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On the Trade-Off between Power-Efficiency and Blocking Probability in Fault-Tolerant WDM Networks

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QoS provisioning and fault tolerance are desired objectives in all communication networks; however, they are conflicting with the energy saving goal in green networks. Because the mechanisms used in traditional networks like redundancy for fault tolerance or over-provisioning for QoS guarantee are in contradiction with the methods used in green networks to save energy such as turning off the underutilized components. Addressing the interaction between two sides of this contradiction is an interesting and challenging problem because they affect the revenue and OPEX of the communications service providers. Despite of numerous researches on green networks, very few works, consider power consumption reduction with respect to performance parameters in fault-tolerant networks. In this paper, we find the optimal trade-off between power consumption and blocking probability of lightpath connection requests (as the performance metric) in WDM networks with dedicated path protection mechanism by modeling the problem as a multi-objective mixed integer linear programming model. Moreover, a heuristic routing algorithm is proposed to find working and backup lightpaths per request. Its link weighting mechanism allows network administrators to control the trade-off. We evaluate the optimization model and the heuristic algorithms in two network topologies under different traffic loads. The results indicate the superiority of our heuristic algorithms, in terms of power consumption and blocking probability, to existing algorithms. Moreover, the results of the optimization model reveal that there exist a little difference between the optimal solution and our heuristic algorithm.

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1. Introduction

Nowadays, due to potential economic benefits and expected environmental impact, the problem of decreasing power consumption in wired networks has turned out to become a major challenge (Bianzino et al., 2012a). The notion of green networking is highly related to considering power consumption in designing architecture, devices, and protocols of communication networks. The economic benefits of green networks can be thought as the electricity consumption cost of network devices and cooling equipment. The environmental impact of computer networks is related to the volume of Green House Gases (GHG) and CO_2 emissions by ICT industry; which is 2 – 10% of total CO_2 produced by human (Global Action Plan, 2007; Webb, 2008).

Recent studies indicate that the energy consumption in the network core is increasing, even up to 12 times (Lange, 2009). Wavelength Division Multiplexing (WDM) is the de facto technology to build the core networks, which are used for provisioning lightpath connection requests. Due to the high transfer capacity of the optical WDM networks, they have significant power consumption (Jirattigalachote et al., 2011) that implies that they can be considered a considerable potential for power saving. Therefore, in this paper, we focus on greening WDM core networks.

Green networking is challenging because there is a sharp contrast between traditional network design principles and the network greening approaches. The traditional network design aims to achieve Quality of Service (QoS) and fault tolerance through over-provisioning and exploiting redundant network resources, respectively. However by contrast, greening the networks is achieved using methods such as **resource consolidation**, **selective connectedness**, **proportional computing**, and **virtualization** (Bianzino et al., 2012a). The common objective of these methods is to decrease power consumption by more efficient utilization of network resources in such a way that more unused resources can be switched off. Therefore, there exists a contradiction between the methods for greening networks and the approaches for QoS provisioning and fault tolerance in the traditional networks design.

Greening WDM core networks is even more challenging owning the following facts (Bandyopadhyay, 2008). First, as mentioned, the networks consume a noteworthy amount of power. Second, each lightpath in WDM networks carries a high volume of traffic at a few (e.g., 2.5-10) Gbps data rate. Therefore, rejecting a lightpath request blocks a significant amount of user traffic. Third, in WDM networks, each fiber can carry 100 or more lightpaths, so disruption of a link is a serious event (Bandyopadhyay, 2008). Therefore, in green WDM networks, in addition to power consumption, lightpath blocking probability as a QoS metric and fault tolerance (survivability) should be jointly considered. These aforementioned parameters form the main aspects of our work as well.

The trade-off between blocking probability and saving energy is an open interesting problem in practice, because they respectively determine the revenue and OPEX of the service provider networks while they are conflicting with each other. Higher blocking probability in one hand, means less revenue, but in the other hand, it also decreases the OPEX because less resources and consequently less energy is used in the network that means more energy cost saving; and vice versa. This trade-off is made by the routing algorithm used in the network that in one hand, determines blocking probability because requests are blocked if no feasible path is found by the algorithm; in the other hand, it controls the power consumption because the elements on active paths should be turned on.

The ability of existing routing algorithms to make the trade-off is not fully understood, so when a service provider uses a routing algorithm, it does not know how much revenue is lost and how much energy cost is saved by the algorithm. Moreover, service providers need a tool to *control* the trade-off; i.e., a routing algorithm that can make the desired trade-off by adjusting its parameters. For example, when the revenue by accepting a request is much more than the energy cost, the algorithm should favour blocking probability over the power consummation and vice versa. In this paper, we address both the requirements; i.e., the trade-off is analysed and the adjustable routing is developed.

The trade-off between these conflicting objectives in WDM networks has not yet been fully investigated in the literature. In (Sansò and Mellah, 2009), the authors consider three parameters in network design, namely power consumption, average delay as the performance metric, and reliability. Whereas a multi-objective optimization model is proposed to address the trade-off between power consumption and average delay, that performance metric is different than the metric considered in this paper. In (Wiatr et al., 2012), the trade-off between power consumption and some performance metrics (e.g., blocking probability, path length and etc.) is addressed through a *heuristic* routing algorithm in a WDM network. However, in this paper, we use multi-objective optimization models for this purpose in addition to heuristic algorithms. In (Jirattigalachote et al., 2011), improving the power consumption and blocking probability in WDM networks with Dedicated Path Protection (DPP) is accomplished by finding shortest paths based on two heuristic link weighting methods. In (Bao et al., 2012; He and Lin, 2013), WDM networks with Shared Path Protection (SPP) are considered and heuristic algorithms based on link power consumption are proposed. The performance of the algorithms is evaluated from various aspects such as blocking probability. But these studies (Jirattigalachote et al., 2011; Bao et al., 2012; He and Lin, 2013) did not analyse the trade-off.

In our work, the main problem is to investigate the trade-off between power consumption and blocking probability in WDM networks with DPP requirement. In this problem, we assume that lightpath requests dynamically arrive at the network. If two link-disjoint lightpaths, which have unused free wavelength channel, are found for the request, it is accepted; otherwise, the request is blocked. Thus, the network resources (paths, links, and channels) must be selected in such a way that improves power consumption and blocking probability. The main contributions of our work are as follows:

- We propose a multi-objective integer linear programming model where power consumption and blocking probability are two objectives of the model. The solution of the optimization model for different preferences of power and blocking provides the Pareto frontier, which is the optimal trade-off between power consumption and blocking probability. It is a lower-bound for the trade-off and used to measure the efficiency of heuristic routing algorithms.
- We propose a novel heuristic routing algorithm for provisioning lightpath request by means of appropriate weighting of network links. The proposed algorithm meanwhile satisfying the DPP requirement aims to improve the power consumption and blocking probability; moreover, it can control the trade-off between them.

- We evaluate the trade-offs that made by a few heuristic algorithms, including the proposed one, in comparison to the optimal trade-off by the optimization model in various network and load parameter settings.

In the rest of this paper, related work is reviewed in Section 2. Formal definition of the system model, power model, and detailed problem description are presented in Section 3. Section 4 contains elaboration of the optimization model, and the complexity and details associated with it. In Section 5, we will introduce our novel green heuristic routing algorithm that addresses drawbacks of previous works. The experimental results of the optimization model and comparison with heuristic routing algorithms in two standard topologies are presented in Section 6. We finally conclude this work in Section 7.

2. Related Work

In this section, we will first roughly review previous works and their main ideas. Next, a categorization of the previous works is proposed, and eventually, our study is compared to the most closely related works in the literature in Table 1.

In recent years, many studies and researches have been carried out on Green Networking, of which one can refer to (Bianzino et al., 2012a; Dharmaweera et al., 2014) as two comprehensive surveys. Most of the studies in the literature focus on Optical WDM, IP-over-WDM and IP networks, all of which goal to decrease the total power consumption of the network. The main idea of existing works is primarily based on switching off the components of the network, which there is little or no traffic on them.

One of the first efforts in this field of study is the article titled "Greening of the Internet" (Gupta and Singh, 2003). The authors in Gupta and Singh (2003) suggest switching the components of the network to sleep mode, and investigate its effects on the implementation of some protocols such as OSPF and IBGP. In Bianzino et al. (2012b), a distributed algorithm, which utilizes OSPF protocol, is proposed for switching off the links. The authors in Cianfrani et al. (2012) propose an integrated routing algorithm with OSPF protocol, which makes an effort to increase the number of sleep links by sharing the shortest path tree between neighbor nodes. In Amaldi et al. (2013), a multi-objective optimization model is proposed to minimize power consumption and congestion of the network simultaneously.

A model of power consumption of routers is proposed in Chabarek et al. (2008), based on which the authors developed an ILP optimization model to minimize the power of the network. In Chiaraviglio et al. (2012) decreasing the power consumption in an ISP network is taken under consideration by employing an ILP model.

As mentioned, three main aspects of the problem considered in this paper are power consumption, survivability and blocking probability (as the performance metric). According to these aspects, we categorize other related works into two groups. In the first group, only power consumption and performance are taken into account without fault tolerance requirement. Studies in the second group simultaneously analyze all three aforementioned parameters.

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2.1. Green Strategies with performance considerations

In Addis et al. (2014a), a multi-period optimization model is proposed to minimize the power consumption of network which is based on different traffic profiles in various periods within a day. In this model, maximum link utilization is considered as the performance metric. Another optimization model for decreasing power consumption is proposed in Zhang et al. (2011), which assumes that the network traffic is dynamic. Due to the complexity of the optimization model, finding the optimal solution is not practical; therefore, the authors proposed heuristic algorithms in which, the path length and blocking probability are taken under consideration. Authors in Coiro et al. (2011a) propose an optimization model to decrease power consumption in networks with static traffic. They also suggest several heuristic algorithms for networks with dynamic traffic, but the optimal results are not compared to those of heuristic algorithms. In the aforesaid work, the path length and blocking probability are considered as well.

In Wiatr et al. (2012), the trade-off between power consumption and performance parameters; e.g., blocking probability, path length, and link utilization is considered by assigning different costs to links. In particular, it can be concluded that enhancing the power consumption may cause performance degradation, and conversely improving the performance parameters may end up with increase in power consumption. The authors in Coiro et al. (2011b) make an effort to switch off the unused optical fibers in a WDM network with dynamic traffic by assigning appropriate costs to them. The link utilization parameter of different algorithms is compared to each other as well. The work in Xia et al. (2011) proposes a power-aware provisioning scheme based on an auxiliary graph which computes the power consumption of each provisioning operation, and the blocking probability is also taken under consideration as well.

Whereas these studies consider both power consumption and a performance metric, they do not analyze the optimal trade-off between the objectives in fault-tolerant WDM networks.

2.2. Green Strategies with performance considerations in survivable network

For the first time, the problem of decreasing power consumption of networks along with performance and reliability objectives is considered in Sansò and Mellah (2009). In Sansò and Mellah (2009), a multi-objective optimization model is suggested which its goal is decreasing the power consumption and the mean delay of the network. In Lin et al. (2014), an energy-aware routing algorithm is suggested for finding two link disjoint paths, in which the maximum link utilization does not exceed a pre-set threshold value.

In Jirattigalachote et al. (2011), Muhammad et al. (2010), Addis et al. (2012), Addis et al. (2014b), Cavdar et al. (2010), Bao et al. (2012), Monti et al. (2011), He and Lin (2013) and Hou et al. (2013) the three aforementioned parameters are evaluated in various conditions. Table 1 illustrates a brief comparison between this paper and the other work. As it is shown in Table 1, some of existing works consider power consumption and blocking probability in survivable networks. However, in general, most of them pay less attention to the trade-off between them. They do not analyze the trade-off explicitly and just report the results of power consumption and blocking probability parameters. The authors in Jirattigalachote et al. (2011) try to enhance aforesaid parameters to

Table1. Comparison of related work to this paper

Reference	Objective function	Traffic model	Approach	Protection scheme	Network type	Routing approach
Jirattigalachote et al. (2011)	Power and blocking probability	Dynamic	Heuristic	DPP	WDM	Fixed-alternate
He and Lin (2013)	Power and link utilization	Dynamic	Heuristic	SPP	WDM	Adaptive
Monti et al. (2011)	Power	Static	Heuristic	DPP	WDM	Adaptive
Bao et al. (2012)	Power	Dynamic	Heuristic	SPP	WDM	Adaptive
Addis et al. (2012)	Power	Static	ILP & Heuristic	SPP	IP	Adaptive
Muhammad et al. (2010)	Power	Static	ILP	DPP	WDM	Fixed-alternate
Cavdar et al. (2010)	Capacity and power	Static	ILP	SPP	WDM	Adaptive
Hou et al. (2013)	Power	Dynamic	Heuristic	DPP	WDM	Adaptive
Addis et al. (2014b)	Power	Static	ILP & Heuristic	SPP & DPP	IP	Adaptive
Our work	Power and blocking probability	Dynamic & Static	ILP & Heuristic	DPP	WDM	Adaptive

some extent; however, they only compare heuristic algorithms and do not obtain the Pareto frontier for finding the optimal trade-off.

3. System Model and Problem Statement

This section at the beginning describes the network and power models which are used in this paper. Then, it formally defines the problem of this paper according to the network and power models. Finally to clarify the problem, an example of survivable green provisioning is provided.

3.1. Network Model

The network considered in this paper is a wavelength-routed optical WDM network, where network nodes are optical cross-connects (OXCs), and network links are optical bidirectional fibers. The physical network topology is modeled by graph $G = (V, E)$ where V is the set of nodes, and E is the set of links. Each link $(i, j) \in E$ contains W_{ij} wavelength channels with the same bandwidth. The network is provisioned to accept requests for lightpath connections.

The network is fault-tolerant using the *dedicated path protection* scheme (1:1 protection) wherein each working lightpath is protected by another backup lightpath. These lightpaths are link-disjoint. Whereas the backup lightpath is not used by default, wavelength channels are reserved along the lightpath and the reserved channels are *not* shared with other working lightpaths. If there is a fault in the working lightpath, traffic switches to the backup lightpath immediately.

Each connection request $r_i = (s_{i,}, d_i, t_i^s, t_i^h)$ arrives at time t_i^s and demands two (working and backup) lightpaths from source node s_i to destination node d_i. The request is accepted, if a working path and a link-disjoint backup path from s_i to d_i are found such that an unused channel is available in all the links (fibers) belong to the lightpaths. Otherwise, the connection is blocked. The request uses the channels during holding time t_i^h. At time $t_i^s + t_i^h$, it is finished and the allocated resources (channels) are released. Note that, we assume each connection request requires only one wavelength channel and moreover, each node has wavelength conversion capability between all channels; i.e., we do not consider the “wavelength continuity” constraint.

3.2. Power Model

In order to compute total power consumption of the network, a power model is required. In previous studies, different power models, which almost are similar, have been used. In some work (Jirattigalachote et al., 2011; Muhammad et al., 2010; Chiaraviglio et al., 2012; Wiatr et al., 2012; He and Lin, 2013), total power consumption of the network is the sum of power consumption of all nodes and links which are powered on. In another work (Zhang et al., 2014), total power of the network is computed in terms of power consumption by each lightpath. The authors in (Chabarek et al., 2008) modeled power consumption of a router according to its physical configuration (i.e., the chassis type and the installed line cards) and current usage (i.e., traffic profile). In this paper, we use the power model which is also used in Jirattigalachote et al. (2011) and Muhammad et al. (2010) with minor changes. The model is explained in the following.

In this model, three power modes are assumed for an optical component (i.e., link or node): *active*, *sleep*, and *off*; that are summarized in Table 2. A component is in *active* mode, if at least a working lightpath is passing through it. It is in *sleep* mode, if only backup lightpaths use it. In this mode, each component can be activated instantly in the case of fault in the network. If there is not any lightpath going through a component, it will be in *off* mode.

In the *off* mode, components do not consume any power. In the *active* mode, nodes consume a certain amount of power, which consists of two parts; i.e., power consumption of optical exchange components that is traffic independent; and traffic dependent power consumption which is proportional to the number of lightpaths using the node. Power consumption of links in *active* mode is proportional to the physical length of the link. In *sleep* mode, links consume a negligible amount of power; however, power consumption of nodes in this mode is the same as the *active* mode.

More formally, total power consumption of the network is

$$P_{total} = \sum_{n \in V} (P_{node,n} \cdot x_n) + \sum_{(i,j) \in E} (P_{amp,ij} \cdot y_{ij}), \quad (1)$$

where $P_{node,n}$ is the power consumed by node $n \in V$ and $P_{amp,ij}$ is the power consumed by amplifiers in link $(i,j) \in E$. The x_n and y_{ij} are two binary variables that are equal to 1 if node n and link (i,j) are in active mode respectively. Note that x_n is also equal to 1 for sleep nodes; these variables are equal to 0 otherwise.

The power consumption of the node n is

$$P_{node,n} = P_{OXC} + P_{TX}(c_n + d_n) + P_{RX}(\bar{c}_n + \bar{d}_n) + c_n * P_{wc}, \quad (2)$$

where P_{OXC} is power consumption of switching fabric, c_n and $\bar{c}_n$ are respectively the number of working lightpaths beginning (exiting) from and finishing (entering) at n, d_n and $\bar{d}_n$ are the number of backup lightpaths beginning from and finishing at n. P_{TX} and P_{RX} are the power consumption of a transmitter and a receiver. P_{wc} is the power consumed by a wavelength converter. Since we do not enforce the wavelength-continuity constraint, each node has the wavelength conversion capability. Therefore, the power consumed by the wavelength converter is also computed for all nodes (except the destination) in working lightpaths.

The power consumption of the link (i,j) is

$$P_{amp,ij} = k_{ij}.P_{amp}, \quad (3)$$

where P_{amp} is the power consumption of an optical amplifier and

$$k_{ij} = \left(2 * \frac{d_{ij}}{d_{span}}\right) + 2, \quad (4)$$

is the number of amplifiers needed along (i,j), where d_{ij} is the length of (i,j), and d_{span} is the length of fiber which is spanned by an amplifier. It is assumed that it is a constant value.

Table 2. Power consumption in three different modes.

Mode	Functionality	Power consumption	
		Node	**Link**
Off	Null	None	None
Sleep	Prompt to switching to active mode	Same as the Active Mode	Negligible
Active	Full	According (2)	According (3)

3.3. Problem Definition

In green WDM networks, two objectives are simultaneously considered: network-level power consumption should be minimized meanwhile the probability of blocking connection requests also needs to be minimized. These objectives are contradicting, since minimizing the blocking probability leads to acceptance of more connections that needs more resources allocated for working and backup lightpaths; hence, more nodes and links should be turned on that increases the power consumption of the network and vice versa. In this paper, trade-off between these objectives is studied in fault-tolerant WDM network. The problem is stated more formally in the following.

There is a WDM network $G = (V, E)$ wherein, W_{ij} channels are available at link $(i,j) \in E$. The parameters of the power model, e.g., P_{OXC}, P_{amp}, and d_{span} are known. Lightpath connection requests arrive one-by-one. At the arrival time of connection r_i, t_i^s, network is searched for two link-disjoint lightpaths from s_i to d_i that have unused channel(s). If both the lightpaths are found, the connection is accepted; otherwise, it is blocked. Accepting the connection may cause some components to be turned on. Hence, the total power consumption of the network is changed. When an accepted connection finishes, its allocated resources are released that may lead to turning some components off and reducing the power consumption of the network.

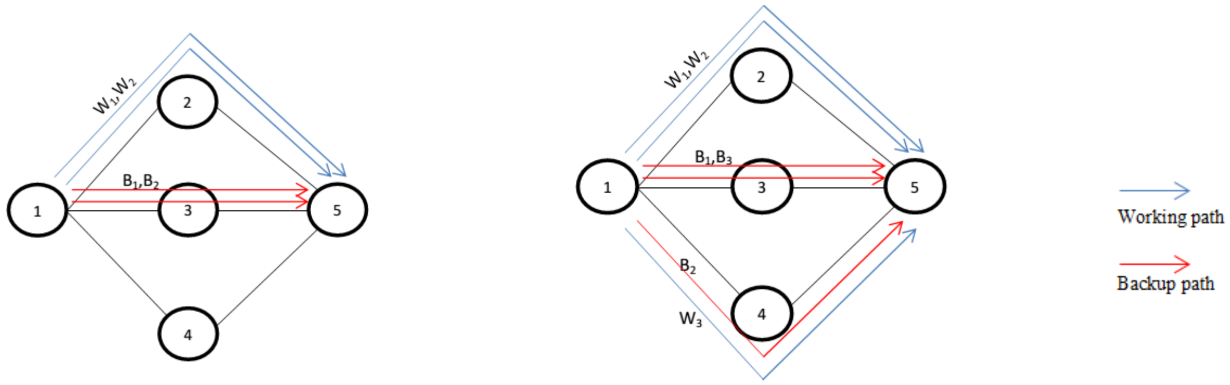
For a given set of requests, the first objective, blocking probability, is the number of blocked requests divided by the total number of requests. The second objective for the set, total network power consumption, is

$$\frac{\sum_{i=2}^{T}(t_i - t_{i-1})P_{t_{i-1}}}{t_T - t_1}, \quad (5)$$

where $\mathcal{T} = \{t_1, \ldots, t_T\}$ is the set of arrival or departure times; i.e., when the mode of some components may change, and P_{t_i} is the power consumption of the network at time t_i.

Accepting or blocking connection requests, and henceforth, network power consumption are determined by the routing algorithm which is used to find the working and backup lightpaths. An ideal routing algorithm aims to minimize both blocking probability and network power consumption simultaneously; however, due to the contradiction between the objectives, any practical algorithm should make a trade-off between them.

The examples shown in Fig. 1 clarify the role of routing algorithm in the trade-off. Assume that $W_{ij} = 2$ for all links, and there are three connection requests $r_1 = (1,5,1,10), r_2 = (1,5,2,10)$, and $r_3 = (1,5,3,10)$. The first routing algorithm, Fig. 1(a), aims to minimize power consumption and does not consider blocking probability. At time $t_1^s = 1$, r_1 arrives. The routing algorithm selects working path $1 \to 2 \to 5$ and backup path $1 \to 3 \to 5$ for this request. Upon arrival of r_2 at time $t_2^s = 2$, the routing algorithm again selects the same working and backup paths in order to minimize power consumption by avoiding turning node 4 on. When r_3 arrives at time $t_3^s = 3$, it is blocked because path $1 \to 4 \to 5$ can only be used either for working or backup path, but not for both them, and there is not any path with free channels. The second routing algorithm, Fig. 1(b), tries to accept more connections requests. For request r_1 again, working path $1 \to 2 \to 5$ and backup path $1 \to 3 \to 5$ are selected. For r_2, similar to the first algorithm, path $1 \to 2 \to 5$ is selected as the working path; however, this algorithm selects backup path $1 \to 4 \to 5$ for this request in order to avoid using all available channels at links (1,3) and (3,5). In this case, request r_3 is also accepted since unused channels are available on both working path $1 \to 4 \to 5$ and backup path $1 \to 3 \to 5$. However, it is at the cost of more power consumption by turning on node 4 and links (1,4) and (4,5).



(a) More energy saving approach (b) Less blocking probability approach

Fig.1. Example of survivable green routing to trade-off between energy saving and blocking probability

4. Proposed Optimization Model

This section presents the multi-objective mixed integer programming (MIP) optimization models to solve the problem stated in section 3.3, and discusses about the complexity of the models.

4.1. Time Based Exact Model

In theory, the optimal solution of the *off-line* version of the problem can be found by solving the optimization model of it. In this model, it is assumed that the network G, the power model and the set of connection requests $R = \{r_1, \ldots, r_m\}$ are given. Hence, *the information of all requests is available at the beginning*[2]. The solution of the model determines 1) acceptance or blocking of each request, which is represented by $O(m)$ binary variables; 2) working and backup paths of accepted requests, which are denoted by $O(2m|E|)$ binary variables; 3) operation mode of components in the network, which are also represented by $O(|E| + |V|)$ integer variables.

Computational complexity is the major problem of this kind of modeling. The first reason of the complexity is the binary variables in the model that lead to an Integer Programming (IP) model which is in general difficult to solve. The second source of the complexity arises from modeling the dynamics of the network traffic *over the time*. Upon arrival or departure of requests, the state of the network changes; that means we need decision variables to model the network, connections, routing over the time (at the arrival and departure times). Therefore, the order of binary variables in the model is $O(2m(m + 2m|E| + |E| + |V|))$ that implies a very huge IP problem. In Capone et al. (2006), a similar off-line modeling was used to obtain performance bound of QoS routing in MPLS networks. Whereas that problem is much simpler than our problem, because power consumption and fault tolerance are not considered, the optimization model cannot be solved even for small networks in a reasonable time.

Since off-line optimization model is useless in practice, and cannot be used to find the minimum blocking probability and power consumption in real networks, in the following, we develop another optimization problem that statistically approximates the off-line model.

4.2. Approximated Statistical Model

In this section, a special case of the problem is modeled as a multi-objective mixed integer linear programming (MILP). In this case, we assume that all requests arrive at the same time. Therefore, holding time is not matter, because no new request arrives after departure of another request. Based on this assumption, it is not necessary to consider the dynamics of the traffic and network. In this case, in fact, network state is static. All requests arrive simultaneously; at the same time, accepting or blocking of each request is determined and the working and backup paths of the accepted requests are found. These states do not change later, since there is not any new further request.

In this problem, the objective is to minimize the total network power consumption and blocking probability of requests simultaneously via optimally routing the working and backup paths. We use the well-known scalarization technique (Miettinen and Mäkelä, 2002) to develop the multi-objective MILP model of the problem in the following.

It is assumed that the following information is given as input parameters:

- $G = (V, E)$: Physical network topology
- W_{ij}: number of wavelengths on link (i, j)
- $R = \{r_1, \ldots, r_m\}$: set of connection requests where $r_i = (s_i, d_i, 0, t_i^h)$
- P_{max}: maximum total power of the network when all optical components are powered on
- $0 \le \alpha \le 1$: the adjustment parameter that trades off between the objectives of optimization model (i.e., normalized power consumption of the network and blocking probability)
- d_{ij}: length of a link (i, j)
- The parameters of the power model, including e.g., P_{OXC}, P_{amp}, and d_{span} that explained in Section 3

The following decision variables are used in the model:

[2] Whereas the assumption is not realistic, it is commonly used to obtain performance bound of online algorithms with respect to the optimal off-line algorithm, which is known as competitive ratio (Krumke, 2006).

- x_{ij}^r: binary variable that is 1 if link (i,j) is used in the working path of request r
- y_{ij}^r: binary variable that is 1 if link (i,j) is used in the backup path of request r
- b^r: binary variable that is 1 if request r is blocked
- n_i: binary variable that is 1 if node i is powered on
- l_{ij}: binary variable that is 1 if link (i,j) is powered on
- p_{total}: total power consumption of the network
- P_i: power consumption of node i which is powered on
- P_{ij}: power consumption of link (i,j) which is powered on

Objective

Minimize:

$$\alpha\left(\frac{P_{total}}{P_{max}}\right)+(1-\alpha)\left(\frac{\sum_{r\in R} b^r}{|R|}\right) \tag{6}$$

Constraints

$$\sum_{(i,j)\in E} x_{ij}^r - \sum_{(j,i)\in E} x_{ji}^r = \begin{cases} 1-b^r & \text{if } s_r = i \\ -(1-b^r) & \text{if } d_r = i \\ 0 & \text{otherwise} \end{cases}, \quad \forall i \in V, \forall r \in R \tag{7}$$

$$\sum_{(i,j)\in E} y_{ij}^r - \sum_{(j,i)\in E} y_{ji}^r = \begin{cases} 1-b^r & \text{if } s_r = i \\ -(1-b^r) & \text{if } d_r = i \\ 0 & \text{otherwise} \end{cases}, \quad \forall i \in V, \forall r \in R \tag{8}$$

$$x_{ij}^r + y_{ij}^r \le 1 \ \ \forall (i,j) \in E, \forall r \in R \tag{9}$$

$$\sum_{r\in R} x_{ij}^r + \sum_{r\in R} y_{ji}^r \le W_{ij} \ \ \forall (i,j) \in E \tag{10}$$

$$P_{total} = \sum_{i\in V} P_i + \sum_{(i,j)\in E} P_{ij} \tag{11}$$

$$P_i = n_i * P_{OXC} + P_{TX}(c_i + d_i) + P_{RX}(\bar{c}_i + \bar{d}_i) + c_i * P_{wc}, \forall i \in V \tag{12}$$

$$P_{ij} = l_{ij} * \left[\left(2 * \left(\frac{d_{ij}}{d_{span}}\right)\right) + 2\right] * P_{amp} \ \ \forall (i,j) \in E \tag{13}$$

$$c_i = \sum_{r\in R} \sum_{j:(i,j)\in E} x_{ij}^r \quad \forall i \in V \tag{14}$$

$$\bar{c}_i = \sum_{r\in R} \sum_{j:(j,i)\in E} x_{ji}^r \quad \forall i \in V \tag{15}$$

$$d_i = \sum_{r\in R} \sum_{j:(i,j)\in E} y_{ij}^r \quad \forall i \in V \tag{16}$$

$$\bar{d}_i = \sum_{r\in R} \sum_{j:(j,i)\in E} y_{ji}^r \quad \forall i \in V \tag{17}$$

$$n_i \ge x_{ij}^r + y_{ij}^r \ \ \forall i \in V, \forall (i,j) \in E, \forall r \in R \tag{18}$$

$$n_i \ge x_{ji}^r + y_{ji}^r \ \ \forall i \in V, \forall (j,i) \in E, \forall r \in R \tag{19}$$

$$l_{ij} \ge x_{ij}^r \ \ \forall (j,i) \in E, \forall r \in R \tag{20}$$

Equation (6) is the multi-objective function that minimizes the normalized power usage (i.e., the total power consumption of the network divided by the maximum power consumption of the network) and blocking probability. In this equation, α is the scalarization parameter that makes trade-off between these objectives. Constraints (7) and (8) are the well-known flow conservation constraints for routing connection request r from node s_r to d_r for working and backup lightpaths, respectively. According to these constraints, if request r is not blocked, i.e., $b^r = 0$, two paths are found for it. Constraint (9) guarantees the paths are link-disjoint. Constraint (10) ensures that the number of working and backup lightpaths passing through a link does not exceed the number of available wavelength channels on it. This constraint implies reserving channels for both working and backup paths that implements dedicated path protection. Equation (11) computes the total power consumption of the network, which is the sum of the power consumption of the nodes and links that are powered on. Equations (12) and (13) computes the power consumption of the active nodes and links respectively, according to equations (2) and (3) in the power model. Equations (14) and (15) compute the number of working paths originating from and terminating at i respectively. Equations (16) and (17) compute the number of backup paths originating from and terminating at i respectively. Constraint (18) and (19) force a node to be active if at least one working or backup lightpath passing on it, and constraint (20) forces a link to be active if at least one working lightpath passing on it.

4.3. Discussion of Optimization Model

Our proposed model is an off-line model. It has the information of all m given requests at the beginning and finds the working and backup lightpaths for each of them. In fact, it models a *snapshot* of the online mode in a specific traffic load. This will be explained in more details in the following.

According to Little formula, for arrival rate λ and holding time $1/\mu$, there are, on average $m = \lambda/\mu$ connections in the network. Operation of an online algorithm can be observed in a time window (snapshot) that contains m successive connection requests. In each window, the online algorithm routes m requests *one-by-one*. Over the time, there are a few numbers of such windows. The power consumption and blocking probability of the online algorithm is the *average* of the value of the parameters in the windows.

In the off-line optimization model, the optimal values of the aforementioned parameters are found in just one temporal window with m requests. If the optimization model is solved for multiple windows with different m connections and the average of optimal value of the parameters is taken, then, the *average* can be considered as the optimal trade-off between power consumption and blocking probability. Therefore, it statistically (on average) approximates the behavior of online algorithms without explicitly modeling the arrival and departure of connections.

The proposed optimization model falls in the class of Capacitated Multi-commodity Minimum-Cost flow problems (CMCF) (Ghamlouche et al., 2003), because in the model multiple commodities, i.e., lightpath connection requests, have to be routed in a graph with capacity constraints. CMCF problems are known as NP-hard problems. Hence, the mixed integer model is also hard to solve which is due to the binary variables. In the off-line formulation, the number of binary variable (without auxiliary variables) is about

$$O(2|E||R| + |R| + |V| + |E|), \quad (21)$$

which is a quite large number. Therefore, finding the optimal solution becomes very time consuming in the standard topology like COST239 network. To solve the optimization model in more reasonable time, we use the LP relaxation method. In this method, we relax the binary constraint on x_{ij}^r and y_{ij}^r variables. It is assumed that these are continues variables, i.e., $0 \leq x_{ij}^r, y_{ij}^r \leq 1$. This assumption is very common in literature that implies multiple paths from its source node to its destination node. In this case, the average solution of the model will be a *lower-bound* on the trade-off.

5. Proposed Heuristic Traffic Grooming

This section first, reviews an existing weighting method which is proposed in the context of heuristic green routing algorithms for lightpath provisioning with dedicated path protection in WDM networks. Then, by analyzing the drawbacks of it, a novel link weighting method is proposed to improve the power consumption of the network and blocking probability. Finally, the pseudo-code and analysis of the computational complexity of the proposed heuristic algorithm is presented.

5.1. Existing Weighting Methods in Green Routing Algorithms with DPP

Recently, in Jirattigalachote et al. (2011), the *energy-aware dedicated path protection with differentiation of primary and secondary paths* (EA-DPP-Dif) and the *energy-aware dedicated path protection with mixing secondary with primary paths* (EA-DPP-MixS) algorithms have proposed.

The EA-DPP-Dif algorithm when routes working or backup paths, tries to separate working (primary) paths from backup (secondary) paths as much as possible by discouraging the mixture of these two types of paths (Jirattigalachote et al., 2011) in order to reduce the power consumption of the network. The EA-DPP-MixS algorithm also tries to separate working paths from backup paths; however, only when it routes working paths to reduce the power consumption of the network. In the backup path provisioning phase, EA-DPP-MixS is not afraid of mixing working paths and backup paths (Jirattigalachote et al., 2011) in order to reduce blocking probability.

In Table 3, the link weight assignments by EA-DPP-Dif and EA-DPP-MixS are summarized. In this table, L denotes the set of all network links, C denotes the set of links used by at least one working path, and D denotes the set of links used by at least one backup path. Thus $C \setminus D$ is the set of links that only used by working paths, i.e., they are in active mode, $C \cap D$ is the set of links used by both working and backup paths, i.e., they are in active mode, $D \setminus C$ is the set of links that only used by backup paths; hence, they are in sleep mode, and $L \setminus (C \cup D)$ is the set of links which are not used by any path; that implies they are in the off mode.

Table 3. Link weight assignment for different heuristic algorithms (Jirattigalachote et al., 2011).

	Algorithm	$C \setminus D$	$C \cap D$	$D \setminus C$	$L \setminus (C \cup D)$
Working Path	EA-DPP-Dif	0	P_{total}	$\|L\|.P_{total}$	$P_{amp,ij}$
	EA-DPP-MixS	0	$P_{amp,ij}$	$\|L\|.P_{total}$	P_{total}
Backup Path	EA-DPP-Dif	$\|L\|.P_{tota}$	P_{total}	0	$P_{amp,ij}$
	EA-DPP-MixS	0	0	0	$P_{amp,ij}$

As seen in Table 3, in provisioning working paths, both EA-DPP-Dif and EA-DPP-MixS assign zero weight to the links used by working path only, thus these links are selected with more probability. They assign $|L|.P_{total}$ weight to the links used by backup path only; therefore, the links are selected with less probability. In backup path provisioning phase, EA-DPP-Dif assigns zero weight to links used by backup paths only, thus the links are selected with more probability. However, EA-DPP-MixS considers zero weight for all links except links not used by any path; hence, links used by working and/or backup paths are selected with equal probability. It leads to better load balancing than the EA-DPP-Dif and lower blocking probability.

5.2. Proposed Link Weighting Method

Before presenting our proposed heuristic green survivable routing algorithm, we investigate some drawbacks in the EA-DPP-Dif and EA-DPP-MixS algorithms. We list the issues as follows:

1. As seen in Table 3, in the working path provisioning phase, EA-DPP-Dif and EA-DPP-MixS algorithms assign $|L|.P_{total}$ weight to links used by backup path only (i.e., $D \setminus C$ link set) whereas these algorithms respectively assign weights $P_{amp,ij}$ and P_{total} to off links (i.e., $L \setminus (C \cup D)$ link set). Since $|L|.P_{total} > P_{amp,ij}$ and $|L|.P_{total} > P_{total}$, off links are selected with higher probability than sleep links. This is in contradiction with reducing the total power consumption of the network.
2. In the working path provisioning phase, EA-DPP-Dif assigns P_{total} weight to links used by working and backup path (i.e., $C \cap D$ link set); whereas, this algorithm assigns weight $P_{amp,ij}$ to off links ($L \setminus (C \cup D)$ set). Therefore, off links are selected with higher probability than links used by working and backup paths. This is also in contradiction with reducing the total power consumption of the network.
3. As shown in Table 3, the algorithms in some cases assign zero weight to links. This causes that the number of hops (path length) is not considered; consequently, long paths may be selected by the algorithms that waste network resources and increase blocking probability.
4. In the backup path provisioning phase, EA-DPP-MixS assigns zero weight for all links except off links; thus, all links in set $C \cup D$ are used with equal probability. Whereas it leads to better load balancing than the EA-DPP-Dif, this algorithm does not consider the number of unused wavelength channels at each link. Using links with more free wavelengths balances load even more efficiently and achieves lower blocking probability.

5. In link weighting mechanisms, the ratio between link weights is more important than the absolute value of the weights. For example, to minimize energy consumption, the weight of active links should be much less than the weight of off links in order to avoid turning on the off links. EA-DPP-Dif and EA-DPP-MixS algorithms, similar to some previous studies (Jirattigalachote et al., 2011; Wiatr et al., 2012; He and Lin, 2013; Zhang et al., 2014), use parameters like P_{total} and $P_{amp,ij}$ for link weighting which are network dependent; thus, the ratio between weights is different in different networks; and consequently, improving the objectives is network dependent.

To resolve these issues, we propose a new link weighting method which is named *Control Energy & Blocking in Dedicated Path Protection via considering Residual Resource* (CEB-DPP-RR). The CEB-DPP-RR weighting method is summarized in Table 4 where n is the number of free wavelength channels on a link, and $N1$, $N2$, and $N3$ are constant numbers where $N1 \leq N2 \leq N3$. Considering the number of unused wavelength channels on links as free resources of the network can improve load balancing in the network; and hence, reduces the blocking probability of the requests. This resolves the issue no. 4. Using the fixed values ($N1$, $N2$, and $N3$) causes that link weights and consequently improvement of the objective function is network independent, that resolves the issue no. 5. This also allows network manager to control the trade-off between minimizing power consumption and minimizing blocking probability with changing these numbers; i.e., greater difference between these values causes more reduction in power consumption of the network and less difference lead to reduce blocking probability.

In the working path provisioning phase, CEB-DPP-RR algorithm assigns $N3/n$ weight for $D \setminus C$ and $L \setminus (C \cup D)$ link sets, because the off and sleep links are nearly similar from the view of power consumption. This weighting resolves the issue no. 1. As shown in Table 4, the weight of links in set $C \cap D$ is less than the weight of the links in $L \setminus (C \cup D)$ set that resolves the issue no. 2. In order to resolve the issue no. 3, zero weights in Table 3 are replaced by $N1/n$, where $N1$ is less than $N2$ and $N3$.

Table 4. CEB-DPP-RR link weight assignment.

	$C \setminus D$	$D \cap C$	$D \setminus C$	$L \setminus (C \cup D)$
Working Path Provision Phase	$N1/n$	$N1/n$	$N3/n$	$N3/n$
Backup Path Provisioning Phase	$N3/n$	$N2/n$	$N1/n$	$N1/n$

5.3. Pseudo-code of Algorithm

The pseudo-code of the proposed online heuristic green survivable lightpath provisioning algorithm is presented in Fig. 2. The inputs of the algorithm are the physical network topology i.e., $G = (V, E)$ and a connection request i.e., $r_i = (s_{i,}, d_i, t_i^s, t_i^h)$. The algorithm outputs are the working and backup link-disjoint paths for the request r_i. The variable $block$ is defined to store the number of blocked requests.

Variables w and b represent the working and backup paths respectively (line 1). Before routing, the algorithm temporarily removes the links that all wavelengths are allocated (line 2) since these links cannot be used for the new request.

For the new request r_i, a working path and a backup path which are link-disjoint should be found. In finding a path, in order to consider path length, two weights are assigned to each link and the path is found in two steps. In the first step, K minimum (physical) length paths are found using Yen's algorithm (Martins and Pascoal, 2003), and in the second step, the shortest path is selected among those K paths according to the weights in Table 4 (lines 4 and 6). Before finding the backup path, the algorithm removes the links of working path w from the topology temporarily (line 5) and finds corresponding link-disjoint backup path (line 6).

If the working and backup paths are found (line 8), resources are allocated for the paths in the network. Then the mode of the links and nodes (*off, sleep, active* modes) are updated (line 9 and 10). If enough resources are not available for routing, the request r_i is blocked (lines 11-13).

Input: Graph $G = (V, E)$, arrival request $r_i = (s_{i,}, d_i, t_i^s, t_i^h)$
Output: Link-disjoint working and backup paths

1. Define w and b for storing working and backup paths respectively.
2. Temporarily prune the links that all their wavelengths are allocated from $G = (V, E)$.
3. Update links weight in $G = (V, E)$ according to Table 4.
4. Find K minimum (physical) length paths by Yen's algorithm between node s_i and node d_i, and select a path with minimum weight according to Table 4 and store it in w.
5. Prune the links used by w from $G = (V, E)$ temporarily.
6. Find K minimum (physical) length paths by Yen's algorithm between node s_i and node d_i, and select a path with minimum weight according to Table 4 and store it in b.
7. Add all the pruned links to the $G = (V, E)$.
8. **If** w != null and b! = null **then**
9. Allocate w and b to r_i since t_i^s to $t_i^s + t_i^h$.
10. Update mode of nodes and links in $G = (V, E)$.
11. **Else**
12. Block the arrival request r_i.
13. $block$++;
14. **End**

Fig. 2. The pseudo-code of online heuristic green survivable provisioning

5.4. Computational complexity analysis

The network pruning in step 2 has $O(|E|W)$ time complexity. Updating of link weights in step 3 has $O(|E|)$ time complexity. The Yen's algorithm which finds K shortest paths requires $O(K|V|(|E| + |V| \; log \; |V|))$ time. Sorting the K paths according to their weights has $O(K\log(K))$ time complexity. The pruning of the links of the working path requires $O(|E|)$ time, and updating nodes and links modes has $O(|V| + |E|)$ time complexity. Therefore, by putting all them together, the running-time complexity of the algorithm is

$$O(K|V|(|E| + |V| \log|V|) + |V| + |E| + K\log(K)). \tag{22}$$

6. Simulation Results and Analysis

In this section, we evaluate the heuristic algorithms and the optimization model that are proposed for analyzing the trade-off between power consumption and blocking probability. In Section 6.2, the performances of the heuristic routing algorithms are compared in different traffic load conditions[3]. Then, in Section 6.3, the solution of the optimization model and those heuristic routing algorithms are compared in a Pareto frontier diagram. For a better evaluation, the *shortest path with DPP* (SP-DPP) algorithm is also simulated, in addition to the heuristic algorithms. It assigns weight of each link equals to its length.

6.1. Simulation Setup

In this section, the settings of the simulation environment and method are explained.

Network Topologies: The simulations were conducted in two standard network topologies; i.e., Pan-European (COST 239) (Batchelor et al., 2000) and US network (USNET) (Xia et al., 2010). COST 239 comprises 11 nodes and 26 bidirectional fiber links, and USNET comprises of 24 nodes and 43 bidirectional fiber links. They are depicted in Fig. 3. In Section 6.2, where the heuristic algorithms are compared to each other, it is assumed that each optical fiber consists of 20 wavelength channels; however, the number is 10 channels in Section 6.3, where the optimization model is evaluated.

Power Model: The power consumption parameters of the optical components are taken from (Jirattigalachote et al., 2011; He and Lin, 2013) which are summarized in Table 5. It is assumed that P_{OXC}, P_{TX}, P_{RX}, P_{wc} are the same for all nodes, and P_{amp} is the same for all amplifiers in the network; also, it is assumed that all amplifiers span the same length $d_{span} = 80$ km (Jirattigalachote et al., 2011).

Table 5. The value of the power model parameters in the simulations.

Parameter	Value (W)
P_{OXC}	6.4
P_{TX}, P_{RX}	7
P_{wc}	1.7
P_{amp}	12

Network Load: Two different but similar kinds of network load are simulated in Section 6.1 and Section 6.2. In Section 6.1, *dynamic online load*, where the requests arrive one-by-one over the time, is simulated to evaluate the heuristic algorithms. In Section 6.2, *static off-line load*, where the entire requests are known at the beginning, is simulated to be used as the input of the optimization model. More details about each kind of the loads are given in corresponding sections.

Evaluation Metrics: In our experiments, power consumption and blocking probability parameters and the trade-off between them are scrutinized. The power consumption is normalized by its maximum value; i.e., the case when all optical components are powered on in the network.

6.2. Evaluation of the Proposed Heuristic Algorithms

Dynamic Online Network Load: In order to simulate the dynamic network traffic, we generate lightpath connection requests that arrive to the network following a Poisson process with rate λ. The connection hold-time follows an exponential distribution with mean $1/\mu$. Therefore, according to the Little's law, the average number of concurrent requests that offered to the network is λ/μ that is measured in the unit of *Erlang*. Source and destination of the requests are uniformly selected among all network nodes. To increase the offered network load, arrival rate λ is increased while service rate μ is set to a fixed value, 2 connections per second. In our simulations, in each traffic load, $3 * 10^4$ lightpath connection requests are injected into the network.

Simulation Method: The heuristic algorithms are implemented in a connection/flow level simulator that is developed in Java language; its source code and executable binary files are available in PourEmami and Bakhshi (2015). Since the heuristic algorithms are *online*, in this simulator, the requests are routed upon their arrival time in a one-by-one manner, without any prior knowledge about future requests.

To evaluate the proposed algorithm CEB-DPP-RR and its ability to control the trade-off between power consumption and blocking probability, three different values for parameters $N1$, $N2$, and $N3$ are used in the simulations which are summarized in Table 6 (W denotes the number of wavelength channels on the links).

Table 6. Values of $N1$, $N2$, $N3$ in different versions of CEB-DPP-RR.

Algorithm	$N1$	$N2$	$N3$
CEB-DPP-RR	1	$W/2$	W
CEB-DPP-RR (MP)	1	$N3/2$	$9 * 10^8$
CEB-DPP-RR (MB)	1	1	1

CEB-DPP-RR tries to find a reasonable trade-off between power consumption and blocking probability in the case that both of them have almost equal preference in the network. If the power saving is of more importance (in spite of increase in blocking probability), CEB-DPP-RR *More Power efficient* (CEB-DPP-RR (MP)) can be used in the case. This algorithm aims to reduce the probability of combining working and backup paths on a link (because $N1 \ll N2, N3$) that leads to increase in the number of sleep links. When reducing the blocking probability has more preference (in spite of increase in power consumption) CEB-DPP-RR *More Blocking efficient* (CEB-DPP-RR (MB)) can be used. This algorithm is, in fact, similar to the minimum hop count routing algorithm and makes an effort to reduce resource usage in the network that leads to better blocking probability.

Results: The results of power consumption and blocking probability for various traffic loads from 50 to 230 Erlangs, in COST 239 and USNET topologies are depicted in Fig.4 and Fig.5, respectively. In Fig. 4(a), it is shown that in topology COST 239, CEB-DPP-RR and CEB-DPP-RR (MP) are superior to other algorithms in terms of power consumption. In particular, CEB-DPP-RR (MP) saves about 6% more power than the EA-DPP-Dif algorithm. The same measurement indicates about 3% increase in power saving for CEB-DPP-RR in comparison to EA-DPP-Dif algorithm. SP-DPP and CEB-DPP-RR (MB) are worse than the others in terms of power consumption so that they end up with at least 6% increase in power consumption, compared to the other algorithms (e.g., EA-DPP-MixS).

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[3] For fair comparison between the heuristic algorithms, all of them should be simulated in the same condition. Therefore, routing approach is the *adaptive routing* mechanism for all the algorithms in the simulations.

As shown in Fig. 5(a), in COST 239 topology, CEB-DPP-RR (MB) achieves superior performance in terms of blocking probability, compared to the others. The main reason for this superiority relates to the improvement in load balancing of the network. Not only CEB-DPP-RR is superior to EA-DPP-Dif, EA-DPP-MixS, and SP-DPP in terms of power consumption, but also this superiority is evident in terms of blocking probability. The better performance of our proposed algorithm is due to using the number of free wavelengths on each link explicitly (i.e. n in Table 4). Additionally, in terms of blocking probability, CEB-DPP-RR (MP) exhibits worse performance than the SP-DPP, and better performance than EA-DPP-MixS.

As shown in Fig. 4(b), in USNET topology and in terms of power consumption, the algorithms CEB-DPP-RR, CEB-DPP-RR (MP), EA-DPP-Dif, and EA-DPP-MixS perform closely to each other and the difference between them reaches up to 4%. CEB-DPP-RR (MB) and SP-DPP algorithms consume at least 12% more power than the others. As it is shown in Fig. 5 (b), in USNET topology and in terms of blocking probability, CEB-DPP-RR (MB) achieves better performance among others. SP-DPP, CEB-DPP-RR (MP) and CEB-DPP-RR algorithms are highly close to each other, EA-DPP-MixS and EA-DPP-Dif are the worst of all. It is noteworthy that in USNET topology, we have higher blocking probability and the performance of the algorithms is close to each other than COST 239, which is due to the presence of low degree nodes in that topology (Jirattigalachote et al., 2011).

6.3. Evaluation of the Optimization Model

Static Off-line Network Load: As explained in Section 4.3, the optimization model considers a snapshot (time window) of network load with $m = \lambda/\mu$ concurrent requests, which is denoted by set R, and finds the optimal trade-off. To simulate the snapshot, m requests with random source and destination nodes are created that they comprise the set R, and used as the input of the MILP model. The input requests for the heuristic algorithms, which are compared against the optimization model, are generated according to the "Dynamic Online Network Load" that is explained in Section 6.2.

Simulation Method: The proposed optimization model (as presented in Section 4) is implemented by **`zimpl`** (ZIB) modelling language, the implemented model is thereafter solved via **`scip`** version 3.0.2 (ZIB) and **`gurobi`** version 5.6.3. The experiments were run on a computer with Intel Core 2 Duo 2.3 GHz processor, 4 GB of RAM and 64-bit operating system. It should be noted that each round of solving the optimization problem mostly takes at least 24 hours.

As mentioned, in solving the optimization problem, it is assumed that each bidirectional fiber link consists of 10 wavelength channels, $W = 10$. The parameter α was varied between 0 to 1 to achieve the complete Pareto optimal frontier which is the lower bound for power consumption and blocking probability of heuristic algorithms (Fig. 6 and Fig. 7). It is obtained as follows.

For a given parameter α and a traffic load, in terms of Erlang $m = \lambda/\mu$, a point of Pareto frontier is found by solving the optimization model for m connection requests. Varying the parameter α and repeating the procedure produces the other points. For a given Erlangs, blocking probability and power consumption of a heuristic algorithm, were found by simulating the algorithm for a large number of connection requests that arrive at rate λ and have average hold-time $1/\mu$. The values of power consumption and blocking probability parameters determine a point that is associated with (represents) the algorithm in the figures.

Results: In Fig. 6 and Fig. 7, Pareto optimal frontier, illustrates the trade-off between power consumption and blocking probability in the optimum case, for respectively 75, 100 Erlangs and in both COST 239 and USNET topologies.

When the parameter α is equal to 1, the blocking probability is removed from the objective function (6) and thus the maximum value of blocking probability and the minimum value of power consumption is yielded. In this case, all arrival requests are blocked and accordingly the power consumption reaches 0% and the blocking probability would be 100%[4].

When parameter α is equal to zero, the power consumption parameter is removed from the objective function (6). Therefore, in this case, the maximum value of power consumption and the minimum value of blocking probability are obtained. However, blocking probability may not equal to zero in this case; for example as depicted in Fig. 6(a) and 6(b), when the parameter α is equal to zero, about 10% and 30% of arrival requests are blocked for COST 239 and USNET, respectively. This is due to overload condition of the network, wherein the amount of existing network resources are not sufficient to accept all requests; therefore, in the best case about 90% and 70% of arrival requests are accepted for COST 239 and USNET, respectively.

When the value of α varies from 0 to 1, as equation 6 indicates, the weight of the power consumption term in the objective function is increased; and consequently, the weight of blocking probability is decreased. Therefore, as Fig. 6 and Fig. 7 show, the power consumption decreases and blocking probability increases by increasing α.

In addition to the Pareto frontier diagram, performance of other heuristic routing algorithms in terms of the trade-off between power consumption and blocking probability is available in Fig. 6 and Fig. 7. As expected, the Pareto frontier is a lower bound for the performance of heuristic routing algorithms, since it is the optimal solution achieved in off-line condition (static traffic) by exploiting the available information of all requests, while the heuristic algorithms are performed in online condition (dynamic traffic) without any information about future requests.

The distance between the heuristic solutions (which are points) and the optimal solution is perceptible from the figures. Small distance implies more efficiency to make trade-off between power consumption and blocking probability. As seen in the figures, the distance of the proposed algorithms is smaller than other algorithm that shows that they can make the trade-off more efficiently in comparison to other heuristic algorithms.

7. Conclusions and future work

In this paper, we addressed the trade-off between power consumption and blocking probability in a WDM network with DPP method. A multi-objective ILP model was developed for the problem which is used to find a lower bound on the trade-off between these parameters. In addition to the optimization model, we proposed a heuristic link weighting algorithm, abbreviated as

[4] Whereas the100% blocking probability is not acceptable in practice, we change the parameter α from 0 to 1 to create the complete Pareto frontier.

CEB-DPP-RR; its fundamental ability is to control the trade-off between the aforesaid parameters. Moreover, CEB-DPP-RR *explicitly* considers available network resources (i.e., the number of free wavelength channels at each link) in routing. The results, depicted by a Pareto optimal frontier, indicate that there is a little difference between the optimal solution and those of our heuristic algorithms.

In future, this work can be extended in different directions. We aim to address the trade-off between the power consumption and other QoS-related parameters such as path length and link utilization. In this paper, the DPP mechanism is considered, analyzing the trade-off in the case of SPP method for fault tolerance is an interesting open problem. Finally, to obtain a tighter lower bound on the trade-off, the time-based exact online model (Section 4.1) should be developed and solved which need considerable effort.

References

[1] Addis B, Capone A, Carello G, Gianoli LG, Sanso B. Energy aware management of resilient networks with shared protection. In: Sustainable Internet and ICT for Sustainability (SustainIT); 2012. p. 1–9.

[2] Addis B, Capone A, Carello G, Gianoli LG, Sanso B. Energy management through optimized routing and device powering for greener communication networks. IEEE/ACM Transactions on Networking (TON) 2014a;22(1):313–325.

[3] Addis B, Capone A, Carello G, Gianoli LG, Sanso B. On the energy cost of robustness and resiliency in IP networks. Computer Networks 2014b;75:239–259.

[4] Amaldi E, Capone A, Gianoli LG. Energy-aware IP traffic engineering with shortest path routing. Computer Networks 2013;57(6):1503–1517.

[5] Bandyopadhyay S. Dissemination of Information in Optical networks. Berlin: Springer; 2008.

[6] Bao NH, Li LM, Yu HF, Zhang ZZ, Luo HB. Power-aware provisioning strategy with shared path protection in optical WDM networks. Optical Fiber Technology 2012;18(2):81–87.

[7] Batchelor P, Daino B, Heinzmann P, Hjelme DR, Inkret R, Ja ¨ ger HA et al. Study on the implementation of optical transparent transport networks in the European environment-Results of the research project COST 239. Photonic Network Communications 2000;2(1):15–32.

[8] Bianzino AP, Chaudet C, Rossi D, Rougier J. A survey of green networking research. Communications Surveys & Tutorials, IEEE 2012a;14(1):3–20.

[9] Bianzino AP, Chiaraviglio L, Mellia M, Rougier J. Grida: Green distributed algorithm for energy-efficient ip backbone networks. Computer Networks 2012b;56(14):3219–3232.

[10] Capone A, Fratta L, Martignon F. Dynamic online QoS routing schemes: Performance and bounds. Computer Networks 2006;50(7):966–981.

[11] Cavdar C, Buzluca F, Wosinska L, Energy-efficient design of survivable WDM networks with shared backup. In: Global Telecommunications Conference (GLOBECOM 2010), IEEE; 2010. p. 1–5.

[12] Chabarek J, Sommers J, Barford P, Estan C, Tsiang D, Wright S. Power awareness in network design and routing. In: INFOCOM 2008, The 27th Conference on Computer Communications, IEEE; 2008. p. 457–465.

[13] Chiaraviglio L, Mellia M, Neri F. Minimizing isp network energy cost: Formulation and solutions. IEEE/ACM Transactions on Networking (TON) 2012;20(2):463–476.

[14] Cianfrani A, Eramo V, Listanti M, Polverini M, Vasilakos AV. An OSPF-integrated routing strategy for QoS-aware energy saving in IP backbone networks. Network and Service Management, IEEE Transactions on 2012;9(3):254–267.

[15] Coiro A, Listanti M, Valenti A, Matera F. Power-aware routing and wavelength assignment in multi-fiber optical networks. Optical Communications and Networking, IEEE/OSA Journal of 2011a;3(11):816–829.

[16] Coiro A, Listanti M, Valenti A. Dynamic power-aware routing and wavelength assignment for green WDM optical networks. In: Communications (ICC), IEEE International Conference on; 2011b. p. 1-6.

[17] Dharmaweera MN, Parthiban R, Sekercioglu YA. Toward a Power-Efficient Backbone Network: The State of Research. IEEE Communications Surveys Tutorials 2014;17(1):198-227.

[18] Ghamlouche I, Crainic TG, Gendreau M. Cycle-based neighbourhoods for fixed-charge capacitated multicommodity network design. Operations research 2003;51(4):655–667.

[19] Global Action Plan. An inefficient truth. Global Action Plan Report, http://globalactionplan. org. uk; 2007.

[20] Gupta M, Singh S. Greening of the Internet. In: Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications; 2003. p. 19–26.

[21] He R, Lin B. Dynamic Power-aware Shared Path Protection Algorithms in WDM Mesh Networks. Journal of Communications 2013;8(1):55-65.

[22] Hou W, Guo L, Gong X. Survivable power efficiency oriented integrated grooming in green networks. Journal of Network and Computer Applications 2013;36(1):420–428.

[23] Jirattigalachote A, Cavdar C, Monti P, Wosinska L, Tzanakaki A. Dynamic provisioning strategies for energy efficient WDM networks with dedicated path protection. Optical Switching and Networking 2011;8(3):201–213.

[24] Krumke SO. Online optimization: Competitive analysis and beyond. ZIB, 2006.

[25] Lange C. Energy-related aspects in backbone networks. In: Proceedings of 35th European Conference on Optical Communication (ECOC 2009),(Wien, AU); 2009.

[26] Lin G, Soh S, Chin KW, Lazarescu M. Energy Aware Two Disjoint Paths Routing. Journal of Network and Computer Applications 2014;43:27–41.

[27] Martins EQ, Pascoal MM. A new implementation of Yen’s ranking loopless paths algorithm. Quarterly Journal of the Belgian, French and Italian Operations Research Societies 2003;1(2):121–133.

[28] Miettinen K, Mäkelä MM. On scalarizing functions in multiobjective optimization. OR spectrum 2002;24(2):193–213.

[29] Monti P, Muhammad A, Cerutti I, Cavdar C, Wosinska L, Castoldi P et al. Energy-efficient lightpath provisioning in a static WDM network with dedicated path protection. In: 13th International Conference on Transparent Optical Networks (ICTON); 2011. p. 1–5.

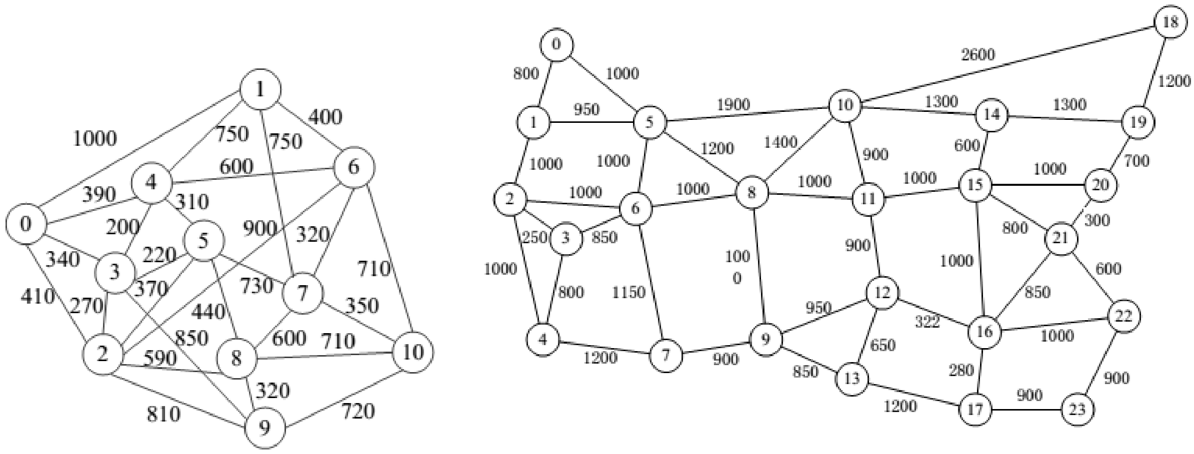
[30] Muhammad A, Monti P, Cerutti I, Wosinska L, Castoldi P, Tzanakaki A. Energy-efficient WDM network planning with dedicated protection resources in sleep mode. In: Global Telecommunications Conference (GLOBECOM 2010); 2010. p. 1–5.

[31] PourEmami SI, Bakhshi B. CEB-DPP-RR-Simulator [Software]. Available from http://ceit.aut.ac.ir/~bakhshis/papers/CEB-DPP-RR-Simulator.zip, (last visited May 11, 2015).

[32] Sansò B, Mellah H. On reliability, performance and Internet power consumption. In: Design of Reliable Communication Networks 2009, 7th International Workshop on, IEEE; 2009. p. 259–264.

[33] Webb et al. SMART 2020: Enabling the low carbon economy in the information age. The Climate Group. London 2008;1(1):1–1.

[34] Wiatr P, Monti P, Wosinska L. Power savings versus network performance in dynamically provisioned WDM networks. Communications Magazine, IEEE 2012;50(5):48–55.
[35] Xia M, Tornatore M, Zhang Y, Chowdhury P, Martel C, Mukherjee B. Green provisioning for optical WDM networks. Selected Topics in Quantum Electronics, IEEE Journal of 2011;17(2):437–445.
[36] Xia M, Tornatore M, Zhang Y, Chowdhury P, Martel C, Mukherjee B. Greening the optical backbone network: A traffic engineering approach. In: Communications (ICC), 2010 IEEE International Conference on; 2010. p. 1–5.
[37] Zhang S, Shen D, Chan CK. Energy-efficient traffic grooming in WDM networks with scheduled time traffic. Lightwave Technology, Journal of 2011;29(17):2577–2584.
[38] Zhang X, Wang H, Zhang Z. Survivable green IP over WDM networks against double-link failures. Computer Networks 2014;59:62–76.
[39] ZIB, Zib Optimization Suite [Software]. Available from http://scip.zib.de, (last visited November 23, 2014).



(a) COST 239

(b) USNET

Fig. 3. (a) COST 239 network topology, (b) USNET network topology.

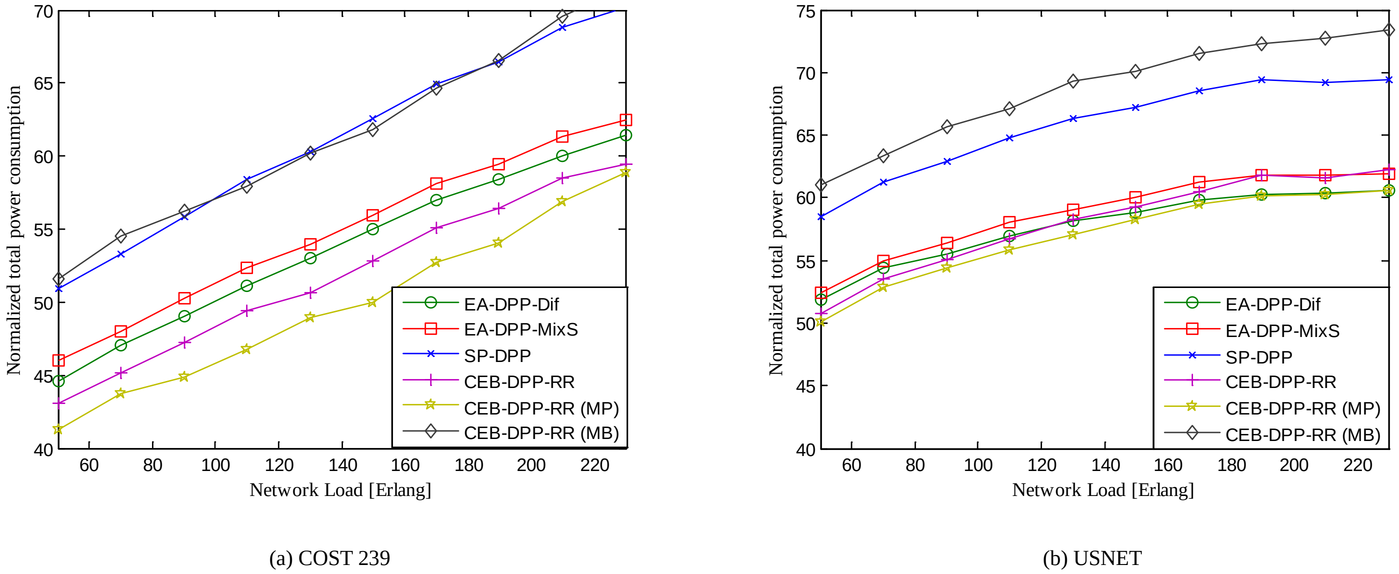
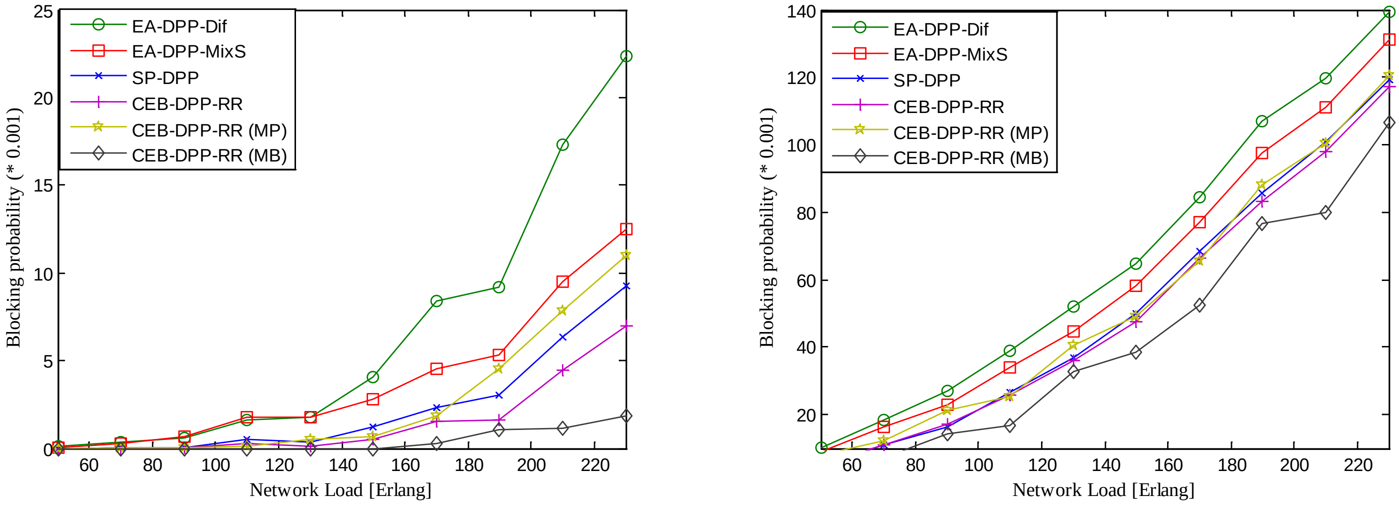


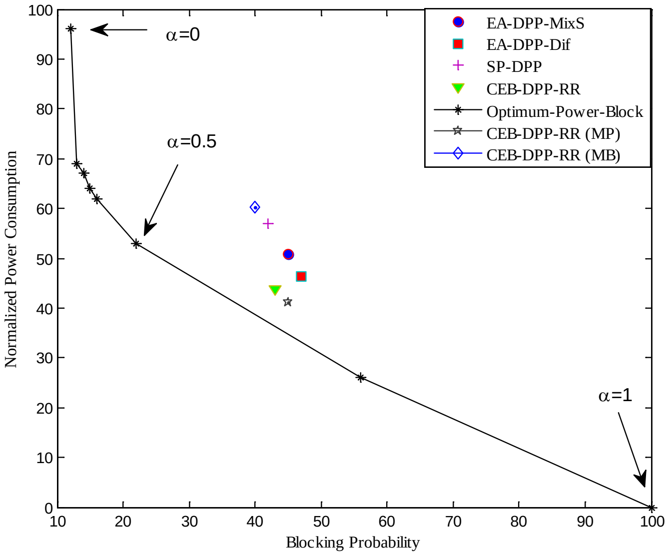
Fig. 4. Normalize power consumption of the network in various offered load,
(a) COST 239, (b) USNET



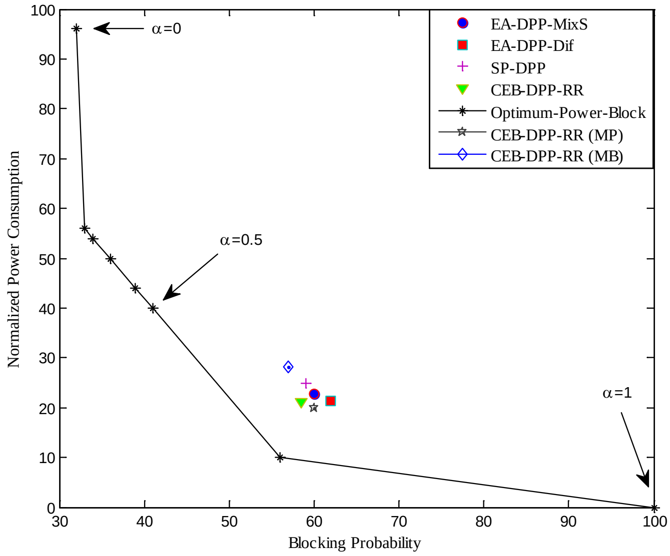
(a) COST 239

(b) USNET

Fig. 5. Blocking probability of the network in various offered load,
(a) COST 239, (b) USNET

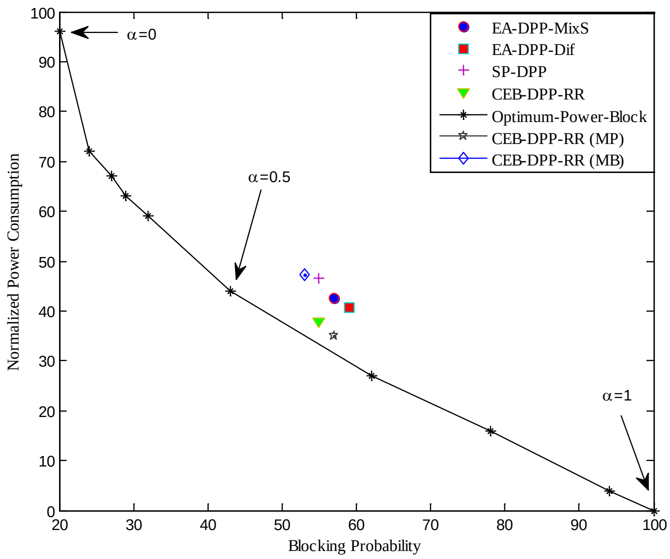


(a) COST 239

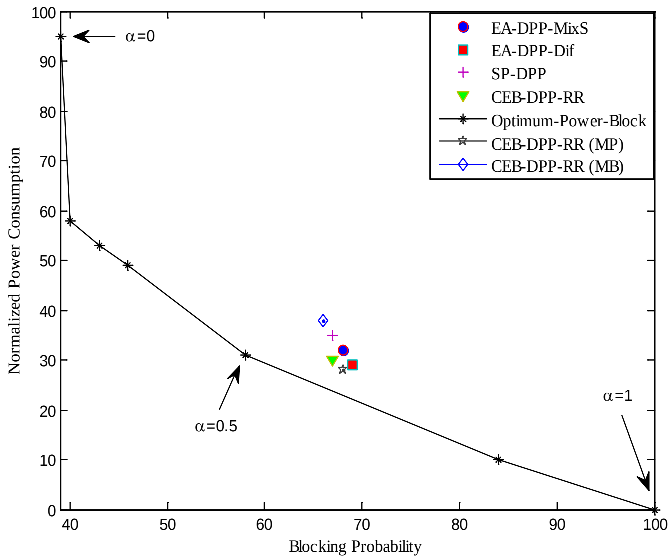


(b) USNET

Fig. 6. Pareto-optimal frontier of power consumption and blocking probability and comparison with heuristic algorithms in 75 Erlangs, (a) COST 239, (b) USNET



(a) COST 239



(b) USNET

Fig. 7. Pareto-optimal frontier of power consumption and blocking probability and comparison with heuristic algorithms in 100 Erlangs, (a) COST 239, (b) USNET