$ ports are needed. Likewise, for a node connected with N such links, the dimension of the switch/node is $Nf_lK \times Nf_lK$. When $K = W$, we have the original BiPro. When $K < W$, a saving in the port count can be achieved, but a call may be blocked due to insufficient ports (in addition to insufficient wavelengths). In any case, K must be larger than $W/2$, or $(W - 2K)$ wavelengths could never be utilized due to its intrinsic port deficiency.

Accordingly, the dimension of the multiplexer and demultiplexer on the end of every fiber (Fig. 1) is reduced from $W \times 1$ and $1 \times W$ (in

BiPro) to $K \times 1$ and $1 \times K$ in BiProLP. As there are C_K^W possible combinations of input wavelengths for a $K \times 1$ multiplexer, the multiplexer in BiProLP must be reconfigurable to direct any wavelength within the spectrum (*i.e.* W wavelengths) onto any specific port, and so does each demultiplexer. The reconfigurable multiplexer/demultiplexer can be built with various techniques [11,18–20], such as tunable filter, waveguide switch, and MEMS switch.

It should be noted that BiProLP can be implemented in a much economical way under the following situation. Consider a multi-fiber optical network, where $f_l \geqslant 2$. Every parallel fiber, in BiPro, requires one circulator and W input or output switch ports. Unlike the earlier approach of reducing port count, we can just remove the circulators of some fibers in the link. Effectively, we turn those fibers back into unidirectional and at the same time, we cut down their ports per fiber-end to $W/2$ (from W). In so doing, we even eliminate the need for reconfigurable multiplexers. Although this is a feasible approach, it is less flexible in wavelength allocation as compared to BiProLP described above.

4.2. Port-pair cost function

BiProLP has less flexibility on wavelength allocation than BiPro. At most f_lK wavelengths of a link can be assigned to operate in the same direction simultaneously. So with BiProLP, a path (either active or backup) can be set up on link l only if (1) link l has sufficient wavelengths and (2) the two nodes connected by l have enough input/output port-pairs. Note that the wavelength and port consumption information[2] can be made available by routing protocol. This may slightly increase the routing overhead. As the link cost function in BiProLP is identical to that in BiPro, we only focus on deriving the port cost function below.

Fig. 5 shows two nodes, u and v, are connected by a bi-directional link l with capacity f_lW. Each node provides f_lK input/output port-pairs for link l (or K pairs for each fiber). From link l's perspective, it has f_lK port-pairs in each direction between u to v. For convenience, we use italic "*right*" or "*left*" to indicate the direction $u \rightarrow v$ or $v \rightarrow u$.

We first derive the port-pair cost in the *right* direction as indicated in Fig. 5. (The derivation for the *left* direction is the same and thus skipped.) Similar to wavelength consumption status in Fig. 3, all port-pairs along the *right* direction can be divided into three parts/sets: $\boldsymbol{A}_{l\text{-}right}$, $\boldsymbol{B}_{l\text{-}right}$ and $\boldsymbol{R}_{l\text{-}right}$ (with corresponding size of $A_{l\text{-}right}$, $B_{l\text{-}right}$ and $R_{l\text{-}right}$). $A_{l\text{-}right}$ is the total amount of port-pairs occupied by APs via l (in the *right* direction, by default hereinafter). $B_{l\text{-}right}$ is the total amount of port-pairs reserved for all BPs. Like wavelength sharing, the reserved port-pairs on BPs can be shared if the corresponding APs are disjointed. We call it port-pair sharing. Keep in mind that port-pair sharing is unidirectional, as port's transmission direction is fixed. So BP1 and BP2 in Fig. 2 cannot share the same port-pair in BiProLP, although they can still share wavelengths. Finally, $R_{l\text{-}right}$ $(=f_lK-(A_{l\text{-}right}+B_{l\text{-}right}))$ denotes the number of residual port-pairs.

To set up an AP via link l from $u \rightarrow v$, we must check both port-availability $R_{l\text{-}right}$ and wavelength availability R_l. If both are larger than w, the AP can be set up with w as both link cost and port-pair cost. Otherwise, the call is rejected. The path port-pair cost is defined as the sum of the port-pair costs on individual links along the selected path.

Next we consider routing the BP on l for AP a. Let $\boldsymbol{\pi}_{l\text{-}right}(\boldsymbol{a})$ be the subset of $\boldsymbol{B}_{l\text{-}right}$ that can be shared to carry the BP for AP a. The size of $\boldsymbol{\pi}_{l\text{-}right}(\boldsymbol{a})$ is denoted by $\pi_{l\text{-}right}(a)$. Then $S_{l\text{-}right}(a)$, the total number of available backup port-pairs for carrying a's BP, is given by

$$S_{l\text{-}right}(a) = \pi_{l\text{-}right}(a) + R_{l\text{-}right}. \tag{6}$$

The link port-pair cost function for setting up a BP is

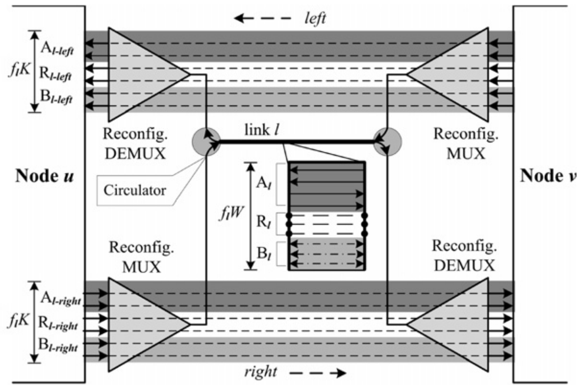

Fig. 5. State information maintained by BiProLP scheme. The direction, from node u to v, is referred to as *right*.

[2] In fact, wavelength consumption statistics can be directly deduced from port consumption data, as detailed in Section 4.3.

$$\text{port} - \text{pair cost (backup)} = \begin{cases} 0 & \text{if} \quad \pi_{l\text{-}right}(a) \geqslant w,\ l \notin a \\ w - \pi_{l\text{-}right}(a) & \text{if} \quad 0 \leqslant \pi_{l-right}(a) < w,\ l \notin a \\ \infty & \text{if} \quad S_{l-right}(a) < w, \quad \text{or} \quad l \in a \end{cases}. \tag{7}$$

The way to derive $\pi_{l\text{-}right}(a)$ and $\boldsymbol{\pi}_{l\text{-}right}\ (\boldsymbol{a})$ is a little bit different from deriving $\gamma_l(a)$ in Eq. (4). Assume link m belongs to a. Let $\boldsymbol{\Phi}^{m\text{-}right}_{l\text{-}right}$ denote the set of APs go through link m's *right* port-pairs and have their BPs passing through *right* port-pairs of link l. Let the number of APs in set $\boldsymbol{\Phi}^{m\text{-}right}_{l\text{-}right}$ be $D^{m\text{-}right}_{l\text{-}right}$. Similarly, we can define $\boldsymbol{\Phi}^{m\text{-}left}_{l\text{-}right}$ and $D^{m\text{-}left}_{l\text{-}right}$ for APs carried by *left* port-pairs on m and have their BPs passing through *right* port-pairs on l. It should be noticed that the port-pairs reserved for $\boldsymbol{\Phi}^{m\text{-}right}_{l\text{-}right}$ and $\boldsymbol{\Phi}^{m\text{-}left}_{l\text{-}right}$ cannot be shared. We have

$$\pi_{l\text{-}right}(a) = B_{l\text{-}right} - \max_{m \in a}\left(D^{m\text{-}right}_{l\text{-}right} + D^{m\text{-}left}_{l\text{-}right}\right). \tag{8}$$

The routing algorithm adopted by BiProLP also follows the two-step routing approach, as summarized in Fig. 6.

4.3. Statistic of port-pair and wavelength consumption

The BiProLP scheme makes a routing decision based on both wavelength and port-pair consumption statistic in the network, which can be collected by the routing protocol. In this section, we show that wavelength consumption data on link l, *i.e.* A_l, B_l and B^m_l, can be directly deduced from link l's port-pair consumption data, *i.e.* $A_{l\text{-}right}$, $A_{l\text{-}left}$, $D^{m\text{-}right}_{l\text{-}right}$, $D^{m\text{-}left}_{l\text{-}right}$, $D^{m\text{-}right}_{l\text{-}left}$ and $D^{m\text{-}left}_{l\text{-}left}$. That implies a saving in routing information exchange.

From Fig. 5, we can see that every wavelength carrying an AP must occupy a port-pair along *right* or *left* direction (without sharing), and thus we have

$$A_l = A_{l\text{-}right} + A_{l\text{-}left}. \tag{9}$$

We would like to remark that there is no such relationship among B_l, $B_{l\text{-}right}$, and $B_{l\text{-}left}$, as wavelength sharing can be bi-directional but port-pair sharing cannot.

Consider an arbitrary link $m \in \{\boldsymbol{E} - l\}$. For all BPs whose APs are in one of the four sets $\boldsymbol{\Phi}^{m\text{-}left}_{l\text{-}right}$, $\boldsymbol{\Phi}^{m\text{-}right}_{l\text{-}right}$, $\boldsymbol{\Phi}^{m\text{-}left}_{l\text{-}left}$ and $\boldsymbol{\Phi}^{m\text{-}right}_{l\text{-}left}$, they share the same risk (of m's failure) and thus cannot have backup port-pair or wavelength sharing on link l. So a total amount of $\left(D^{m\text{-}right}_{l\text{-}right} + D^{m\text{-}left}_{l\text{-}right} + D^{m\text{-}right}_{l\text{-}left} + D^{m\text{-}left}_{l\text{-}left}\right)$ port-pairs as well as wavelengths must be reserved for these BPs on link l. Therefore, we have

$$B^m_l = \left(D^{m\text{-}right}_{l\text{-}right} + D^{m\text{-}left}_{l\text{-}right} + D^{m\text{-}right}_{l\text{-}left} + D^{m\text{-}left}_{l\text{-}left}\right). \tag{10}$$

According to Eq. (5), the total number of reserved wavelengths on bi-directional link l, *i.e.* B_l, should be

$$B_l = \max_{\forall m \in E}\left(D^{m\text{-}right}_{l\text{-}right} + D^{m\text{-}left}_{l\text{-}right} + D^{m\text{-}right}_{l\text{-}left} + D^{m\text{-}left}_{l\text{-}left}\right). \tag{11}$$

From Eqs. (9)–(11), we can see that BiProLP scheme only needs to exchange port-pair consumption data.

```
Algorithm BiProLP:
/*Input: wavelength & port-pair consumption information and
 *connection request (s, d, w).
 *Output: A pair of link disjointed AP and BP.*/
Call widest-shortest path algorithm based on R_l, R_l-right and
R_l-left to find a path a from s to d;
if (the path cost or path port-pair cost of path a is infinite)
   return(FAILURE);              //the call is blocked
else
{
     Compute π_l-right (a), π_l-left (a), S_l-right (a), S_l-left(a), γ_l(a)
   and S_l(a) using Eqns. (8)(6)(4)(2) for each link l;
     Call shortest-widest path algorithm to find path b;
     if(the path cost or path port-pair cost of path b is
   infinite)
          return(FAILURE);          //the call is blocked.
     else
          return a as AP and b as BP;    //successfully found!
}
```

Fig. 6. Pseudo code of BiProLP routing algorithm.

5. Simulation results

In this section, we compare the performance of our proposed BiPro and BiProLP schemes with a unidirectional protection scheme (UniPro). In UniPro, the same two-step routing algorithm is applied except that the unidirectional WDM transmission is assumed.

The following performance measures are used: call blocking probability, average hop-revenue, active path length, and backup path length. Among them, call blocking probability is the most important measure as it directly reflects the traffic-carrying capability of a network. Average hop-revenue is defined as the average of every admitted call's shortest-hop distance based on the static topology.

A higher value indicates that the given algorithm does not jeopardize against long-hop calls. Active path length determines the end-to-end delay performance experienced by the user traffic and backup path length reflects the performance of the user traffic when a network fault occurs.

We present the simulation results based on two network topologies below. Topology I is shown in Fig. 7 and is adopted from [2]. It has 15 nodes and 28 links. Topology II in Fig. 8 is adopted from [6] and is based on the US Sprint backbone network, which has 15 nodes and 33 links. We assume each link consists of two fibers, *i.e.* $f_l = 2$ and each fiber has a capacity of $W = 16$ wavelengths. For BiProLP, each fiber has K input ports and K output ports, where the value of K is varied in our simulations. We consider a dynamic traffic model where calls arrived at the network following a Poison process with mean rate λ. For each call, the source and destination nodes are randomly selected, and the duration of a call is exponentially distributed with mean $1/\mu$, where μ is the mean call departure rate. The network load is thus defined as λ/μ, and is varied in our simulations from 120 to 250 for Topology I and from 120 to 340 for Topology II. The wavelength requirement of each call (w) is set to 1. For each tested protection scheme under a specific network load, every data point is the average over 1 million calls. Accordingly, the blocking probability obtained has a confidence interval of ±0.002, the revenue ±0.003, active path length ±0.0037 hops, and backup path length ±0.005 hops, all at the confidence level of 95%.

In our simulations, we implemented BiProLP with six different port number values, *i.e.* $K = 7, 8, 9, 10, 16, 20$. From Figs. 9–16, we can see that as K increases, the performance of BiProLP improves very quickly until $K = 16$ (the number of wavelengths in each bi-directional fiber, *i.e.* W). When the port number K is equal to or larger than

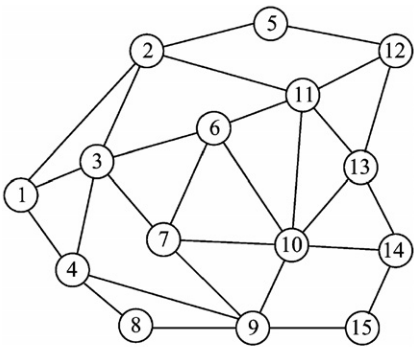

Fig. 7. Simulation topology I.

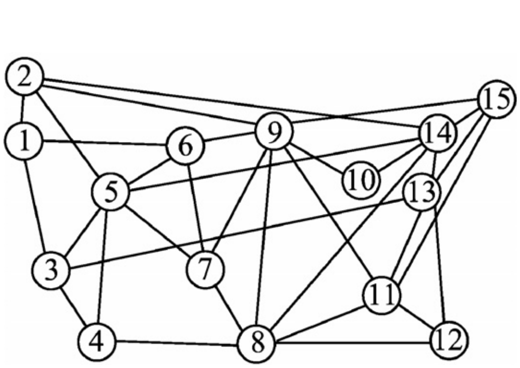

Fig. 8. Simulation topology II.

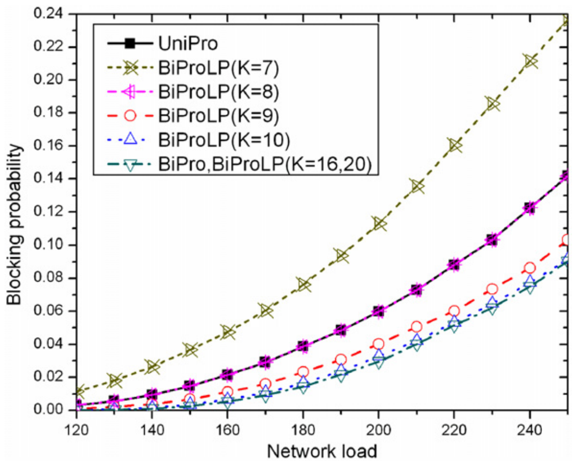

Fig. 9. Blocking probability vs. network load (topology I).

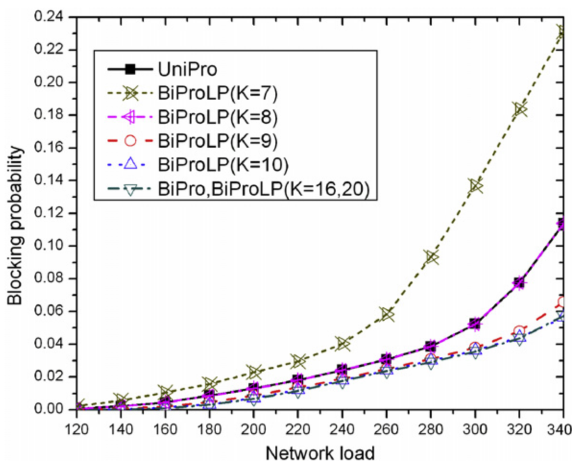

Fig. 10. Blocking probability vs. network load (topology II).

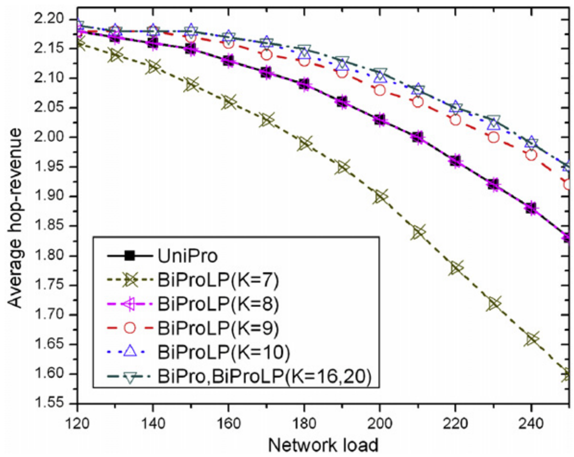

Fig. 11. Average hop revenue vs. network load (topology I).

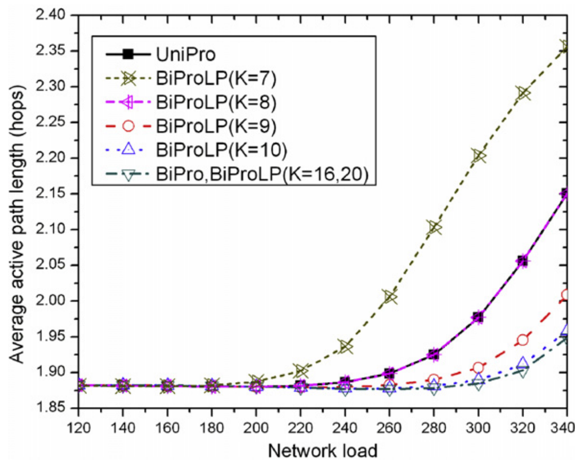

Fig. 14. Average active path length (hops) vs. network load (topology II).

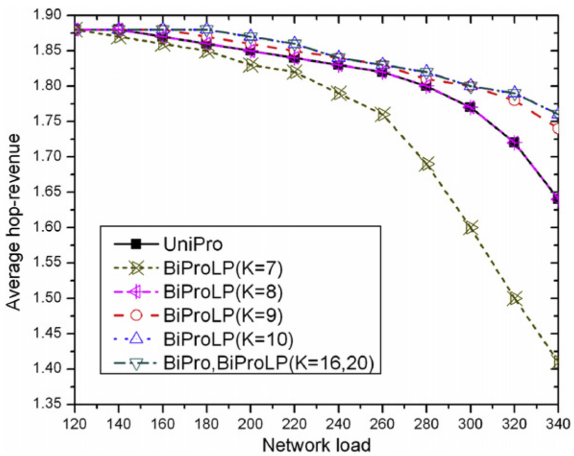

Fig. 12. Average hop revenue vs. network load (topology II).

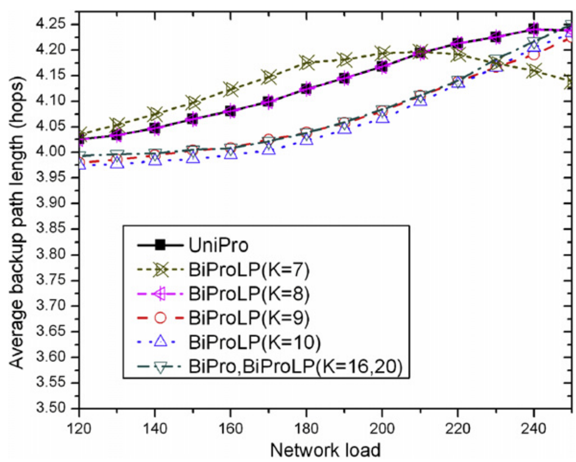

Fig. 15. Average backup path length (hops) vs. network load (topology I).

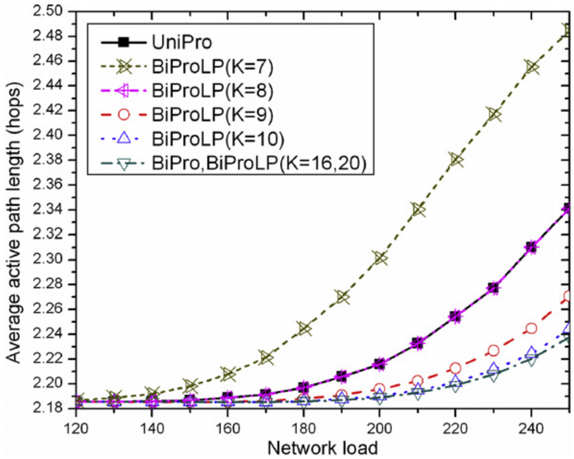

Fig. 13. Average active path length (hops) vs. network load (topology I).

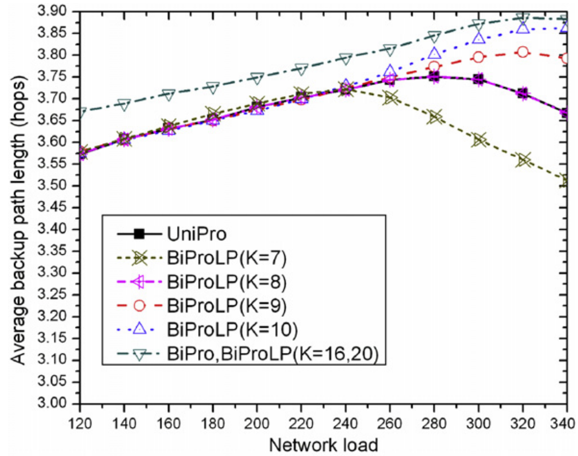

Fig. 16. Average backup path length (hops) vs. network load (topology II).

the wavelength number W, the limited-port constraint disappears and BiProLP gives the same performance as BiPro. In other words, BiPro provides the upper bound performance of BiProLP. From Figs. 9–16, it is also interesting to note that the performance of BiProLP ($K = 8$) is the same as UniPro. This is because the lack of sufficient ports throttles the bi-directional backup wavelength sharing in BiProLP to render the UniPro performance. When $K = 7$ ($<W/2$), BiProLP, as expected, performs poorly and even worse than UniPro. This is because when $K < W/2$, there are $(W - 2K)$ wavelengths could never be utilized. For clarity, in the following, we only focus on BiProLP with $K = 9, 10$ in comparing with BiPro and UniPro.

Figs. 9 and 10 show blocking probability vs. network load, one for each topology. In both figures, we can see that BiPro gives the lowest call blocking probability, whereas UniPro gives the highest (except for BiProLP with $K = 7$). BiProLP (with $K = 9$ and 10) are sandwiched by them. The performance gain using bi-directional WDM is remarkable, for example, when the network load is 160 in topology I, the blocking probabilities of UniPro, BiProLP ($K = 9$), BiProLP ($K = 10$), BiPro are, respectively, 2.14%, 1.11%, 0.65%, and 0.53%. We can see that the UniPro's blocking probability is almost twice of BiProLP ($K = 9$), more than three times of BiProLP ($K = 10$) or BiPro. This gain on blocking probability is mainly due to two outstanding features of bi-directional protection scheme: (1) the load-adaptive bandwidth allocation within the scope of each fiber and (2) the highly efficient bi-directional backup resources sharing.

From Figs. 9 and 10, we can also see that BiProLP lowers the cost of BiPro. For instance, when the network load is 300 in topology II, BiProLP ($K = 10$) cuts down the port cost by about 37.5% w.r.t. BiPro (using 16 ports per fiber). The corresponding increase in call blocking probability is just 1.68%. This also indicates that a small K value ($K = 9$ or 10 in our case) can already give satisfactory performance.

Figs. 11 and 12 show average hop-revenue vs. network load. As expected, the average hop-revenue decreases with the load. This is because longer-hop calls are more difficult to accommodate when resources are tight. However, different schemes have different decreasing rates – UniPro has the fastest decreasing rate and BiPro decreases slowest. In both sets of simulation results, BiPro gives the highest revenue value, followed by BiProLP ($K = 10$), BiProLP ($K = 9$), and UniPro. This shows that bi-directional path protection schemes are able to provision more long-distance calls than unidirectional schemes.

Figs. 13–16 show average active and backup path length (in hops) vs. network load. We can see that both average active path lengths of BiPro and BiProLP are remarkably shorter than UniPro. The backup path lengths of BiPro and BiProLP are shorter or similar to UniPro when network load is low. When network load is high, BiPro and BiProLP with $K = 9, 10$ admit more longer-hop calls than UniPro, which causes a minor increase on average backup path length. One may notice that in both Figs. 15 and 16, the average backup path length decreases when the network load goes beyond a certain threshold. This is due to the use of shortest–widest path routing for backup paths. In general, when the network load is light, many links are underutilized and the widest paths found tend to have longer lengths. As the load increases, the chance of finding a longer widest path decreases significantly.

Except for results reported above, we have also done simulations with different routing algorithms such as with the plain shortest path algorithm for both AP and BP, and also more simulations with different topologies. In all the simulations we conducted, similar conclusions as reported above hold.

6. Conclusions

In this paper, we investigated path protection based on the bi-directional WDM transmission technology. Two original bi-directional protection schemes, BiPro and BiProLP, were proposed to maximize both wavelength and port-pair sharing among backup paths. Due to the flexible resources allocation brought by bi-directional WDM, the network's capability in adapting to time varying traffic distributions has been greatly improved. Comparing with the traditional unidirectional protection scheme, we showed that our schemes yield noticeably lower call blocking probability, higher system capacity, and shorter active/backup path length. We also showed that the BiProLP scheme provides an additional flexibility in lowering the deployment cost with only marginal degradation in performance.

Acknowledgement

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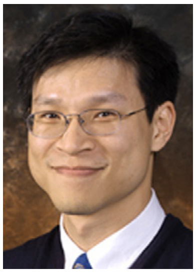

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