Dynamic Power-Aware Shared Path Protection Algorithms in WDM Mesh Networks

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***Abstract*—In this paper, we investigate the dynamic establishment of dependable connections in wavelength division multiplexing (WDM) mesh networks with the objectives of power saving and resource efficiency. According to the resource usage, i.e., assigned for primary paths, backup paths or free, and the state of network components (nodes and fiber links), i.e., active, sleep or off, we propose a dynamic power-aware shared path protection (DPA-SPP) algorithm. In order to reduce power consumption, to improve sharing of spare capacity, and to reduce blocking probability for connection requests, DPA-SPP encourages to establish a primary path for each connection request on active resources, to pack backup paths on sleep resources, and to leave more idle resources for future connection requests as far as possible while with a consideration to prevent a link with a very few number of free wavelengths to become a bottleneck link, which is beneficial to further improve the successful probability of connection establishments. Based on dynamic traffic with different load, the performance of DPA-SPP has been investigated via extensive simulations. The results show that DPA-SPP can efficiently improve the spare resource sharing and reduce the blocking probability while still achieving a considerable energy saving.**

***Index Terms*—Green networks; energy saving; shared path protection; spare capacity; dynamic**

I. INTRODUCTION

Due to the rapid growth of broadband users and emerging bandwidth-intensive applications, such as video on demand (VoD), high-definition television (HDTV), interactive gaming, etc., the traffic supported by the Internet has scaled up significantly in the last decade [1]-[3]. In optical networks employing wavelength-division-multiplexing (WDM) technology, hundreds of independent wavelength channels can be multiplexed along a single fiber, each with a transmission rate exceeding 10Gb/s or even 40 Gb/s [4]. With equivalent to Tb/s effective bandwidth, WDM networks have been playing a key role in the backbone networks and Internet. However, with the increase of transmission rate and capacity, more and more equipment and components are required to deploy globally, and the energy consumption is also grown at a high rate. If the appetite for energy continues to scale up rapidly, energy shortage will hamper the expansion of future Internet [3]-[7]. Therefore, it is imperative to develop energy-efficient backbone networks.

Recently, many research efforts have been focused on designing energy-efficient (or power-efficient) WDM optical networks as environmental-friendly solutions for backbone networks. The work in [1] provided a comprehensive survey of energy-conservation protocols and energy-efficient architectures over different domains of telecom networks. A power consumption model for transparent circuit-switched WDM networks has been provided in [2]. Based on the model, an ILP formulation with the objective to minimize the power consumption has been given and a simple heuristic algorithm has also been proposed to solve it. In the pioneering work of [5], the authors introduced the power-aware routing and wavelength assignment (PA-RWA) problem and gave an ILP-based formulation with the goal to minimize the power consumption. A heuristic algorithm has also been presented to solve it under a static traffic demand. Concentrating on minimizing the energy consumption for an IP over WDM network, an MILP optimization model and efficient heuristics with the lightpath bypass strategy have been developed in [6]. In [7], a network-based power-consumption model, taking into account energy consumption in switching and transmission equipment, has been proposed for optical IP networks to estimate the energy consumption of the Internet.

However, the aforementioned work mainly focused on the static design problem for energy-efficient WDM networks. A dynamic PA-RWA algorithm has been proposed in [8] to improve the energy efficiency of WDM networks by packing traffic on as few links as possible to minimize the number of optical amplifiers being active in the networks. As an extension of [8], an ILP formulation for the static lightpath establishment and a few heuristics for the dynamic lightpath establishment with the consideration of power consumption in multi-fiber WDM networks have been proposed in [9]. The author in [10] provided an energy-efficient dynamic connection provisioning scheme for WDM networks, based on an intelligent load control mechanism and an auxiliary model. In [11] and [12], the authors investigated the adverse effect on network blocking probability performance of PA-RWA solution, and proposed a weighted approach to make a trade-off between power saving and blocking probability. The authors in [3]

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investigated green provisioning strategies for traffic-grooming WDM networks from the component layer to network layer, and developed a power-aware scheme to minimize the total operational power.

A single fiber failure can cause the failures of all the lightpaths passing through the fiber, which leads to the loss of huge amount of data and revenue. Therefore, effective survivability mechanisms are stringent requested to minimize the data loss in WDM networks [13], [14]. There are two ways against single fiber failure in optical layer, i.e., dynamic restoration and preplanned protection [13], [14]. Protection, reserving spare capacity during lightpath setup, is essential for recovering from failures in a short time period. It has two main forms: shared protection (SP) and dedicated protection (DP). Conventionally, SP can broadly be classified into shared link-protection (SLP) and shared path-protection (SPP) [13, 14]. For each connection request, SPP first sets up a primary path, and then reserves a fiber-disjoint backup path and wavelengths for it. The reserved resources on one backup path can be shared among other backup paths if their corresponding primary paths are fiber-disjoint. Conventional SPP only focuses on improving the spare capacity sharing without considering the energy saving. In order to efficiently utilize the network resources and to improve the energy efficiency, it is better to consider the two problems simultaneously.

In [15], the authors investigated the energy-efficient network planning problem for resilient WDM networks that exploits the sleep mode of devices with dedicated path protection, and formalized it as an ILP formulation. Under the assumption that all lightpath requests are known in advance, an ILP-based formulation and a heuristic algorithm for the energy-efficient shared backup protection in WDM networks have been developed in [16] and [17], respectively. None of the above work has involved in the energy-aware survivable connection provisioning problem in a dynamic scenario. The authors of [4] proposed and evaluated different energy-efficient algorithms to dynamically provision 1:1 dedicated path protected connection for WDM networks with a sleep mode option. In [18], the authors proposed a sleep mode based power-aware SPP algorithm to achieve the power efficiency of WDM networks. However, in order to increase the load carried in active components and to turn off (or switch into sleep) as many network components as possible, the aforementioned power-aware strategies, with an overemphasis on power saving, tend to pack primary paths and backup paths in active links and sleep links respectively without considering resource efficiency. Potentially, they may choose a long path with more hops and lead to a high possibility of overutilization for some links in the network, particularly with an increase of network load. More hops mean more resources being occupied and more links being overutilization mean more possibility to lead to a temporary division in the network, which results in a less chance to successfully establish a dependable path for future connection requests. On the other side, the conventional SPP, i.e., power-unaware shared path protection (PU-SPP), with the objective to improve the utilization of spare resources, makes a great effort to reduce the resources occupied by backup paths while with an overlook to avoid more sleep components to be activated for energy saving. In order to reduce energy consumption, it is much better for SPP to jointly consider power saving and improvement of network performance in term of traditional metrics such as blocking probability and resource utilization. Moreover, most of the previous power-aware strategies only consider the energy consumption of fiber links but omitting to reduce the power consumption of nodes. Accordingly, a more general case for reducing power consumption should pick a route with less number of links and nodes in sleep or off state for a primary path and a route with less number of links and nodes in active state for a backup path.

The main objective of this paper is to investigate energy efficient shared path protection under a dynamic scenario, mainly focusing on the reduction for power consumption of nodes and links, the improvement for sharing of spare capacity and the prevention of link overutilization to reduce blocking probability of connection requests. We first introduce bottleneck link to indicate a link whether or not being overutilization, and then propose a dynamic power-aware shared path protection (DPA-SPP) algorithm for WDM mesh networks to jointly consider power saving and resource utilization. Our work differs from previous work [17], [18] in that we not only concentrate on power-saving for SPP with a joint consideration for the power consumptions of both nodes and links, but also endeavor to achieve a global efficiency in resource allocation by improving the share ratio of spare capacity and to prevent links being overutilization. The latter is favorable to further reduce blocking probability.

The rest of this paper is organized as follows. Section II presents the network model and describes the intuition of DPA-SPP by comparing its operation with two other shared path protection algorithms with different objectives. Section III describes the proposed algorithm. Simulation results are presented in Section IV. Conclusions follow in Section V.

II. System Model And Problem Analysis

A. Network Model

Define a network topology $G(N, L, W)$ for a given WDM mesh network, where N is the set of nodes, L is the set of bidirectional links, and W is the set of available wavelengths per fiber. $|N|$, $|L|$ and $|W|$ denote the number of nodes, links and wavelengths, respectively. Each node contains an electronic control system (ECS), a 3D Micro Electromechanical System (MEMS) based optical switching matrix, enough tunable transceivers, and a pair of passive optical MUX/DEMUX for each line interface [8],[9],[18].

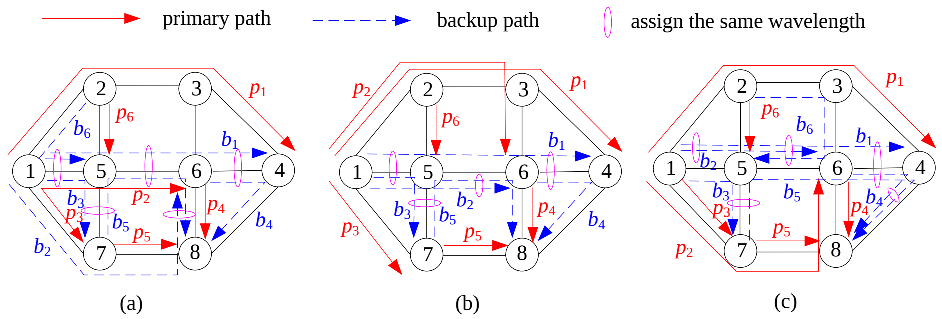


Figure 1. Comparison of different shared path protection algorithms for 6 connection requests $r_1(1, 4)$, $r_2(1, 6)$, $r_3(1, 7)$, $r_4(6, 8)$, $r_5(7, 8)$ and $r_6(2, 5)$: (a) a power-unaware SPP (PU-SPP) mainly focusing on spare resource sharing; (b) a conventional power-aware SPP (PA-SPP) mainly focusing on energy saving; (c) a power-aware SPP with a joint consideration of energy efficiency and network performance (DPA-SPP).

All network components (nodes or fiber links) have three different modes, i.e., active, sleep and off [4]. Any component included in a primary path is in active mode. An active component has a full function with a certain amount of power consumption. Any component only reserved for backup paths (i.e., not used by any primary path) is in sleep mode, which consumes a negligible amount of power and can be promptly activated if needed. In off mode, a component is not in an operation state (i.e., it is idle and its resources are not used.) and consumes no power [4].

Without loss of generality, we assume that all nodes have enough interfaces to process all the traffic that can potentially flow through it and have full wavelength conversion capabilities. Connection requests arrive at the network dynamically with no knowledge of future arrivals, and there is only one connection request with a bandwidth requirement of one wavelength unit arriving at the network at a time, defined by $r(s, d)$, where $s, d \in N$ denote the source node and the destination node of the connection request.

B. Problem Statement

To enhance power saving, the aforementioned power-aware SPP strategies (PA-SPP) deliberately pack primary paths and backup paths in different fiber links as far as possible regardless of resource utilization and link overutilization. On the other side, the conventional power-unaware SPP strategies (PU-SPP) only emphasize the improvement of the sharing of spare resources with a disregard for energy saving. Correspondingly, PA-SPP has higher resources occupation and higher possibility for link overutilization, which results in higher blocking probability and lower resource utilization, and PU-SPP has higher energy consumption.

Fig. 1 shows an example to compare PA-SPP and PU-SPP with a power-aware shared path protection (DPA-SPP) considering the trade-off between power consumption and resource usage, where all the links represent bidirectional fibers and have the same physical length and each fiber have two wavelengths. Let $r_1(1, 4)$, $r_2(1, 6)$, $r_3(1, 7)$, $r_4(6, 8)$, $r_5(7, 8)$ and $r_6(2, 5)$ be the first six connection requests for the specified source and destination node pairs. For the first request r_1, due to all the resources being free, both PU-SPP (Fig. 1 (a)) and PA-SPP (Fig. 1 (b)) choose route p_1(1-2-3-4) as the primary path and a link-disjoint route b_1(1-5-6-4) as the backup path. The connection occupies one wavelength in each link along p_1 for traffic transmission and reserves one wavelength in each link of b_1 as spare resource to maintain service continuity against a single link failure. When r_2 arrives, PU-SPP, without differentiating the links with resources that are free (in off mode), occupied by primary paths or reserved for backup paths, mainly focuses on improving the resource utilization, and picks the shortest route p_2(1-5-6) as the primary path and a link-disjoint path b_2(1-7-8-6) as the backup path. It uses one wavelength in each fiber along p_2 and reserves one wavelength in each fiber along b_2. On the other hand, the PA-SPP with the objective to minimize the power consumption by turning off idle components or by switching components only reserved for backup paths into sleep mode, deliberately chooses the link that has already been included in primary paths for previously established connections as the primary path, and packs backup path on network components included in backup paths for previous connections. As a result, it picks route p_2(1-2-3-6) as the primary path and route b_2(1-5-6) as the backup path, and occupies one wavelength in each fiber along p_2 and reserves a wavelength in each fiber along b_2. When r_3 arrives, there is no difference between PU-SPP and PA-SPP. Both of them pick the shortest route p_3(1-7) as the primary path and a link-disjoint path b_3(1-5-7) as the backup path. They use one wavelength in each fiber along p_3 and share the wavelength in the fiber along 1-5 previously reserved for r_1 due to no common link between p_1 and p_3 corresponding to requests r_1 and r_3 and reserve a wavelength in the link along 5-7. When r_4 arrives, there is also no difference between PU-SPP and PA-SPP. Both of them pick the shortest route p_4(6-8) as the primary path and a link-disjoint path b_4(6-4-8) as the backup path. They use one wavelength in each fiber along p_4 and share the wavelength in the fiber along 6-4 previously reserved for r_1 and reserve a wavelength in each link along 4-8. For r_5, PU-SPP and PA-SPP pick route p_5(7-8) as the primary path and a link-disjoint path

b_5(7-5-6-8) as the backup path and use one wavelength in each fiber link along p_5. PU-SPP shares the wavelength in the fiber along 7-5, 5-6 and 6-8 previously reserved for r_3, r_1 and r_2, respectively. PA-SPP shares the wavelength in the fiber along 7-5 and 5-6 previously reserved for r_3 and r_2, and reserves a new wavelength in the fiber along 6-8.

Since PA-SPP only considers energy saving by packing more primary paths on active components and more backup paths on components in sleep mode without considering the sharing of spare resource, it may increase the unbalance of resource usage and lead to more links without free resource for future requests. Therefore, it is more possible to increase the blocking probability for future connections. For example, when a new request r_6(2, 5) arrives in Fig. 1, PU-SPP can choose p_6(2-5) as the primary path and b_6(2-1-5) as the backup path. It uses one wavelength in the fiber along p_6 and reserves one wavelength in the fiber along 2-1 and shares one wavelength in the fiber along 1-5 previously reserved for r_1. However, PA-SPP can choose p_6(2-5) as the primary path, but cannot find a link-disjoint backup path with available spare capacity, since it strives hard to pack primary paths and backup paths on active and sleep components respectively without considering the improvement of resource utilization and the prevention of link overutilization.

In order to accept more connection requests and to improve the resource utilization, it is better for a dynamic SPP to jointly consider power-saving and spare capacity sharing and to keep links from overutilization as much as possible. The main objective of this paper is to propose such a dynamic power-aware SPP (DPA-SPP). Fig. 1 (c) gives an example for the operation of DPA-SPP for the above six connection requests. For the first request r_1, being the same as PU-SPP and PA-SPP, DPA-SPP chooses route p_1(1-2-3-4) as the primary path and b_1(1-5-6-4) as backup path, and occupies one wavelength in each fiber along p_1 for traffic transmission and reserves one wavelength in each link of b_1 as the spare resource. For r_2, with a great effort to pack primary path and backup path on different links and to avoid using up the wavelengths in links (1, 2) and (2, 3) or (1, 5) and (5, 6), DPA-SPP picks route p_2(1-7-8) as the primary path instead of (1-2-3) being picked by PA-SPP and (1-5-6) being picked by PU-SPP. It assigns one wavelength in each link along p_2. Correspondingly, b_2(1-5-6) is chosen as backup path and it shares the wavelength in links (1, 5) and (5, 6) reserved for b_1, due to no common link involved in p_1 and p_2. For requests r_3 and r_4, DPA-SPP picks the shortest route p_3(1-7) and p_4(6-8) as the primary path and a link-disjoint path b_3(1-5-7) and b_4(6-4-8) as the backup path for r_3 and r_4, respectively. It uses one wavelength in each fiber along p_3 and p_4 and reserves one wavelength in the fiber along b_3 and 4-8 and shares the wavelength in the fiber along 6-4 previously reserved for r_1. For request r_5, it picks route p_5(7-8) as the primary path and a link-disjoint path b_5(7-5-6-4-8) as the backup path. It uses one wavelength in each fiber along p_5 and reserves a new wavelength in the fiber along 5-6 and shares the wavelength in the fiber along 7-5, 6-4 and 4-8 previously reserved for r_3, r_1 and r_4, respectively. When r_6 arrives, it picks p_6(2-5) as the primary path and a link-disjoint route b_6(2-3-6-5) as the backup path. It uses one wavelength in the fiber along p_5 and reserves one wavelength in each fiber along (2-3-6) and shares the wavelength in the fiber (6-5) previously reserved for r_1.

TABLE I. LINK USAGE FOR PU-SPP, PA-SPP AND DPA-SPP

Algorithm	Successfully Accepted requests	Number of links		
		Active	Sleep	Off
PU-SPP	6	9	3	1
PA-SPP	5	7	5	1
DPA-SPP	6	7	6	0

Table I presents the link usage of PU-SPP, PA-SPP and DPA-SPP shown in Fig. 1. Considering the negligible power consumption of components in sleep or off (idle) mode compared with active mode, it is clearly shown from Table I that an power-aware approach, i.e., PU-SPP or DPA-SPP, has a better energy saving. Table I shows that the number of active links is 7 for PA-SPP and DPA-SPP, and the number of links in sleep or off mode is 6. On the other hand, PU-SPP has 9 links in active mode and only 4 links in sleep or off mode. Obviously, with the objective to minimize the number of active components, power-aware strategies can achieve more energy saving. Although only 5 connections can be successfully established by PA-SPP for the 6 arriving requests in Fig. 1 (b), there is 5 links without available wavelength for future requests, i.e., (1, 2), (2, 3), (1, 5), (5, 6) and (6, 8). On the other side, DPA-SPP not only considers power saving but also aims at the improvement of resource sharing and the prevention of link overutilization. It also has 5 links without available wavelengths even if it successfully accepts all the 6 connection requests. Potentially, compared with PA-SPP, DPA-SPP has a higher chance to accept more future connection requests, which leads to a smaller blocking probability and a higher resource utilization.

III. DESCRIPTION OF THE PROPOSED ALGORITHM

The critical issue addressed in this paper is how to select a primary path and a link-disjoint backup path with the objectives to improve spare capacity sharing and to reduce energy consumption for a dynamic connection request. As mentioned above, PA-SPP tends to select the path with more active components as primary path and the path with more sleep components as backup path, although those paths are not the shortest path while using other metrics (such as hop number and resource utilization, etc.). It may increase the average path length and occupy more resources in the network. To deal with this problem, a new dynamic power-aware SPP (called DPA-SPP) will be proposed in this paper with a comprehensive consideration of power saving and improvement of resource utilization and network performance.

Upon the arrival of connection request $r(s, d)$, DPA-SPP first computes a primary path and assigns one wavelength in each fiber along the path. And then, it picks a fiber-disjoint path as the backup path. Since spare resource can be shared among different backup paths whose corresponding primary paths are fiber-disjoint, it is unnecessary to reserve one wavelength in all backup paths [14]. The amount of the reserved wavelength is determined by the link-usage information that is available to the routing algorithm. This incremental information is feasible to obtain from traffic engineering extensions to routing protocols [19]. Before describing the proposed scheme, following notations are introduced.

(i, j): a fiber link interconnecting node i and node j in the topology G, which represents two unidirectional links between the two nodes.

c_{ij}: the cost of (i, j), which is determined by the physical topology and the current state of the network.

P: the set of links passed by any primary path.

B: the set of links involved in any backup path.

a_{ij}: the total number of wavelengths used by primary paths in link (i, j).

r_{ij}: the total number of wavelengths reserved for backup paths in link (i, j).

f_{ij}: the total number of residual wavelength in link (i, j). Obviously, $f_{ij}=|W|-a_{ij}-r_{ij}$.

x_{ij}: a binary variable that is equal to 1 if $f_{ij} < \alpha|W|$, and equal to 0 otherwise, where α is a weighting factor considering the prevention of link overutilization, and $0<\alpha<0.5$. If $x_{ij}=1$, (i, j) is called a bottleneck link, which means that (i, j) has a very few free wavelengths for future connection requests and is overutilization. For a bottleneck link, DPA-SPP encourages to pick another link instead of it to create the connection for the arriving request, in order to avoid using up its resource and potentially leading to a division of the network. However, in a conventional power-aware SPP (PA-SPP), no attention is paid to prevent link overutilization. It only stresses on packing primary path onto active components and putting more components into sleep or off mode.

z_{ij}: a binary variable that is equal to 0 if $(i, j)\in P$, and equal to 0 otherwise.

e_i: a binary variable that is equal to 0 if node i is used by any primary path (node i is in active mode), and equal to 1 otherwise, i.e., node i is in off or sleep mode.

d_{ij}: the physical distance between node i and node j in km, where $i, j\in N$.

d_0: the length of a single mode fiber span, which is fixed to 80km [4].

P_E: the power consumed by an ECS;

P_M: the power consumed by an optical wavelength converter and 3D MEMs-based switching matrix per wavelength in a node.

P_T: the power consumed by a transceiver.

P_{ILA}: the power consumed by an optical in-line amplifier (ILA).

P_{PRE}: the power consumed by a pre-amplifier.

P_{POST}: the power consumed by a post-amplifier.

P_{ij}: the power consumed by amplifiers on link $(i, j)\in L$, which can be modeled as follows.

$$P_{ij} = \left\lfloor d_{ij} / d_0 \right\rfloor P_{ILA} + P_{PRE} + P_{POST} \tag{1}$$

DPA-SPP first computes the K shortest paths as the candidates for the primary path of the current connection request. Because a link without available wavelength cannot be used by the primary path, it should be temporarily removed from G, i.e., modifying the cost of edges as infinity, before computing the primary path. Moreover, in order to reduce the blocking probability of connection requests, to prevent link overutilization and to enhance energy saving as much as possible, DPA-SPP dynamically adjusts the costs of the edges according to the current state of the network. Before computing the primary path, DPA-SPP adjusts the cost of each link in G according to following equations.

$$c_{ij} = \begin{cases} +\infty, \ if\ f_{ij}=0 \\ u_{ij}, \ otherwise \end{cases} \tag{2}$$

$$u_{ij} = \begin{cases} (e_i+e_j)P_E + 2P_M + P_{ij} + Q/2, \ if\ f_{ij}=|W| \\ 2P_M + x_{ij}(P_{max}/f_{ij}), \\ \qquad\qquad if\ (i,j)\in P\ and\ (i,j)\notin B \\ (e_i+e_j)P_E + 2P_M + P_{ij} + x_{ij}(P_{max}/f_{ij}) + Q, \\ \qquad\qquad if\ (i,j)\in B\ and\ (i,j)\notin P \\ 2P_M + x_{ij}(P_{max}/f_{ij}) + Q/4, \\ \qquad\qquad if\ (i,j)\in P\ and\ (i,j)\in B \end{cases} \tag{3}$$

where P_{max} is a constant factor with a big value to prevent link overutilization by encouraging to choose the links with more free wavelengths instead of bottleneck links. P_{max} is defined as the power consumed by amplifiers on the link with the longest distance, which can be written as follows.

$$P_{max} = \max_{(i,j)\in L} P_{ij} \tag{4}$$

In (3), Q is a constant with a very big value as a penalty to discourage picking a specific link, which is defined as follows.

$$Q = |L| \cdot P_{max} \tag{5}$$

In (3), Q, Q/2, and Q/4 are used to control the preference to select different links belong to different sets. According to Eq. (3), DPA-SPP first prefers the link only involved in primary paths for previous connections to establish a primary path. The cost for a link solely used by primary paths is set to the additional energy consumption for the link being used by current connection plus a factor for load balance. And then it encourages choosing the link used by primary paths and backup paths of previous connections, with a bigger cost than the previous case. Furthermore, in order to maximize the number of links that can be turned off, a big cost is assigned to a link being unused, that is, a constant $Q/2$ plus the power consumption of the link being activated from off state, which is much bigger than the cost of the link under above two cases. In order to maximize the number of links that can be put in sleep mode, it is discouraged to provisioning primary paths with resources already reserved mainly for protection purposes. Therefore, a very high cost is assigned to the links used only by backup paths, which is bigger than those of the above three cases.

After modifying the link cost, DPA-SPP computes K shortest paths (if there are no K distinct path, then it should find all possible results) between source node s and destination node d using Yen's K-shortest path algorithm presented in [20]. All found paths make up of a set, denoted by S_K. In fact, the paths in S_K are the first K most energy-efficient paths of all potential paths between the source and destination node with a consideration for reduction of bottleneck links. If S_K=NULL, which means that no primary path is available for the connection request, the request is blocked immediately. Otherwise, a link-disjoint backup path will be computed for each path in the set S_K one by one, also with the consideration of energy saving and improvement of resource usage. Since spare capacity can be shared by connections being not simultaneously failure to improve the resource utilization, before computing a backup path for the chosen primary path P_l from S_K, modify the cost of link in G according to following equations.

$$c_{ij} = \begin{cases} +\infty, \, if \, (i, j) \in P_l \\ m_{ij} \cdot u_{ij}, \, otherwise \end{cases} \tag{6}$$

where m_{ij} and u_{ij} are dynamic cost weights for (i, j) considering spare capacity sharing and energy saving, respectively, which are defined as follows.

$$m_{ij} = \begin{cases} \xi, \, if \, q_{ij} + 1 \le r_{ij} \\ \min\{1, q_{ij} + 1 - r_{ij}\}, if \, r_{ij} < q_{ij} + 1 \le r_{ij} + f_{ij} \\ +\infty, \, otherwise \end{cases} \tag{7}$$

$$u_{ij} = \begin{cases} Q/4, \text{if } f_{ij} = |W| \\ x_{ij}(P_{max}/f_{ij}) + Q, \text{ if } (i, j) \in P \text{ and } (i, j) \notin B \\ \xi + x_{ij}(P_{max}/f_{ij}), \text{ if } (i, j) \in B \text{ and } (i, j) \notin P \\ x_{ij}(P_{max}/f_{ij}) + Q/2, \text{ if } (i, j) \in P \text{ and } (i, j) \in B \end{cases} \tag{8}$$

where ξ is a small number being very close to 0. q_{ij} is the maximum number of wavelength needed on link (i, j) if any of the links along P_l fails, which can be computed based on the network state before the new connection is routed [19]. Equation (7) encourages picking the link with the least amount of additional bandwidth to set up the backup path. Equation (8) makes a deliberate attempt to pack as many backup paths as possible on sleep components and to discourage the use of links involved in previous primary paths for backup paths. A very small cost is set to the link only involved in previous backup paths, and a highest cost is set to the link only included in primary paths. Accordingly, (6) always select the links with the least amount of additional bandwidth to set up backup paths while with a consideration of energy saving. It is favorable to improve the bandwidth utilization and to reduce the energy consumption.

Once modifying the costs of all links, a shortest path algorithm (e.g., Dijkstra's algorithm [14]) is used to compute a distinct route with minimum weight for P_l, denoted by P_c. If it fails to find a path, DPA-SPP picks up next path from S_K and repeats above procedure. Otherwise, put P_l and P_c into a set X, and pick up next path from S_K and repeat above procedure.

Obviously, X is a set containing all available path pairs for $r(s,d)$. If X=NULL, then reject the connection request. Otherwise, only choose an optimal path pair (primary path P_p and backup path P_b) with the minimal C_{pb} from the set X to provision the service for current request according to (9).

$$C_{pb} = \{P_T + \sum_{(i,j)\in P_p} (e_i P_E + P_M + z_{ij} P_{ij})\} + \beta \sum_{(i,j)\in P_p \cup P_b} t_{ij} \tag{9}$$

where t_{ij} is a binary variable. If one additional wavelength is needed on link (i, j) to establish the connection, t_{ij}=1. Otherwise, t_{ij}=0. β is a constant to adjust more attention being paid on energy saving or on improvement of resource usage. Different value of β means that (9) is favorable to choose a pair of paths passing through links whether with less additional resources or with less additional energy consumption. A bigger value of β means a higher degree of spare capacity sharing, and it is favorable to improve the bandwidth utilization.

Fig. 2 shows the flow chart of the proposed DPA-SPP algorithm. Its complexity is mainly determined by the complexity of Yen's K-shortest path algorithm and the procedure of comparison operations and adjustments of link cost, which is approximately $O(K|N|^3+K|L|)$. If K=1, the complexity of Yen's K-shortest algorithm is reduced from $O(K|N|^3)$ to $O(|N|^2)$. Consequently, the complexity of DPA-SPP is reduced to $O(|N|^2+|L|)$.

IV. Simulation Results and Analysis

In this section, we will evaluate the performance of DPA-SPP via extensive simulations by comparing it with two other shared path protection algorithms, i.e., PU-SPP and PA-SPP. PU-SPP mainly focuses on the sharing of spare capacity, while PA-SPP stresses on the energy saving with less concern on the network performance in term of traditional metrics, such as blocking probability, resource utilization, etc. In the rest of the section, we first describe the test network topology and performance metrics used in our simulations before presenting the results.

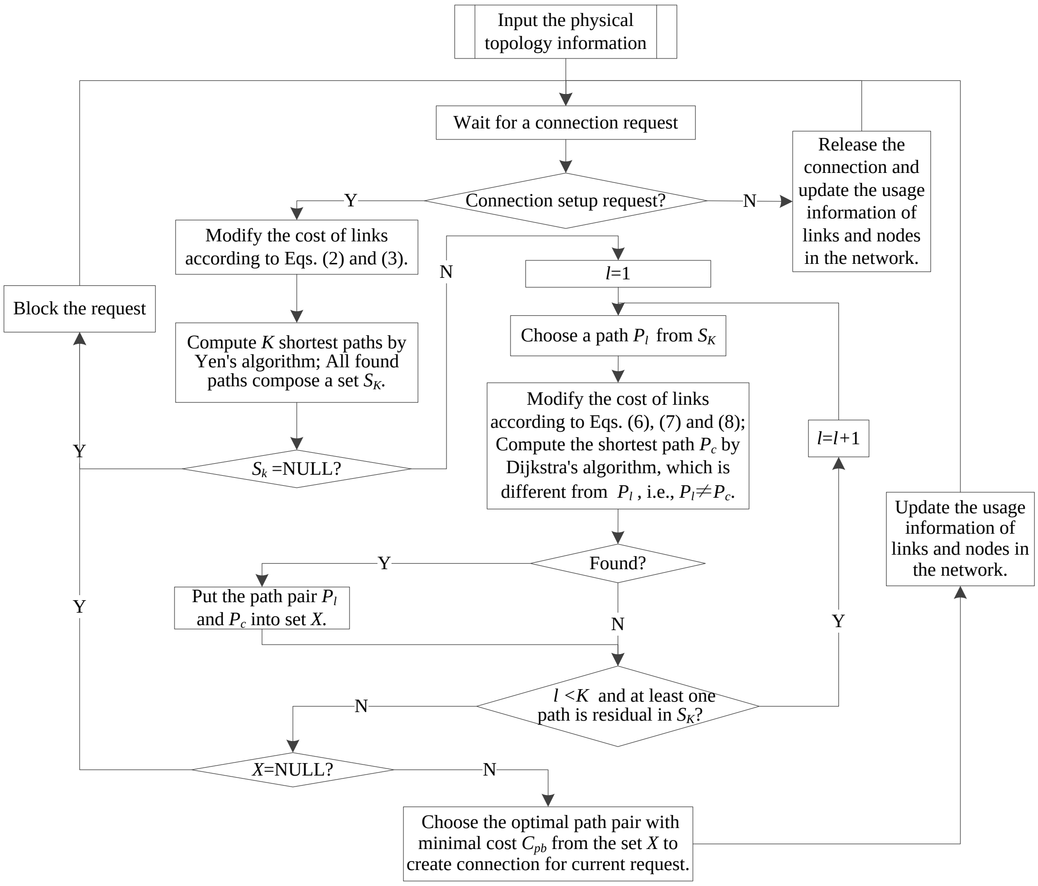
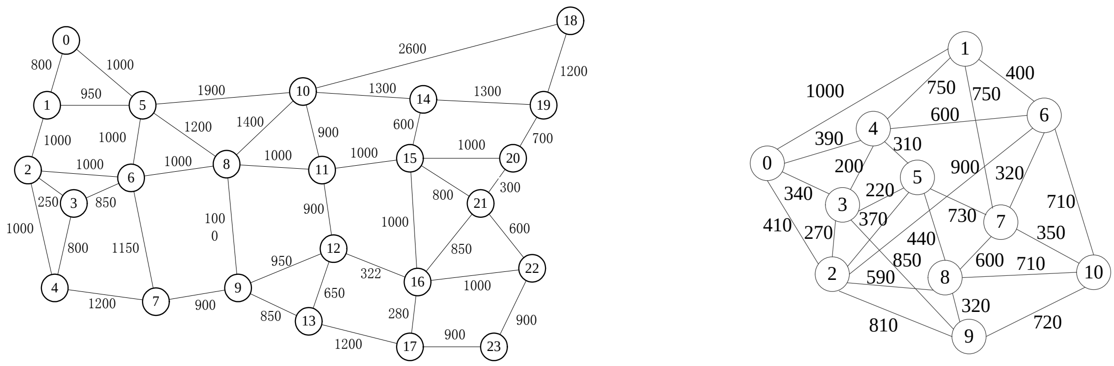


Figure 2. Flow chart of the proposed algorithm



(a) (b)

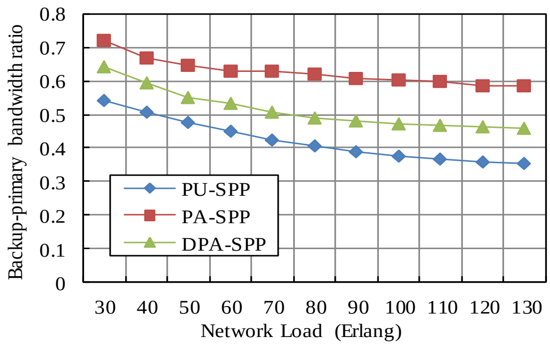
Figure 3. Topology of test networks with fiber lengths (in km) marked on each link: (a) sample US network (USNET); (b) Pan-European test network topology (COST 239).

A. Network Topology

The two test networks are the Pan-European test network topology (COST 239) with 11 nodes and 26 bidirectional fiber links and a sample US network topology (USNET) consisting of 24 nodes and 43 bidirectional fiber links [4] shown in Fig. 3, where nodes are interconnected by bi-directional fiber links, and physical distance of a fiber (in km) is marked on each link. All nodes have wavelength conversion capabilities and the number of wavelengths per fiber is assumed to be 12 and 15 for COST 239 and USNET, respectively. All the traffic connection requests are bidirectional, which are uniformly distributed among all node pairs, and there is no knowledge about future requests. Each time there is only one connection request. The arrival process of a connection request is a Poisson process with arrival rate λ and the connection holding time follows a negative exponential distribution with mean $1/\mu$. If the algorithm could not provision a reliable connection, the request is rejected immediately without waiting queue. In the simulations, let K=3, α=0.3, β=90 and ξ =0.001, and the total number of connection requests is generated up to 10^5. The power consumption values of different devices are assumed according to [8], [16], and [17], which are listed in Table II.

TABLE I. POWER CONSUMPTION OF DIFFERENT DEVICES

Device	Power consumption (W)
Electronic control system	150
Optical wavelength converters and 3D MEMS switching per wavelength	1.757
Transponder	5.9
Pre-amplifier	10
Post-amplifier	20
In-line amplifier	15



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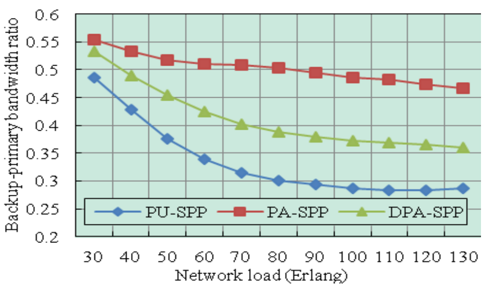


(b)

Figure 4. Backup-primary bandwidth ratio (BBR) versus network offered load: (a) sample US network (USNET); (b) Pan-European test network topology (COST 239).

B. Performance Metrics

The following performance metrics are used to evaluate the three algorithms.

1) Backup-primary bandwidth ratio (BBR): BBR represents the percentage of wavelengths reserved for backup paths over the amount of wavelengths occupied by primary paths, which can be written as follows.

$$BBR = \frac{\sum_{(i,j)\in L} r_{ij}}{\sum_{(i,j)\in L} a_{ij}} \tag{10}$$

It is obvious that a smaller value of BBR means smaller backup bandwidth reserved on all the backup paths, and a higher degree of spare capacity sharing.

2) Blocking probability (BP): BP is defined as the ratio between the number of blocked connection requests and the number of all arriving connection requests during the entire simulation period. In the case of dynamic traffic, BP can approximately reflect the effectiveness of bandwidth utilization. A smaller BP means higher bandwidth utilization ratio, and vice versa.

3) Average power-saving ratio (APR): APR is defined as the difference between the total power consumption of a specific algorithm, i.e., DPA-SPP, PA-SPP and PU-SPP, and the total power consumption of PU-SPP over the total power consumption of PU-SPP, which can be written as follows.

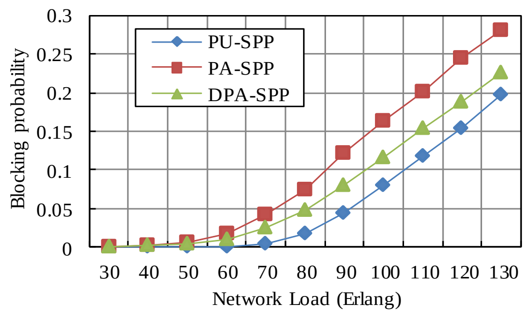
$$APR = \frac{E_U - E_S}{E_U} \tag{11}$$

where E_U represents the total power consumption of PU-SPP, and E_S represents the total power consumption for a specific algorithm, i.e., PA-SPP or DPA-SPP. A bigger value of APR means higher energy saving, and vice versa. Obviously, the value of APR for PU-SPP is always equal to 0.

C. Simulation results

Fig. 4 shows the performance of PU-SPP, PA-SPP and DPA-SPP in terms of backup-primary bandwidth ratio (BBR) for different network load. We can observe that PU-SPP performs best, followed by DPA-SPP and PA-SPP in sequence. The reason for this is that PU-SPP encourages picking a pair of link-disjoint paths with less additional spare resources for all connection requests. On the other side, PA-SPP and DPA-SPP pay more attention to energy saving, especially PA-SPP only considering the reduction of energy consumption while ignoring the enhancement of resource utilization. Therefore, compared with PU-SPP, more spare capacities are reserved in PA-SPP and DPA-SPP, which leads to a bigger value of BPR. With a joint consideration of energy saving and improvement of resource usage, DPA-SPP has a higher sharing of spare resources and resource utilization than PA-SPP. Another observation from Fig. 4 is that the values of BBR for the three algorithms are reduced with an increase of network load. The reason for this is that more network load means more connection requests arriving at the network. Potentially, more connections are established in the network. Therefore, spare capacities can be shared among more connections, which can reduce the value of BBR.

Fig. 5 compares the performance of the three algorithms in terms of blocking probability (BP). In all algorithms, BP is found to increase monotonically with an increase of network load. PA-SPP yields the worst BP and PU-SPP the best, with DPA-SPP falling in between. The reason for this is that DPA-SPP and PU-SPP pay attention to choose a pair of link-disjoint paths with less additional resources for each connection request. It is straightforward that both of them are favorable to reduce the total amount of resources for provisioning a service compared with PA-SPP that only considers power saving. With more available resources, DPA_SPP and PU_SPP can increase the chance to successfully establish connections for connection requests arriving later. Being different from PU-SPP that only emphasizes resource utilization, DPA-SPP jointly considers improvement of resource usage and energy saving. In order to put more components into sleep state for the reduction of energy consumption, it may choose a path with more hops but with active components instead of a path with sleep or idle components but with less hop as primary path, while choose a path with sleep or idle components but with more hops as backup path instead of a path with less hop but with active components. This potentially increases the total resources occupied by primary path and reserved for backup path and leads to a bigger value of BP than PU-SPP. Another observation from Fig. 5 is that under a light network load (being less than 50 Erlang in USNET and 40 Erlang in COST 239), the BPs of PA-SPP and DPA-SPP are very close to PU-SPP while DPA-SPP still performs better than PA-SPP. However, with an increase of network load, DPA-SPP is gradually far from PA-SPP and close to PU-SPP. The reason for this is that many free resources are available to create connections under the case of light network load. Under this case, there is a slight improvement for PU-SPP and DPA-SPP to have more chance to establish connections successfully, although both of them have a higher sharing of spare capacity and resource utilization than PA-SPP. With an increase of network load, resources gradually become the major factor that determines whether a connection can be created successfully. With the objective to enhance resource utilization, PU-SPP and DPA-SPP can reduce the resource occupation, and potentially can accept more subsequent connection requests and reduce the blocking probability. Being different from DPA-SPP, PA-SPP only takes it into account to choose path with less energy consumption without considering resource utilization. Therefore, more resources are occupied for the acceptance of the same number of connection requests; and it has a worse performance of BP than DPA-SPP and PU-SPP. This confirms that an algorithm only focusing on power saving might lead to an unacceptable performance degradation especially under a heavy network load where the network is with a relatively limited resource.



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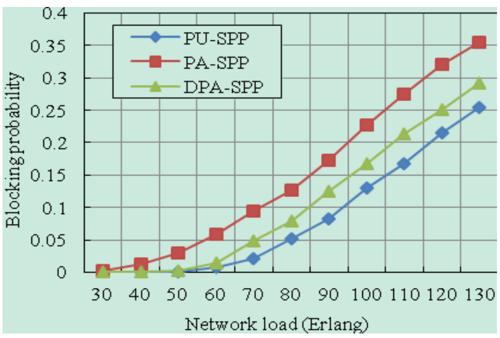
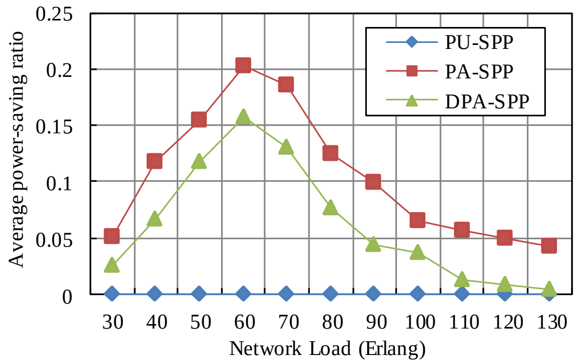


(b)

Figure 5. Blocking probability (BP) versus network offered load: (a) sample US network (USNET); (b) Pan-European test network topology (COST 239).



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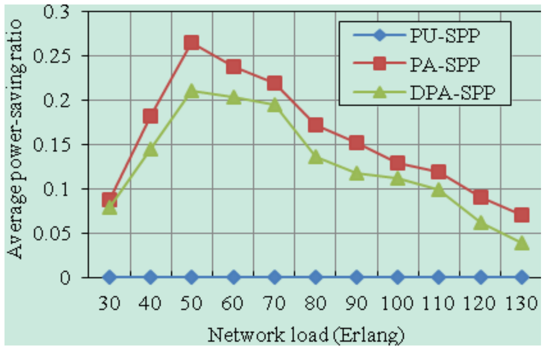

(b)

Figure 6. Average power-saving ratio (APR) versus network offered load: (a) sample US network (USNET); (b) Pan-European test network topology (COST 239).

Fig. 6 shows the performance of the three algorithms in terms of average power-saving ratio (APR). Obviously, considerable power savings (up to 20 percent for PA-SPP and 16 percent for DPA-SPP in USNET, and up to 27 percent for PA-SPP and 22 percent for DPA-SPP in COST 239, respectively) can be achievable. Another observation from Fig. 6 is that with an increase of network load, the value of APR for PA-SPP and DPA-SPP first increase and then decrease. The reason for this is that under a light network load, most of components are in off or sleep mode. There is no significant advantage for PA-SPP and DPA-SPP to reduce energy consumption even if they deliberately pack primary paths and backup paths on active components and sleep components, respectively. With an increase of network load, more connections are established in the network, and more and more primary paths for new requests may be packed on routes with active components in PA-SPP and DPA-SPP, which is useful to reduce energy consumption compared with PU-SPP. For PU-SPP with the objective of resource utilization and without distinguishing the component's states, a primary path is more possible to be carried by a route including idle or sleep components, which are required to be activated with more energy consumption. Therefore, the APRs of PA-SPP and DPA-SPP gradually increase and reach the top with an increase network load. However, under a case of heavy network load, it is more possible that there are a very few components being in off mode and a component may be used by both primary path and backup path. Under this case, it is difficult for PA-SPP and DPA-SPP to pack primary path and backup path on different components in different states. Thus, there is no significant difference for PU-SPP, PA-SPP and DPA-SPP, and the values of APR for PA-SPP and DPA-SPP are gradually close to PU-SPP.

V. CONCLUSIONS

This paper proposes a dynamic power-aware shared path protection algorithm (DPA-SPP) for WDM mesh networks. DPA-SPP considers not only energy saving but also resource utilization and spare capacity sharing. In order to reduce power consumption, to improve sharing of spare capacity, and to reduce blocking probability for connection requests, DPA-SPP encourages to establish a primary path for each connection request on active resources, to pack backup paths on sleep resources, and to leave more idle resources as far as possible while with a consideration to prevent a link with very few number of free wavelengths to become a bottleneck link, which is beneficial to further improve the successful probability for connection establishments. Under dynamic traffic with different load, extensive simulations are performed to compare the performance of our proposal with PU-SPP and PA-SPP. Simulation results show that DPA-SPP can combine the advantages of PU-SPP and PA-SPP to make a tradeoff between resource utilization and energy saving. It can achieve considerable performance gains leading to reductions in spare capacities and average energy consumption.

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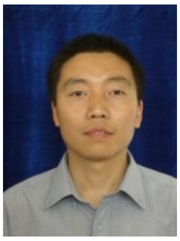

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