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Dynamic provisioning strategies for energy efficient WDM networks with dedicated path protection

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ABSTRACT

Energy consumption in optical backbone networks is increasing due to two main reasons: *(i)* the exponential growth of bandwidth demands, and *(ii)* the increase in availability requirements in order to guarantee protection of the ultra high capacity optical channels provided by wavelength division multiplexing (WDM) networks. Although state of the art reliability mechanisms are very efficient in guaranteeing high availability, they do not consider the impact of the protection resources on the network's energy consumption. Dedicated (1:1) path protection (DPP) is a well-known mechanism that provides one extra link—disjoint path for the protection of a connection request. This secondary path is reserved and maintained in an active mode even though it is not utilized most of the time. This means that in-line optical amplifiers and switching nodes/ports are always consuming power even when they are not used to reroute any primary traffic. Moreover secondary paths are on average longer than their respective primary paths.

These observations motivated us to investigate the energy savings, when all unused protection resources can be switched into a low-power, stand-by state (or *sleep* mode) during normal network operation and can be activated upon a failure. It is shown that significant reduction of power consumption (up to 25%) can be achieved by putting protection resources into *sleep* mode. Moreover, in order to enhance this energy saving figure, this paper proposes and evaluates different energy-efficient algorithms, specifically tailored around the *sleep* mode option, to dynamically provision 1:1 dedicated path protected connection. The trade-off between energy saving and blocking probability is discussed and an efficient mechanism to overcome this drawback is devised. Our results reveal that a 34% reduction of energy consumption can be obtained with a negligible impact on the network's blocking performance.

1. Introduction

The traffic supported by the Internet has grown enormously over the last few years shaping up the requirements that the underlying network infrastructure needs to support. This is mainly because of the drastically increased number of broadband Internet users and emerging applications such as multimedia and e-services, as well as business and residential services. It is also virtually certain that this traffic growth will continue both in the near and long term future, due to the continuously increasing Fiber to the X (FTTX) deployments and the availability of numerous new services to the end user. Considering that currently ICT is

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responsible for about 4% of all primary energy consumption worldwide [1], it is clear that the energy consumption of network equipment will play a significant role in the overall energy footprint of the planet. In this context, energy efficiency considerations in the design and the operation of communication networks have become critical [2,3].

As optical networking employing wavelength division multiplexing (WDM) is capable of carrying a tremendous amount of information, WDM networks are expected to play a key role in supporting the next generation networks and the future Internet. In this type of networks optical fiber links carry a large number of wavelength channels, each modulated at very high data rates exceeding 10 or even 40 Gb/s. Therefore, even a single fiber link failure may cause the loss of connections that carry an enormous amount of information, making survivability an essential requirement. To address this issue different resiliency mechanisms have been developed for WDM networks with the aim of enabling the rerouting of the affected traffic upon a failure, provided that spare (protection) resources are available to be used in case of a failure [4].

This paper focuses on the power consumption of survivable transparent WDM networks where the traffic is rerouted upon a failure using a predetermined and already reserved secondary path. This survivability mechanism is referred to as 1:1 dedicated path protection (DPP). In conventional optical network solutions, protection resources are always in an active state along the secondary path, regardless of its status. This means that in-line optical amplifiers and switching nodes/ports, at intermediate fiber-links and nodes respectively, are always consuming power even when they are not used to reroute any primary traffic. Considering this and the fact that secondary paths are on average longer than their respective primary paths, it becomes evident that the impact of the power consumed by conventional protection solutions cannot be overlooked. In order to address this point, all unused protection resources can be switched into a *sleep* mode during normal network operation. These inactive protection resources can then be *re-activated* when needed, i.e., in case of a failure. The *sleep* mode represents a low-power, stand-by state from which devices can be suddenly awakened and switched back to the operating mode upon the occurrence of a triggering event. It should be noted that the existing optical network's technology is not currently able to support this stand-by feature. However, such a feature is strongly advocated by efforts from standardization bodies and governmental programs [5] and can be the focus of relevant technology evolution and research considering the benefits it provides regarding energy efficiency in network operation.

The contribution of this paper is two-fold. First the potential power savings achieved by setting protection resources in a stand-by (*sleep*) mode are assessed in a dynamic provisioning scenario. Second, different energy-aware algorithms are proposed and compared to explore the potential power savings caused by deactivation of protection resources. While investigating possible solutions to this problem, it was found that in order to fully exploit the energy saving benefits of the *sleep* mode feature, a provisioning solution needs to be able to differentiate between the links used by the primary and the links used by the secondary paths. In addition, it was also noticed that focusing solely on the energy consumption minimization has a detrimental effect on the value of other network performance metrics, i.e., connection blocking probability. This is mainly due to the possible bottlenecks that may be introduced in the network by forcing primary and secondary connections to be provisioned over different links. In other words there is a clear trade-off between achievable energy efficiency and the blocking probability.

With this rationale in mind different energy-aware provisioning algorithms that trade energy minimization for blocking probability, while exploiting the *sleep* mode feature, are proposed. The first energy-aware dedicated path protection algorithm, with differentiation of primary and secondary paths (EA-DPP-Dif), focuses on energy minimization by forcing differentiation between the links used by primary and secondary paths. The objective is to keep them separated from each other as much as possible. This is accomplished by preventing links to be used by both primary and secondary paths (i.e., link with mixed resources). The considerable savings in terms of energy consumption that is achieved by EA-DPP-Dif come at the expense of increased connection blocking probability. The second proposed approach based on energy-aware dedicated path protection with mixing secondary with primary paths (EA-DPP-MixS), tries to lower this impact on the blocking probability by relaxing the differentiation constraint between the links used by primary and secondary paths, while routing secondary paths. As a result, secondary paths can now be provisioned using links with mixed resources. This translates into fewer congested links in the network, but also in a bigger number of links that cannot be set in *sleep* mode. Finally, the paper also presents an approach based on an energy-aware dedicated path protection (EA-DPP) algorithm that tackles the energy minimization problem in a dynamic scenario when the *sleep* mode is not supported by the network devices. The objective of EA-DPP is to lower the overall network's energy consumption by routing primary and secondary paths without unnecessarily switching on any unused link and node.

The benefits of the proposed approaches are assessed via simulation experiments using two continental optical core topologies (COST 239 Pan-European [6] topology and a sample US topology USNet [7]). The simulation results reveal that a significant energy saving can be achieved keeping an acceptable level of connection blocking probability.

The paper is structured as follows: Section 2 provides an overview of the relevant literature. Section 3 presents the power consumption model and describes the intuition behind the proposed energy-aware path selection approach for the dedicated 1:1 protection scheme. Section 4 introduces the problem of survivable routing with minimum energy, the method used to calculate the network's power consumption, and a detailed description of the proposed energy-aware provisioning algorithms. Section 5 provides the performance evaluation results that have been produced through simulations and a relevant discussion. Finally, Section 6 concludes the paper.

2. Related work

Recently a significant amount of work on energy efficient design of optical WDM networks has been published. On the other hand energy-aware dynamic connection provisioning still remains a relatively unexplored area where only a few research works are available. In this regard, the authors in [8] investigate the impact that power minimization has on the overall network's performance in a dynamic provisioning scenario. They propose a weighted power-aware routing approach based on the intuition that in some cases relaxing the power minimization constraint can contribute to the reduction of resource fragmentation in the network and lower the blocking probability. The work in [9] proposes an intelligent load control mechanism and an auxiliary graph model to overcome the blocking probability drawback in energy efficient connection provisioning in optical networks.

For the static traffic case, a novel energy-aware routing scheme is designed in [10] where the authors model the power consumption of a router in a hierarchical manner considering the energy consumption of an activated chassis, the number of line cards in a chassis and the number of ports in a line card by maximizing the efficient utilization of each level, which in turn increases the energy-efficiency in the routing fabric. Energy-aware routing in the context of optical network design commonly focuses on the problem of determining the resources that are under-utilized and accordingly can be turned off to save energy. In [11], authors provide an ILP model and propose heuristic algorithms to address the routing and wavelength assignment problem in energy-aware optical networks. In [12], the authors address the trade-off between network load and energy-efficient design. They show that without increasing the load (keeping it below 50%), up to 50% of links and nodes can be switched off in a hybrid topology including core, edge and aggregation nodes and where traffic is introduced only by aggregation nodes.

In [13], an ILP model for power efficient traffic grooming is proposed. In this study, the authors considered the idle power and traffic dependent power consumed by a lightpath with the aim of decreasing the amount of lightly loaded lightpaths. The same problem is addressed in [7] for both dynamic and static traffic environments. The authors propose an auxiliary graph, to model the energy consumption in optical bypass and traffic grooming nodes and for energy-aware routing of connection requests. Some of these approaches may lead to an increase in the amount of data that would be lost in case of a failure when they are trying to maximize the amount of resources which can be turned off in the network by "packing" the traffic and creating high loaded links. Moreover, most of these approaches do not consider network resilience and the need for protection resources. In [14] it is shown that when designing networks based on power consumption, careful attention should be paid to the trade-off between energy consumption and network performance in order to avoid an unacceptable level of network reliability.

Energy-efficient survivable design of optical networks has been studied both for dedicated and shared protection resources in [15,16], respectively. In these two works optimum solution with the ILP formulations are proposed with the objective of minimizing the power consumption. However, among the previous studies, none has addressed the energy efficient survivable connection provisioning problem in a dynamic scenario.

3. Routing with sleep mode feature enabled

This section first presents the power consumption model when the protection resources are in *sleep* mode. Then it provides a simple illustrative example to explain the main idea behind the proposed energy-aware path selection approaches for dedicated 1:1 protection scheme.

3.1. Power consumption model

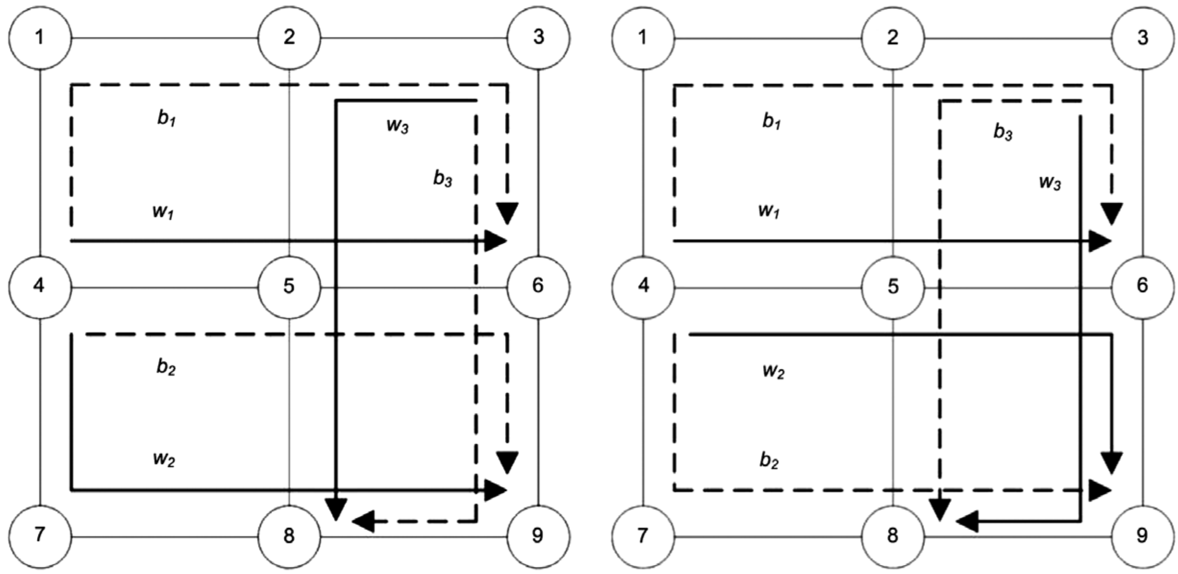
In this study optical network components are assumed to be able to operate in three different power modes: *off*, *sleep*, and *active* (Table 1). In *active* mode, an optical component is fully functional and consumes a certain amount of power, which can consist of two parts, i.e., traffic independent and traffic dependent power (proportional to the number of lightpaths). However, for some optical components where the power consumption is traffic independent, e.g. Erbium-Doped Fiber Amplifier (EDFA), the *active* power proportional to the traffic can be set to zero. In *off* mode, a component does not consume any power since it is not in an operating state. In *sleep* mode, a component is put in a state where it can be promptly activated if needed. In this work it is assumed that network elements in *sleep* mode consume a negligible amount of power. Under this assumption, the total power consumption of a WDM network can be computed as the sum of the power consumed by components in the *active* mode. Therefore the minimization of the power consumption problem is equivalent to the minimization of the number of components in *active* mode. This problem can be tackled in two parts as the problem of maximizing the number of network components that can be potentially put into (1) *sleep* mode and (2) *off* mode. The idea of an energy-aware survivable routing lies behind the effort of separating primary and secondary paths and also on trying to maximize the resources that can be turned off. Table 1 summarizes the power consumption associated with the different operating modes of a network element [16].

3.2. Energy-aware survivable routing

To enhance power saving in the 1:1 DPP scheme obtained by putting protection resources in *sleep* mode, an energy-aware survivable routing scheme aims at routing as many primary paths as possible, using already provisioned working resources, and also at routing as many secondary paths as possible, using already provisioned protection resources. A simple illustrative example is presented in Fig. 1 where an energy-aware routing approach and a conventional energy-unaware (e.g., shortest path) routing approach are compared in a dedicated path protected connection provisioning scenario.

Table 1
Power consumption in different operating modes [16].

Mode	Functionality	Power consumption
Off	Null	None
Sleep	Prompt switching to active mode when triggered	Negligible
Active	Full	Traffic independent power + power proportional to the # of lightpaths



(a) Energy-unaware routing.
(b) Energy-aware routing.

Fig. 1. Comparison of an energy-unaware and an energy-aware routing approaches.

According to the power model, network elements can be set in *sleep* mode when they are assigned exclusively to secondary paths, since in 1:1 DPP they are needed to fully function only when a failure occurs. Thus, an energy-aware routing approach tries to route the connection requests using the minimum number of network elements, and to route primary and secondary paths on separate links, so that those elements used exclusively by secondary paths can be set in *sleep* mode in order to save energy.

Fig. 1 shows an example where an energy-aware routing and an energy-unaware routing approach are compared. Let $r_1(4, 6)$, $r_2(4, 9)$, and $r_3(3, 8)$ be the first three connection requests for the specified source and destination node pairs. It is assumed that all the links in the network in the example have the same physical length, and each link represents bidirectional fibers.

When r_1 arrives, all the resources are not in use (i.e., free), and both the energy-aware and the energy-unaware routing schemes assign route w_1(4-5-6) as the primary path and route b_1(4-1-2-3-6) as the secondary path to r_1. When r_2 arrives, the energy-unaware approach chooses the shortest link-disjoint path pair without differentiating between links that are free, used by primary or used by secondary paths. So the energy-unaware approach picks w_2(4-7-8-9) as the primary path and b_2(4-5-6-9) as the secondary path (see Fig. 1(a)). On the other hand the energy-aware approach deliberately chooses the route that uses already provisioned working resources, i.e., links between node 4 and node 5, and between node 5 and node 6. Following this rationale, w_2(4-5-6-9) is selected as the primary path and b_2(4-7-8-9) is selected as the secondary path (Fig. 1(b)).

Table 2
Link usage for the energy-aware and the energy-unaware routing approaches.

Algorithm	Number of links			
	$C \setminus D$	$C \cap D$	$D \setminus C$	$L \setminus (C \cup D)$
	Active		*Sleep*	*Off*
Energy-aware routing	3	2	7	0
Energy-unaware routing	4	4	4	0

Finally, when r_3 arrives, the energy-unaware approach assigns w_3(3-2-5-8) and b_3(3-6-9-8) as the primary and as the secondary path, respectively. As it was the case for r_2, the energy-aware approach chooses the route that shares working resources with already-provisioned primary paths. As a result, route w_3(3-6-8-9) is selected as the primary path, and b_3(3-2-5-8) is selected as the secondary path for r_3.

Table 2 presents the link usage of the routing example shown in Fig. 1. C denotes the set of links used by primary paths, and D denotes the set of links used by secondary paths while L represents the set of network links. Considering the potential power that can be saved by setting protection resources into a *sleep* mode, it can clearly be seen that using an energy-aware approach, better energy savings can be obtained over the link usage results of the energy-unaware routing solution. Table 2 shows that with the energy-aware approach the number of active links is 5 $(C \setminus D) \cup (C \cap D)$, and the number of links used only by secondary paths $(D \setminus C)$, that potentially can be switched to *sleep* mode, is 7. On the other hand with the energy-unaware approach, 8 links need to be active, and only 4 links can be switched to *sleep* mode. The energy-aware approach aims at minimizing the number of network elements that are concurrently traversed by both primary and secondary paths, and in turn more energy saving can be achieved.

4. Energy-aware survivable connection provisioning

This section first formally introduces the problem of survivable routing with minimum energy. Then the section presents the method used for power calculation followed by a detailed description of the two proposed energy-aware provisioning algorithms that make use of the *sleep* mode for protection resources. To evaluate the power efficiency of the proposed approaches, another provisioning strategy, namely Energy-Aware Dedicated Path Protection (EA-DPP), where the *sleep* mode status is not accounted for during the routing phase is also introduced for comparison purposes.

4.1. Problem statement

The energy-aware routing problem with 1:1 dedicated path protection (DPP) can be formulated as follows:

Given: (a) the physical topology of a network represented by a graph $G = (N, L)$ where N is the set of network nodes, i.e., optical cross-connects (OXCs), and L is the set of network links; (b) a set of bidirectional fibers (F) for each network link, where each fiber carries a set (Γ) of wavelengths; (c) a connection request r_i that needs to be provisioned in $G = (N, L)$ from source node $s(r_i)$ to destination node $d(r_i)$; (d) a set $W^{s(r_i),d(r_i)} = \{w_1^{s(r_i),d(r_i)}, w_2^{s(r_i),d(r_i)}, \ldots, w_u^{s(r_i),d(r_i)}\}$, with up to u alternative routes used to provision a primary path between $s(r_i)$ and $d(r_i)$; (e) for each $w_j \in W^{s(r_i),d(r_i)}$, a set $B_{w_j}^{s(r_i),d(r_i)} = \{b_1^{s(r_i),d(r_i)}, b_2^{s(r_i),d(r_i)}, \ldots, b_v^{s(r_i),d(r_i)}\}$ of up to v alternative routes used to provision a link-disjoint secondary path between $s(r_i)$ and $d(r_i)$.

Output: A link-disjoint path pair (w_i, b_i) for connection r_i where $w_i \in W^{s(r_i),d(r_i)}$ and $b_i \in B_{w_i}^{s(r_i),d(r_i)}$.

Objective: Minimize the increase in total power consumption (P_{total}) of the network by provisioning resources for the new connection request r_i.

4.2. Total power consumption in the network

The total power consumption of the network can be expressed as:

$$P_{\text{total}} = \sum_{n \in N} (P_{\text{node},n} \cdot x_n) + \sum_{l \in L} (P_{\text{amp},l} \cdot x_l), \tag{1}$$

where $P_{\text{node},n}$ is the power consumed by node $n \in N$, $P_{\text{amp},l}$ is the power consumed by link $l \in L$. x_n and x_l are two binary variables that are equal to 1 if node n (resp. link l) is active, and equal to 0 otherwise. The power consumption of node n can be expressed as:

$$P_{\text{node},n} = P_{\text{OXC}} + P_{Tx}(c_n + d_n) + P_{Rx}(\overline{c}_n + \overline{d}_n), \tag{2}$$

where P_{OXC} is the power consumed by the switching fabric at n, c_n and $\overline{c}_n$ are the number of primary paths originating from and terminating at n, d_n and $\overline{d}_n$ are the number of secondary paths originating from and terminating at n, and P_{Tx} and P_{Rx} are the power consumed by a transmitter and a receiver. The power consumption of link l can be expressed as:

$$P_{\text{amp},l} = k_l \cdot P_{\text{amp}}, \tag{3}$$

$$k_l = \left(2 \cdot \frac{d_l}{d_{\text{span}}}\right) + 2, \tag{4}$$

where k_l is the total number of amplifiers along l calculated by using Eq. (4), where d_l is the total link length, d_{span} is the length of a single mode fiber span, and the additive term, i.e., 2, accounts for the optical amplifiers in the pre and post dispersion compensation modules [17]. P_{amp} is the power consumed by an optical amplifier. We assume that if n and l are traversed exclusively by secondary lightpaths they can then be set to *sleep* mode by setting $x_n = 0$ and $x_l = 0$.

4.3. Energy-aware dedicated path protection with differentiation of primary and secondary paths (EA-DPP-Dif)

The EA-DPP-Dif connection provisioning algorithm differentiates the link usage among primary paths and secondary paths during the link cost assignment phase. This algorithm tries to separate primary paths from secondary paths as much as possible by discouraging the mixture of these two types of paths. For each connection arrival a link-disjoint path pair is to be provisioned. In the route selection phase of the algorithm, costs are assigned to the links in such a way that (1) primary and secondary paths are isolated from each other by applying a very high penalty for the mixing of primary and secondary paths and (2) paths are packed by applying another penalty for choosing free links.

The algorithm starts with an initialization phase where, by using Yen's implementation of the k-shortest path algorithm [18], up to u shortest routes for set $W^{s(r_i),d(r_i)}$, and up to v shortest routes for set $B^{s(r_i),d(r_i)}$ are computed. For all possible source and destination pairs in the network, these routes are stored in the database. Furthermore, the number of amplifiers on each network link is calculated according to Eq. (4). Let graph $T(N, L')$, with $L' \subseteq L$ represent the free resources in the network, where a link belongs to L' if and only if it has resources available. Initially, graph $T(N, L')$ is equal to graph $G(N, L)$. Upon arrival of a connection request r_i, a primary path and a secondary path for the request are chosen as follows:

Given: r_i, and graph $T(N, L')$.

(1) Primary path provisioning phase

(a) In order to determine the set of candidate routes, each route in $W^{s(r_i),d(r_i)}$ is analyzed separately. If on a given route w_i at least one common wavelength is available on every link, w_i is stored in the set of candidate routes $\overline{W}^{s(r_i),d(r_i)}$. If after checking all $w_i \in W^{s(r_i),d(r_i)}$, $\overline{W}^{s(r_i),d(r_i)}$ is empty, then the connection request is blocked.

(b) The link costs are assigned, where

$$P_{\text{cost}}(l) = \begin{cases} 0, & l \in (C \setminus D) \\ |L| \cdot P_{\text{total}}, & l \in (D \setminus C) \\ P_{\text{total}}, & l \in (C \cap D) \\ P_{\text{amp},l}, & l \notin (C \cup D). \end{cases} \quad (5)$$

(c) For each route in $\overline{W}^{s(r_i),d(r_i)}$, power-aware costs are calculated as:

$$P_{\text{cost}}^{w_i} = \sum_{l \in w_i} P_{\text{cost}}(l). \quad (6)$$

$P_{\text{cost}}^{w_i}$ is the total power-aware cost of w_i, and $P_{\text{cost}}(l)$ is the cost of each link in w_i, C is the set of links used by primary paths, and D is the set of links used by secondary paths.

(d) The route $w_i \in \overline{W}^{s(r_i),d(r_i)}$ with the minimum path cost is selected as the primary path.

(e) The first available wavelength (i.e., first-fit wavelength assignment algorithm) is chosen for the selected path to provision the primary lightpath.

(2) Secondary path provisioning phase

(a) In order to determine the set of candidate routes, each route $b_i \in B_{w_i}^{s(r_i),d(r_i)}$ is analyzed separately. If at least one common wavelength is available on every link, the route is stored in the set of candidate routes $\overline{B}^{s(r_i),d(r_i)}$. If after checking all $b_i \in B_{w_i}^{s(r_i),d(r_i)}$, $\overline{B}^{s(r_i),d(r_i)}$ is empty, then the connection request is blocked.

(b) The link costs $P_{\text{cost}}(l)$ are assigned:

$$P_{\text{cost}}(l) = \begin{cases} 0, & l \in (D \setminus C) \\ |L| \cdot P_{\text{total}}, & l \in (C \setminus D) \\ P_{\text{total}}, & l \in (C \cap D) \\ P_{\text{amp},l}, & l \notin (C \cup D). \end{cases} \quad (7)$$

(c) The route $b_i \in \overline{B}^{s(r_i),d(r_i)}$ with the minimum path cost $P_{\text{cost}}^{b_i}$ is selected as the secondary path. For each route in the set, power-aware costs are calculated as:

$$P_{\text{cost}}^{b_i} = \sum_{l \in b_i} P_{\text{cost}}(l). \quad (8)$$

(d) The first-fit wavelength assignment scheme is used to provision the secondary lightpath for r_i.

In step 1. (b), to encourage the provisioning of primary paths with already used working resources, the cost of links used solely by primary paths is set to zero. For a link that is unused, the cost is $P_{\text{amp},l}$ which is equal to the power consumption of that link in *active* operating mode. In the case that the link is used for both primary and secondary paths, P_{total} is used as the link cost. P_{total} is computed with the assumption that all network elements are active. Furthermore, in order to maximize the number of links that can be put in *sleep* mode provisioning of primary paths with resources already assigned mainly for protection purposes should be discouraged. So the highest cost is assigned to the links used only by secondary paths, $|L| \cdot P_{\text{total}}$, where $|L|$ is the total number of links in the network.

If more than one candidate route in set $\overline{W}^{s(r_i),d(r_i)}$ have the same power cost, the one with the highest (average) number of primary paths is selected.

In step 2. (b), in order to pack as many secondary paths as possible on the same links, the cost of the links used only by secondary paths is set to the lowest value (i.e., zero), while the cost of the links used only by primary paths is set to the highest value as shown in Eq. (7). Similar to the primary path provisioning phase, the route with the lowest power cost in set $\overline{B}^{s(r_i),d(r_i)}$ is chosen. In the case of a tie, i.e., more than one candidate route in $\overline{B}^{s(r_i),d(r_i)}$ have the same cost, the route with the highest (average) number of secondary paths that are currently running is selected.

4.4. *Energy-aware dedicated path protection with mixing secondary with primary paths (EA-DPP-MixS)*

EA-DPP-MixS approach does not prioritize the isolation of primary and secondary paths as the main objective. Therefore, in contrast to the EA-DPP-Dif algorithm, the mixed links are not taken as one of the highest weighted links as before. Consequently, EA-DPP-MixS is not afraid of mixing primary paths and secondary paths, especially when routing the secondary paths.

EA-DPP-MixS is proposed to reduce the blocking probability of EA-DPP-Dif, where primary paths and secondary paths are packed separately. This may increase the load on some particular links and in turn cause high connection blocking probability. Furthermore, based on the fact that the secondary path is usually longer than the primary path, EA-DPP-Dif may lead to selecting very long routes for secondary paths. EA-DPP-MixS algorithm is proposed to overcome these drawbacks and in general it follows the same steps as the EA-DPP-Dif algorithm except the link cost assignment.

The power-aware cost assigned to links during the primary path provisioning phase in Step 1. (b) is defined as follows,

$$P_{\text{cost}}(l) = \begin{cases} 0, & l \in (C \setminus D) \\ |L| \cdot P_{\text{total}}, & l \in (D \setminus C) \\ P_{\text{amp},l}, & l \in (C \cap D) \\ P_{\text{total}}, & l \notin (C \cup D). \end{cases} \quad (9)$$

And the power-aware cost assigned during the secondary path provisioning phase in Step 2. (b) is defined as follows:

$$P_{\text{cost}}(l) = \begin{cases} 0, & l \in (C \cup D) \\ P_{\text{amp},l}, & \text{otherwise}. \end{cases} \quad (10)$$

Differently from the EA-DPP-Dif algorithm, EA-DPP-MixS assigns lower cost to the links used by both primary and secondary paths, than to the free links. The link cost assignment of secondary path provisioning in EA-DPP-MixS is not dependent on the link usage. This is to avoid introducing a high load on some particular links and to

Table 3
Link cost assignment for the different provisioning strategies.

Algorithm	Link usage			
	$C \setminus D$	$C \cap D$	$D \setminus C$	$L \setminus (C \cup D)$
Primary path provisioning phase				
EA-DPP-Dif	0	P_{total}	$\lvert L\rvert \cdot P_{\text{total}}$	$P_{\text{amp},l}$
EA-DPP-MixS	0	$P_{\text{amp},l}$	$\lvert L\rvert \cdot P_{\text{total}}$	P_{total}
EA-DPP	0	0	0	$P_{\text{amp},l}$
Secondary path provisioning phase				
EA-DPP-Dif	$\lvert L\rvert \cdot P_{\text{total}}$	P_{total}	0	$P_{\text{amp},l}$
EA-DPP-MixS	0	0	0	$P_{\text{amp},l}$
EA-DPP	0	0	0	$P_{\text{amp},l}$

avoid choosing very long secondary paths. According to Eq. (10), secondary paths are more likely to share the same links used for already-provisioned primary paths. This power-aware cost is used to discourage the provisioning of a secondary path on unused links.

Keeping in mind the idea of maximizing the energy saving triggered by maximizing the amount of resources in *sleep* mode, in EA-DPP-MixS the primary paths are still encouraged to use working resources exploited only by primary paths, while the secondary paths can be routed by using the links shared with primary paths in order to decrease the resource underutilization that may be introduced by EA-DPP-Dif.

In the primary path provisioning phase, if more than one candidate route have the same cost, the route with the highest (average) number of primary paths that are currently running is chosen. In the case of a tie in the secondary path provisioning phase, i.e., more than one candidate route in $\overline{B}^{s(r_i),d(r_i)}$ have the same cost, the route with the shortest physical length is chosen.

4.5. Energy-aware dedicated path protection (EA-DPP)

EA-DPP differs from the first two algorithms since it is developed considering the assumption that *sleep* mode is not supported by the network devices. EA-DPP tries to pack all the paths without any differentiation between primary and secondary paths. This is to avoid switching on the network elements that are currently inactive, that in turn introduce additional power consumption. To minimize the additional power that will be consumed by either primary or secondary paths, power-aware link costs are assigned to the links for both primary and secondary paths following the same cost assignment as in Eq. (10). If more than one candidate route in set $\overline{W}^{s(r_i),d(r_i)}$ have the same cost, the one with the shortest physical distance is selected. The rationale is used to break a tie if more than one candidate route in set $\overline{B}^{s(r_i),d(r_i)}$ have the same cost. Table 3 presents the comparison of link cost assignment among the proposed energy-aware algorithms.

5. Performance evaluation

To evaluate our energy-aware routing algorithms, we use (i) the Pan-European test network topology (COST 239) [6], which comprises 11 nodes and 26 bidirectional fiber links, and (ii) a sample US network topology (USNet) [7] consisting of 24 nodes and 43 bidirectional fiber links, with 40 wavelengths per fiber (Fig. 2). We simulate a dynamic network environment where connection requests arrive at the system following a Poisson process and are sequentially served without prior knowledge of future incoming connection requests. Source/destination pairs are randomly chosen, with equal probability, following a uniform distribution among all network nodes. For both network topologies, different values of the offered network load are considered varying from 180 to 324 Erlangs. This is obtained by increasing the arrival rate in each step and by keeping the mean holding time constant following an exponential distribution. Each connection request requires one wavelength unit of bandwidth with wavelength continuity constraint and a link–disjoint path pair where the secondary path is used as a dedicated-protection path. The maximum number of candidate routes for the primary paths and secondary paths are $u = 20$ and $v = 10$, respectively.

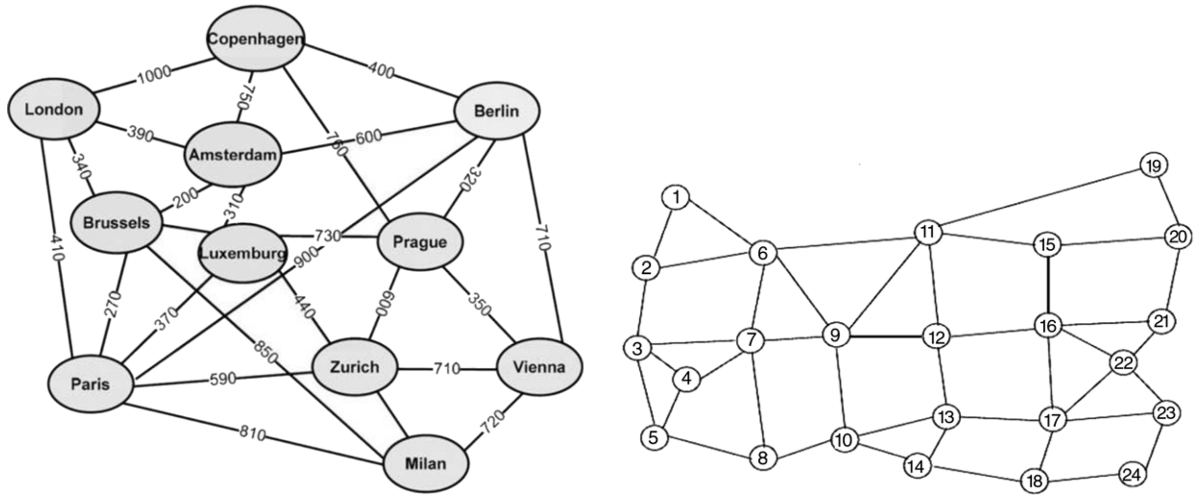
The power consumption values of the optical components are chosen by averaging the data provided in [19–21]. It is assumed that P_{OXC}, P_{Tx}, P_{Rx} are the same for all nodes, and P_{amp} is the same for all amplifiers in the network. The power drained by transceivers, $P_{Tx}+P_{Rx}$, is equal to 14 W, optical amplifier (i.e., EDFA) 12 W, and the switching fabric 6.4 W. It is assumed that all fiber spans have the same length, with $d_{\text{span}} = 80$ km.

For all results, the simulation time is set to achieve a confidence interval value of 5% or better, at the 95% confidence level. As a benchmark, a two-step dedicated path protected provisioning algorithm based on shortest path routing (SP-DPP) is used. SP-DPP works exactly as the algorithms proposed in Section 4. The only difference is in the link cost assignment, i.e., with SP-DPP each link is assigned a cost equal to its length.

The performances of all three algorithms are evaluated considering the total power consumption along with other metrics in the network such as: blocking probability, the load of the maximally loaded link in the network, the total number of wavelength links used by primary and secondary paths, and link utilization. Link utilization is calculated for two different sets of links. (1) links that need to be switched to *active* mode (C) which can be also divided into two subgroups: (a) links utilized only by primary paths ($C \setminus D$), (b) links utilized by both primary and secondary paths ($C \cap D$); and (2) links that can be switched to *sleep* mode namely the links utilized only by secondary paths ($D \setminus C$).

5.1. Total power consumption

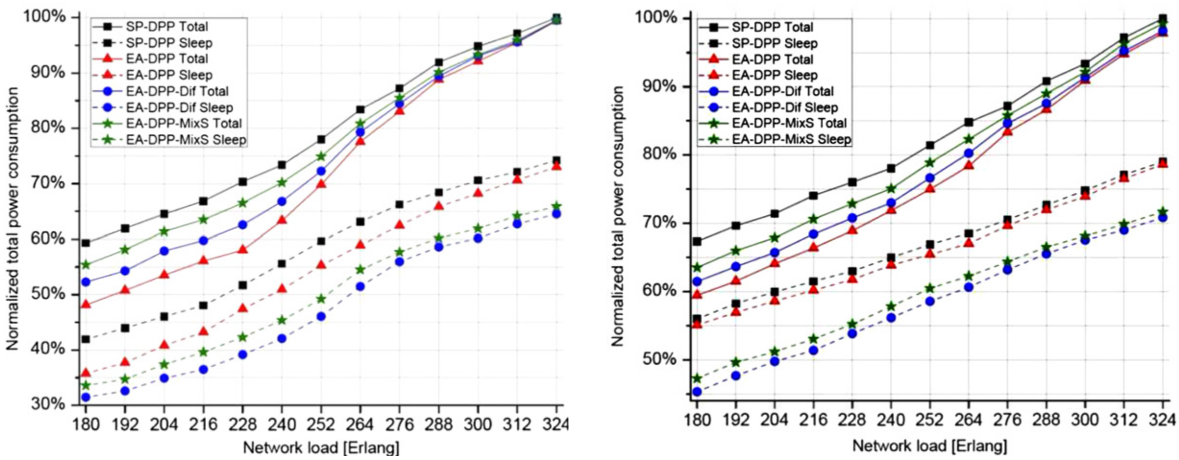
Fig. 3 shows the total network power consumption as a function of the offered network load in Erlangs for COST 239 and USNet network topologies, respectively. The figures present the value of the total power consumption normalized with the highest value of power consumed as a function of the network load. Note that for both networks the same interval for the network load is considered. In both COST 239 and UsNet topologies, the results show a significant reduction of power consumption



(a) COST 239.

(b) USNet.

Fig. 2. (a) Pan-European COST 239 test network, and (b) sample US network USNet.



(a) COST 239.

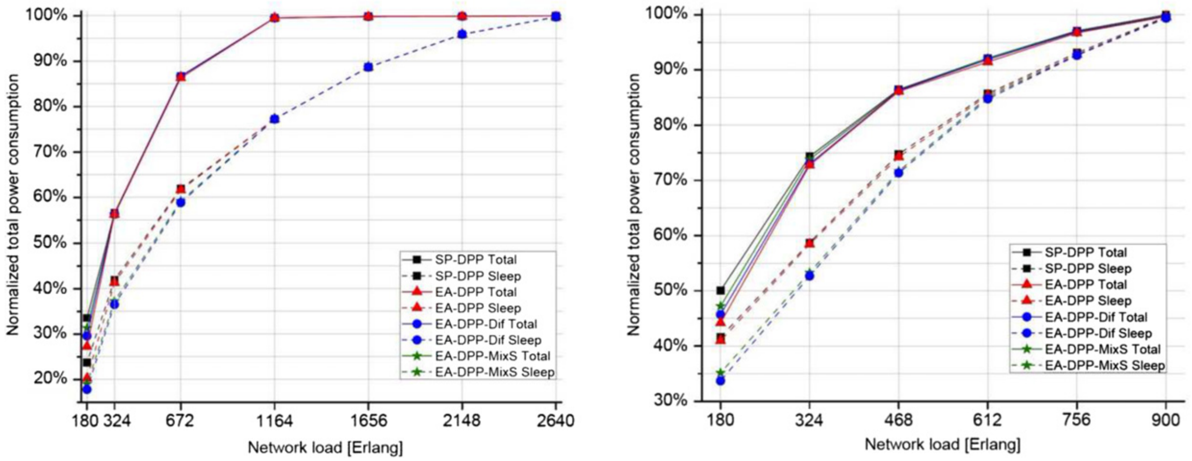
(b) USNet.

Fig. 3. Normalized total power consumption vs. network load for (a) COST 239 and (b) USNet network topologies.

with the proposed energy-aware survivable connection provisioning algorithms, when compared to conventional SP-DPP.

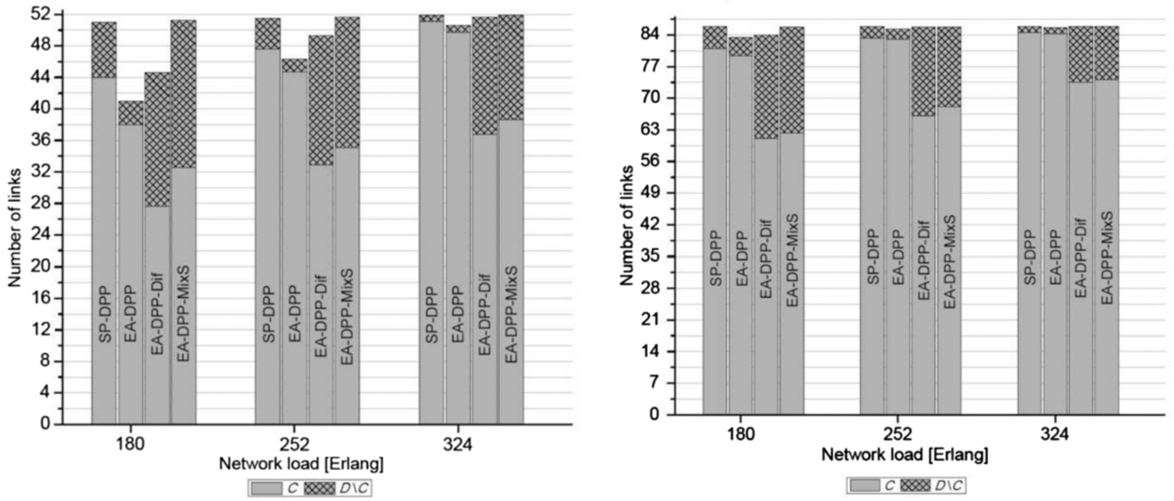
According to Fig. 3 the algorithms able to efficiently exploit the *sleep* mode are EA-DPP-Dif and EA-DPP-MixS. These two algorithms show a very similar behavior, and they both outperform EA-DPP and SP-DPP. By packing primary with primary and secondary with secondary paths, EA-DPP-Dif gives the best reduction in power consumption. We observe that up to 14% (COST 239) and 12% (USNet) of power can be further reduced by EA-DPP-Dif compared to SP-DPP, when the protection resources are in *sleep* mode. The energy saving profile in EA-DPP-MixS follows EA-DPP-Dif very closely while keeping lower blocking probability, which will be discussed in subsection *C*.

When the *sleep* mode is not supported, i.e., both working and protection resources are *active*, the best power savings can be achieved by using EA-DPP. The results show that up to 12% of power savings can be achieved over conventional SP-DPP routing. This is because EA-DPP is *sleep*-unaware, i.e., it does not take into account the *sleep* mode of operation during the routing phase, and it tries to maximize the energy reduction under the assumption that working and protection resources are both constantly active. On the other hand EA-DPP-Dif and EA-DPP-MixS are *sleep*-aware, i.e., they are both designed to minimize the energy consumption as protection resources can be set to *sleep* mode when not required to restore failed connections. With the increase of the load, the number of resources that can be switched-off decreases and the energy savings are reduced, especially when the *sleep* mode is not supported. On the other hand, when the protection resources are switched to *sleep* mode, the energy savings are less affected by the increasing value of the load.



(a) COST 239. (b) USNet.

Fig. 4. Normalized total power consumption under high load conditions for (a) COST 239 and (b) USNet network topologies.



(a) COST 239. (b) USNet.

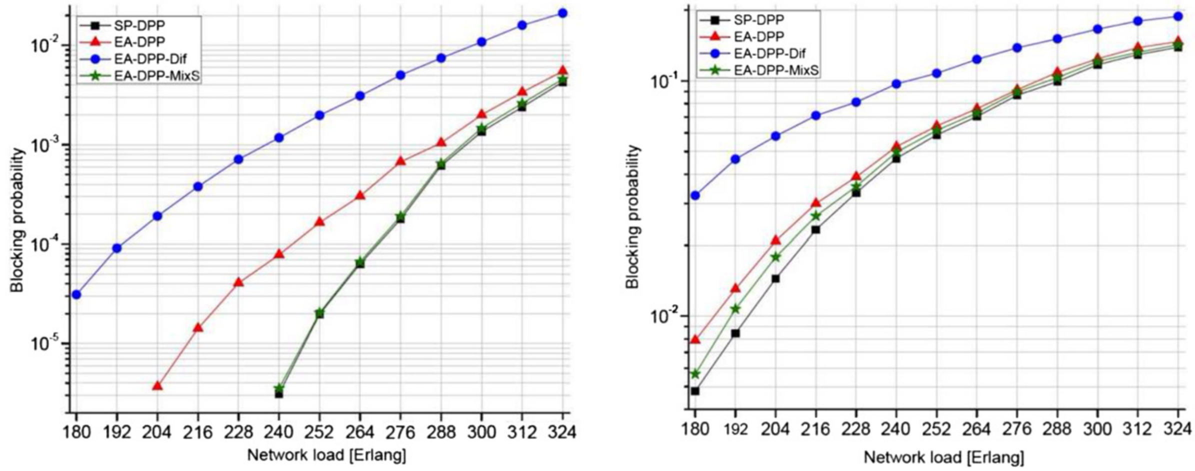
Fig. 5. Number of links used by primary paths (C) and number of links used by secondary paths only ($D \setminus C$) under different load conditions for (a) COST 239 and (b) USNet network topologies.

In order to identify the point beyond which the power consumption curves without *sleep* mode (solid lines) and with *sleep* mode (dashed lines) converge, the value of the normalized total power consumption under very high load conditions is investigated as shown in Fig. 4.

As the network load increases, with the *sleep* mode enabled, the normalized total power consumption values of the *sleep*-unaware algorithms, i.e., SP-DPP and EA-DPP, coincide with the normalized power values of the *sleep*-aware algorithms, i.e., EA-DPP-Dif and EA-DPP-MixS. As expected, the performance difference among the various curves when *sleep* mode is enabled (dashed lines) and when it is not (solid lines) tends to diminish with increasing load values. However, Fig. 4 shows that by setting the unused protection resources into *sleep* mode, up to 22% of the power can still be saved for a load that corresponds to 1164 Erlang in the COST 239 reference topology and up to 27% for a load that corresponds to 468 Erlang in USNet. As shown in Section 5.3 (see Fig. 7) these two load values correspond to a blocking probability in excess of 30%. Even though it is very unlikely that any network is operated under such conditions, the results show that the benefits of placing protection resources into *sleep* mode are still significant for very high loads.

5.2. Link usage

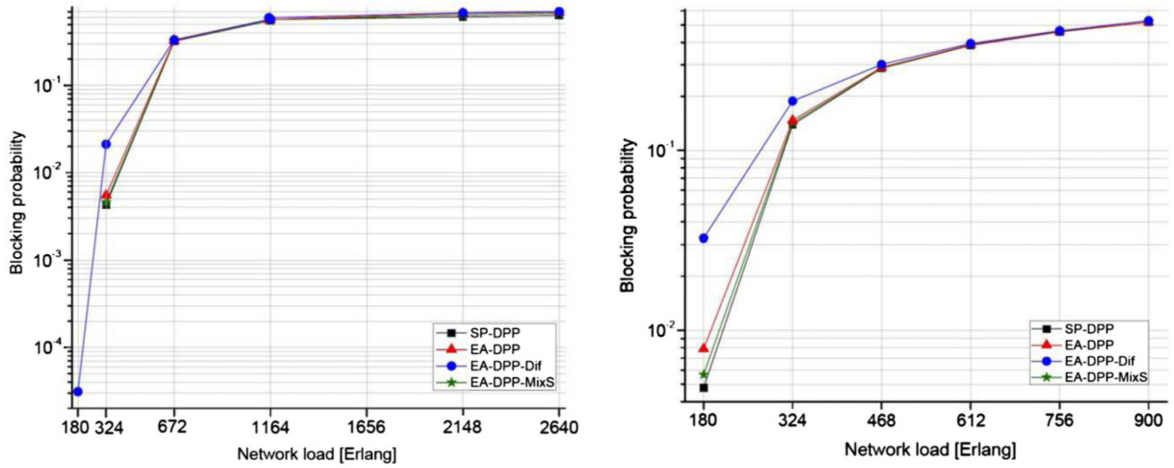
To understand how the power reduction can be obtained by differentiating the link usage between primary and secondary paths, the link usage of the proposed energy-aware approaches are demonstrated for three values of the network load, i.e., 180 Erlang, 252 Erlang, and 324 Erlang, (Fig. 5). For the links that are used exclusively by secondary paths, they can be considered to be switched



(a) COST 239.

(b) USNet.

Fig. 6. Network blocking probability vs. network load for (a) COST 239 and (b) USNet network topologies.



(a) COST 239.

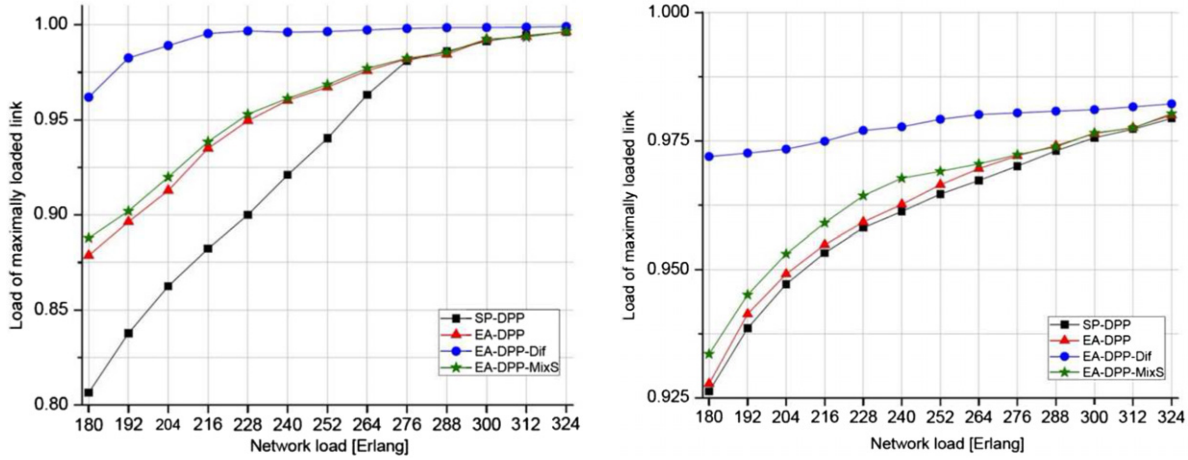
(b) USNet.

Fig. 7. Network blocking probability under high load conditions for (a) COST 239 and (b) USNet network topologies.

to *sleep* mode which is indicated by the darker region in the bar diagrams. The results show that EA-DPP uses the lowest number of links regardless of whether it is used by primary or secondary paths compared to all the other three algorithms. The reason is that it tries to pack all the paths without differentiating the link usage. However among the energy-aware approaches it performs the worst in terms of number of active links since it does not allow the *sleep* mode option. EA-DPP-Dif has the best performance in terms of number of active links followed very close by EA-DPP-MixS. This is due to the fact that EA-DPP-Dif was able to reduce the links with mixed primary and secondary paths.

5.3. Blocking probability and maximum load

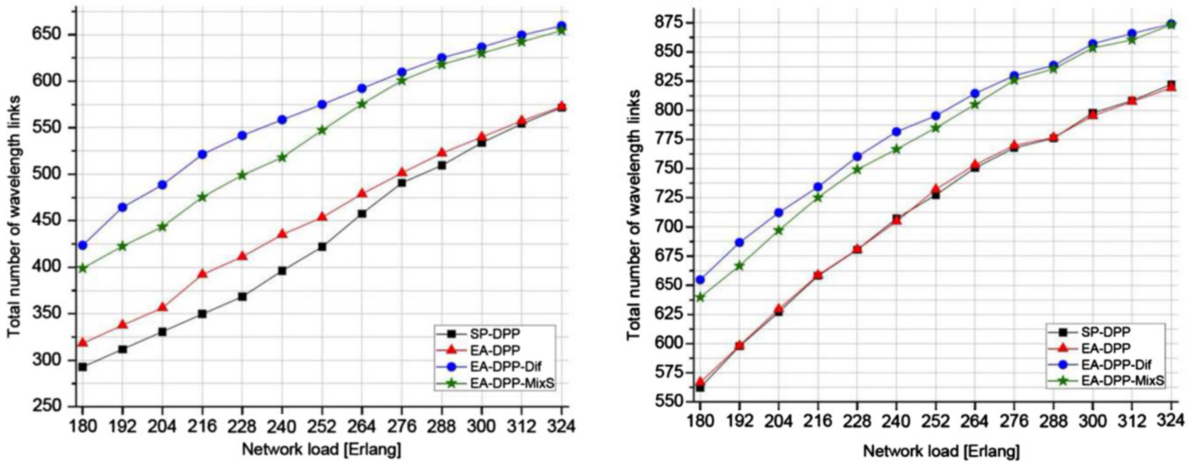
The total blocking probability shown in Fig. 6 accounts for blocking due to insufficient resources, i.e., no wavelength is available for primary or secondary paths. It is an important metric for network performance evaluation since the reduction of the energy consumption in some cases may cause higher blocking probability. Fig. 6 shows that EA-DPP-MixS is a promising solution in terms of blocking among other energy-aware approaches. In both COST 239 and USNet, it can be seen that the blocking performance of EA-DPP-MixS is similar to the SP-DPP routing. Note that the two networks are analyzed for the same range of traffic loads. As a consequence the values of the blocking probability for the USNet is higher than these obtained for COST 239. This is mainly due to the physical topology of USNet, i.e., lower average nodal degree compared to COST 239. However, as confirmed by the power consumption values in Fig. 3, EA-DPP-MixS is still able to show significant energy savings even when the number of alternative paths per node is limited and when most of the resources are used. A condition in which it is not easy to save energy by finding resources that can be set into *sleep* mode. Fig. 7 presents the blocking probability val-



(a) COST 239.

(b) USNet.

Fig. 8. Load of the maximally loaded link in the network vs. network load for (a) COST 239 and (b) USNet network topologies.



(a) COST 239.

(b) USNet.

Fig. 9. Wavelength usage for primary paths vs. network load for (a) COST 239 and (b) USNet network topologies.

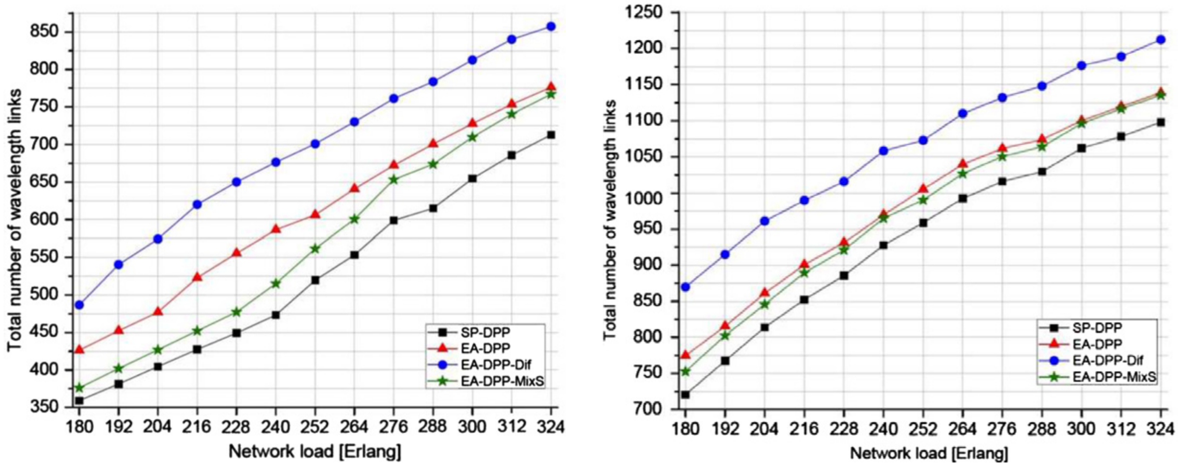
ues for high load conditions. These results provide some useful insights regarding the level of traffic load for which the two groups of algorithms (i.e., with and without the *sleep* mode enabled) presented in Section 5.1 demonstrate similar power consumption performance. It is interesting to note that the total blocking probability curves (Fig. 7) converge much faster than the corresponding power consumption curves (Fig. 4).

EA-DPP-Dif introduces a significantly higher blocking probability as it tries to pack primary and secondary paths separately, thus in turn increases the load of some specific links which may create bottlenecks (Fig. 8). Another interesting observation is that for traffic loads in the order of 300 Erlang, the blocking probability values obtained by EA-DPP get close to those obtained by EA-DPP-MixS and SP-DPP. This is because almost all the links in the network are already in use and, as a consequence, the two energy-aware algorithms, all start choosing the shortest routes. On the other hand, EA-DPP-Dif keeps differentiating between primary and secondary paths, regardless of the increasing number of links already in use.

5.4. Wavelength usage

Figs. 9 and 10 show the number of wavelengths used for primary paths, and for secondary paths, respectively. The figures show that EA-DPP-Dif chooses longer primary and secondary paths.

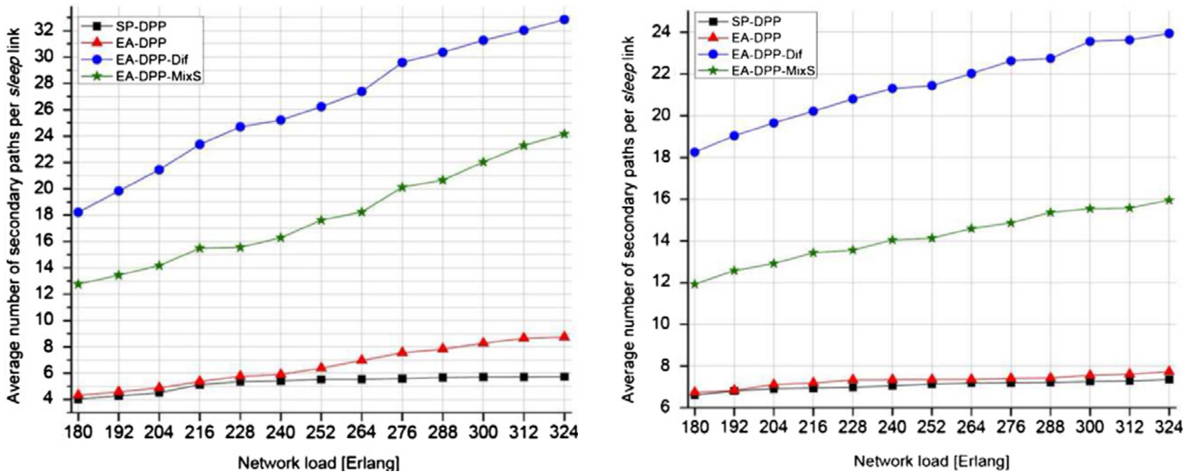
By trying to assign as many primary paths as possible on the already provisioned working resources, EA-DPP-MixS has the second longest primary paths, in terms of wavelength links, followed by EA-DPP, the algorithm which does not consider the *sleep* mode of protection resources. On the other hand, in terms of wavelength links used by secondary paths, EA-DPP-MixS outperforms all the other energy-aware approaches while for EA-DPP-Dif wavelength consumption is still very high for secondary



(a) COST 239.

(b) USNet.

Fig. 10. Wavelength usage for secondary paths vs. network load for (a) COST 239 and (b) USNet network topologies.



(a) COST 239.

(b) USNet.

Fig. 11. Average number of secondary paths per *sleep* link vs. network load for (a) COST 239 and (b) USNet network topologies.

paths. As in the secondary path provisioning of EA-DPP-MixS, the links used by primary and secondary paths are not differentiated, the secondary paths can share the resources with primary paths, and they are shorter, in terms of wavelength links (Fig. 10). This finding also explains why EA-DPP-MixS outperforms EA-DPP-Dif in terms of blocking probability (Fig. 6).

5.5. Average number of secondary paths traversing a sleep link

Fig. 11 presents the average number of secondary paths traversing a *sleep* link. As expected, EA-DPP-Dif exhibits the highest average number of secondary paths per *sleep* link, followed by EA-DPP-MixS. This is because EA-DPP-Dif tries to route as many secondary paths as possible on those links used only for protection purposes. On the other hand EA-DPP-MixS achieves a significant reduction in the average number of secondary paths per *sleep* link as it allows to some secondary paths to be mixed with primary paths. EA-DPP and SP-DPP show the lowest average number of secondary paths per *sleep* link since they do not consider the *sleep* mode option in the routing phase.

6. Conclusion

There are two main contributions of this paper. First the potential power savings achieved by setting protection resources in *sleep* mode are assessed in a dynamic provisioning scenario. Second, different energy-aware algorithms are proposed and compared in order to investigate the best way to fully exploit the benefits offered by the ability to set protection resources in a *sleep* mode. From the comparison of different strategies, it was found that in order to get significant energy saving benefits from the *sleep* mode feature, a provisioning solution needs to be able to differentiate between the links used by the primary paths and the links used by the secondary paths. However, there is a tradeoff between energy efficiency and blocking probability performance when primary and secondary paths are packed on separate links.

The results obtained for two different continental core network topologies indicate that it is possible to overcome this drawback by applying separate routing strategies for primary and secondary paths. Finally the proposed *sleep*-aware algorithms are compared with another energy-aware connection provisioning algorithm, which does not consider the *sleep* mode during the routing phase. It was concluded that techniques taking into account the *sleep* mode option early as in the routing phase (i.e., *sleep*-aware approaches) provides a promising solution, with energy savings of up to 35%.

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