Resource-efficient path-protection schemes and online selection of routes in reliable WDM networks

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The optimal choice of routing and wavelength assignment (RWA) for the working and protection path–pair of the newly generated demand request is often a complex problem in reliable wavelength-division-multiplexed (WDM) networks subject to dynamic traffic. The challenge is twofold: how to provide the required reliability level without over-reserving network resources and how to find a good solution of the RWA problem under constrained computational time. Two important contributions are made. First, the shared path Protection (SPP) switching scheme is generalized to guarantee the required (differentiated) level of reliability to all arriving demands, while, at the same time, ensuring that they contain the required amount of reserved network resources. This generalization is referred to as SPP-DiR. Second, an approach for choosing the working and protection path–pair routing for the arriving demand is proposed. The approach is based on a matrix of preselected path–pairs: the disjoint path–pair matrix (DPM). Results show that, when the SPP-DiR scheme is applied, a small reduction in demand reliability corresponds to a significant reduction of the required network resources, when compared with the conventional SPP. In turn, the demand blocking probability may be reduced more than one order of magnitude. It is also shown that the DPM approach is suitable for obtaining satisfactory RWA solutions in both SPP-DiR and conventional SPP networks. The use of the DPM is most suited when the time for solving the RWA problem is constrained, e.g., when demand requests must be served swiftly.

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1. Introduction

Wavelength-division-multiplexed (WDM) networks are evolving to respond quickly and economically to dynamic traffic demands. A WDM network consists of a number of optical switches interconnected by fiber-optic links to form, in general, an arbitrary topology. The basic services provided by WDM networks are high speed, all-optical end-to-end channels, also referred to as *lightpaths* [1]. Lightpaths are dynamically created between node pairs to both provide the desired network connectivity and accommodate arriving traffic demands.

The unexpected failure of a network element may have severe consequences because of the large amount of traffic carried by the WDM channels. WDM networks can be made more *reliable* by means of protection switching schemes that are implemented at the WDM layer [2]. A protection scheme requires the allocation of spare (or standby) resources, that can be used in the event of a fault occurrence. For a lightpath the protection scheme consists of assigning a *working* and a *protection* path between the source and the destination. The working path carries the offered traffic during normal network operations. When the working path is disrupted by a fault, the interrupted traffic is rerouted over the protection path until the fault is repaired.

Each working (and protection) path that needs to be created in the WDM network is assigned both a route and a wavelength—this is the so-called routing and wavelength-assignment (RWA) problem. When traffic demands dynamically enter and depart from the network, the problem is referred to as the *online* RWA problem. One of the online RWA problem objectives is to reserve the minimum number of network resources (wavelengths) for each arriving traffic demand. It is expected that by minimizing the amount of reserved resources per arriving demand, the blocking probability is reduced—where a demand is *blocked* when it cannot be created because the lack of available wavelengths in the network. In general, finding the optimum solution for the RWA problem is a challenging combinatorial problem, whose complexity—i.e., the size of the solution space—grows with both the network size and the number of demands.

In this paper, two open problems are addressed: how to contain the amount of network resources reserved for the arriving demand and how to solve the online RWA problem swiftly.

In simple terms, the first problem is how to guarantee the desired level of reliability for arriving traffic demands (lightpaths) while avoiding unnecessary over-reservation of network resources. Conventional protection schemes [3] are capable of providing full protection in the presence of a single network fault. These solutions are simple and provide valid approaches in many network situations [4–6]. However, when over-reservation of network resources is not acceptable, some of these solutions may not be adequate. For example, in the dedicated path-protection (DPP) scheme the wavelengths reserved for the protection path of a demand are dedicated to that demand only [7]. The shared path-protection (SPP) scheme may then be used to reduce the amount of resources required by allowing multiple working paths to share some wavelengths that are reserved for protection. For static networks, it is possible to show that under certain circumstances, the same minimum degree of reliability can be guaranteed to the demands by both DPP and SPP, with SPP requiring a significantly smaller amount of network resources [8]. The SPP resource saving is achieved at a cost of increased complexity of the protection scheme. Further reduction of the required resources can be achieved in some instances by use of the concept of *differentiated reliability* (DiR). The DiR concept—when applied to networks with static traffic (offline RWA problem)—yields a significant reduction of the total network resources that are required for accommodating a given set of demands [9, 10].

In this paper the SPP scheme, combined with the DiR concept, is applied to WDM networks with dynamic traffic. The resulting scheme is referred to as SPP-DiR. In the simplest DiR formulation, each arriving demand is assigned a degree of reliability, defined as the probability that the established demand is still available after the occurrence of a *single fault* in the network. The degree of reliability is chosen to match each traffic-demand requirement and must be met by the protection scheme independently of the actual network topology, design constraint, device technology, and demand span. This assumption makes it possible to reserve the minimum amount of network resources that are required for achieving the level of reliability requested by the arriving demand. The origin of this DiR advantage—which conventional protection schemes, e.g., SPP, do not offer—can be clarified as follows. The former scheme's (DiR's) focus is on the reliability degree offered to each individual demand. Conversely, the focus of the latter schemes is on the network reliability offered against any single network fault. Consequently, with the latter schemes the actual reliability degree offered to a demand may vary significantly as a function of the path span and mean time between failure (MTBF) of the network elements. Besides creating unfair handling of demands, the latter schemes may also over-reserve spare resources in the network, which in turn produces an unnecessarily high degree of reliability with some demands.

The second problem addressed in the paper is how to provide—in reliable WDM networks—a satisfactory (suboptimal) solution to the online RWA problem for operation under constrained computational time. One approach that is widely used to select the (working) route for each demand is based on a variation of the multicommodity flow problem [11]. Some examples can be found in Refs. [12–14]. This approach is based on the intuitive reasoning that the careful pruning of the set of possible candidate paths [15] leads to a (suboptimal) solution of the multicommodity flow problem that may be satisfactory from the standpoint of both complexity and performance. A well-known pruning technique consists of choosing only the k-shortest paths found in the graph that represents the network topology [16]. It can be shown that for unprotected networks a relatively small value of k may already produce results that are close to the optimum. In contrast, when we deal with reliable networks, the use of the k-shortest paths may require a much larger value of k. The reason for this is twofold. First, at least one route disjoint path–pair must be found for each source–destination pair. (This is a necessary condition for yielding a feasible RWA solution in single-fault reliable networks.) Second, a sufficiently large number of distinct path–pair candidates must be available between each source-destination pair. This latter condition is needed to allow some degree of flexibility in choosing the best path–pair for the arriving demand. (As shown in Section 4 the approach based on the single shortest disjoint path–pair [11, 17] may not yield satisfactory performance.) When k is large, however, the set of candidate paths remaining after pruning may be too large to provide fast and satisfactory solutions to the RWA problem.

For this second problem, we propose an alternative pruning technique to the k-shortest paths based on the disjoint path–pair matrix (DPM). The objective of the proposed pruning technique is to control and limit (1) the number of route disjoint candidate path–pairs, (2) the number of hops of the working paths, (3) the number of hops of the protection paths, and (4) the hop difference between the working and the protection paths. These objectives can be accomplished by the DPM while maintaining a solution performance that is comparable with the—less controllable—solution obtained by the k-shortest path pruning technique. In addition, the DPM technique requires a smaller search space than the one obtained by the k-shortest path. This fact may yield an advantage to DPM when the computational time available to find a solution is constrained.

The DPM is applied to solve the RWA problem for both the conventional SPP and SPP-DiR schemes based on a centralized network status database. Numerical results are shown using a pan-European topology as a benchmark. When compared with the conventional SPP, the SPP-DiR scheme requires less network resources and yields improved blocking probability, already with a small and controlled reduction of the degree of demand reliability. It is also shown that when compared with a path pruning technique based on the k-shortest path algorithm, the DPM technique yields slightly better solutions when the computational time allowed to solve the RWA problem is constrained to a few milliseconds.

2. SPP-DiR Model for WDM Networks with Dynamic Traffic

This section describes the assumptions made and defines the SPP-DiR scheme and the related RWA problem.

It is assumed that the WDM network has an arbitrary physical topology (mesh), wavelength conversion is not available in the network, only link failures are possible, and any link failure disrupts demands in both directions of propagation. The widely used single link failure assumption [2, 18] is adopted; i.e., the probability that two or more links are down concurrently is considered to be negligible. Rerouting of working lightpaths that are not affected by the fault is not allowed.

The WDM mesh is modeled as a graph $G(\mathscr{N},\mathscr{L})$, where $\mathscr{N}$ represents the set of network nodes and $\mathscr{L}$ the set of network links. It is assumed that, for each direction of propagation, every network link consists of a set of fibers, F. Each fiber carries a set of wavelengths, W. Each link $(m,n) \in \mathscr{L}$ is characterized by three parameters: $|F|$, the number of available fibers; $|W|$, the number of available wavelengths in each fiber; and $P_f(m,n)$, the value of the conditional link failure probability. From the single failure assumption, the conditional link failure probability is the conditional failure probability given that a single link failure has occurred in the network. By assuming the single link failure situation, the link failure probability is given by the product of the conditional link failure probability and the probability of having a single failure. For example, assuming a uniform distribution of faults among all the links, the conditional link failure probability is

$$P_f(m,n) = \frac{1}{|\mathscr{L}|} \quad \forall (m,n) \in \mathscr{L}. \tag{1}$$

It is assumed that the demand arrivals cannot be predicted. Thus, they are modeled as a random process. Demands must be served in the same order as they are generated. Each demand requires one working lightpath to be created between two nodes. Each lightpath is created by use of one single wavelength. Each arriving demand is characterized by a maximum conditional failure probability ($MCFP$). The $MCFP$ represents the maximum acceptable probability that, given the occurrence of a network link failure, the demand data flow will be permanently disrupted.

With the conventional SPP scheme, each working path is assigned a route-disjoint protection path ready to be used if the working path is affected by a link failure. Working and protection paths of the same demand need not have the same wavelength assigned. Only distinct protection paths whose corresponding working paths are route-disjoint can share the same link and wavelength. Each demand is thus 100% survivable against any single fault, i.e., the SPP supports $MCFP = 0$ only.

To offer a wider range of $MCFP$ values, the SPP-DiR scheme is derived from the SPP scheme as follows. For a demand with a less stringent $MCFP > 0$, the protection path does not need to be always available for every possible link failure situation. Thus, it is possible to select a set of links $H_u^{(d)}$ of the working path for which arriving demand d will not need to resort to the protection path. Set $H_u^{(d)}$ must be selected to satisfy the demand required reliability degree, formally expressed by the demand's $MCFP$. Note that, with SPP-DiR, two (or more) demands whose working paths have a common link may also share a link and a wavelength for their respective protection paths. This option is available when at least one of the two demands can afford to be permanently disrupted upon the failure of the link that is shared by the working paths. By the same reasoning, it is also possible to have a working path completely unprotected if the working path failure probability still satisfies the reliability requirement indicated by the demand's $MCFP$.

The SPP-DiR scheme has the potential to yield a more efficient resource utilization when compared with the conventional SPP scheme, while still guaranteeing each demand sufficient resources to satisfy its reliability requirement. The example shown in Fig. 1 illustrates this possibility. All links in the network are bidirectional and can accommodate two wavelengths for each direction of propagation. Assuming uniform link failure distribution, the link conditional failure probability is $P_f(m,n) = \frac{1}{7}\ \forall (m,n) \in \mathscr{L}$. Three demands are shown. Demand d_1 arrives first and requires $MCFP^{(d_1)} = 0$. The chosen working path is *C–B*. The protection path is *C–E–B*. Demand d_2 arrives second and requires $MCFP^{(d_2)} = 0$. The chosen working path is *D–E–A*. The protection path is therefore *D–C–B–A*. Demand

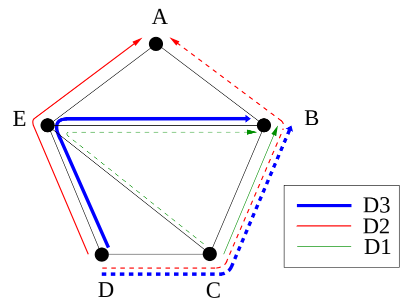


Fig. 1. SPP-DiR example.

d_3 arrives last and requires $MCFP^{(d_3)} = \frac{1}{7}$. This reliability requirement permits demand d_3 to be protected against any single fault but one. Taking advantage of this possibility, it is possible to route the working path along D–E–B and have link $D-E$ unprotected. The protection path for d_3 is D–C–B and is used only in the case of a failure on link (E,B). As shown in the example, protection resources along link (C,B) can be shared between demands d_2 and d_3 even though their working paths are not route disjoint. Note that by requiring a higher reliability degree, i.e., $MCFP^{(d_3)} < \frac{1}{7}$, demand d_3 is then blocked because of a lack of available wavelengths in the network.

Online RWA Problem for SPP-DiR

The online RWA problem for the SPP-DiR scheme consists of choosing both the working and protection path–pair and the wavelength(s) to be assigned to each arriving demand. The choice must be made so that both the amount of available resources that is reserved to accommodate the arriving demand is minimized and the $MCFP$ required by the demand is satisfied. It is expected that such optimization has a favorable effect on the overall network blocking probability. The SPP-DiR RWA problem is formally defined next. The formulation is provided assuming $|F| = 1$ for all links. Its extensions to the case of multiple fibers per link is straightforward.

Let $\lambda_w^{(d)}, \lambda_p^{(d)} \in W$ be the wavelengths that are chosen for the working and protection paths of demand d, respectively; i.e., the *working* and *protection wavelength* $\lambda_w^{(d)}$ and $\lambda_p^{(d)}$ need not be the same. Let $H_w^{(d)}$ be the set of links that are in the working path assigned to demand d, i.e., the set of *working links* for d. Let $H_p^{(d)}$ be the set of links that are in the protection path assigned to demand d, i.e., the set of *protection links* for d. Let $H_u^{(d)} \subseteq H_w^{(d)}$ be the set of working links of d that are unprotected, i.e., upon the failure of a link in $H_u^{(d)}$ demand d is permanently disrupted, Let $MCFP^{(d)}$ be the minimum reliability degree requested by d.

Let D be the set of demands that are already established in the network. Initially, $D = \emptyset$. Let $\hat{d}$ be the arriving demand. Demand $\hat{d}$ is accepted (and added to set D) if all the following conditions can be satisfied:

$$H_w^{(\hat{d})} \cap H_p^{(\hat{d})} = \emptyset, \tag{2}$$

i.e., working and protection paths must be route-disjoint,

$$\forall d \in D,\ d \neq \hat{d},\ H_w^{(\hat{d})} \cap H_w^{(d)} \neq \emptyset\ \Rightarrow\ \lambda_w^{(d)} \neq \lambda_w^{(\hat{d})}, \tag{3}$$

i.e., in any link a working wavelength can be assigned to only one (demand) working path,

$$\forall d \in D,\ d \neq \hat{d},\ (H_w^{(d)} \setminus H_u^{(d)}) \cap (H_w^{(\hat{d})} \setminus H_u^{(\hat{d})}) \neq \emptyset\ \Rightarrow\ H_p^{(\hat{d})} \cap H_p^{(d)} = \emptyset \vee \lambda_w^{(p)} \neq \lambda_p^{(\hat{d})}, \tag{4}$$

i.e., a protection wavelength cannot be shared by multiple demands if they share the same (protected) working link,

$$P_f^{(\hat{d})} = \sum_{(i,j)\in H_u^{(\hat{d})}} P_f(i,j) \le MCFP^{(\hat{d})}, \tag{5}$$

i.e., the conditional failure probability guaranteed to demand that $\hat{d}$ does not exceed the $MCFP$ required by $\hat{d}$. If any one of the above four conditions cannot be satisfied, demand $\hat{d}$ is blocked (and not added to set D).

Note that the protection paths of demands $\hat{d}$ and $d \in D$ are allowed to share wavelength on a common link, i.e.,

$$\lambda_p^{(\hat{d})} = \lambda_p^{(d)} \ \wedge \ (H_p^{(\hat{d})} \cap H_p^{(d)}) \neq \emptyset, \tag{6}$$

only if condition

$$(H_w^{(\hat{d})} \cap H_w^{(d)}) \subseteq (H_u^{(\hat{d})} \cup H_u^{(d)}) \tag{7}$$

is satisfied. Let $H_s^{(\hat{d})} \subseteq H_p^{(\hat{d})}$ be the set of protection links of demand $\hat{d}$ in which the spare wavelength is shared by at least one other protection path already reserved in the network, i.e.,

$$H_s^{(\hat{d})} = \{(m,n) \ : \ \exists d \in D \ : \ (m,n) \in (H_p^{(\hat{d})} \cap H_p^{(d)}) \wedge (\lambda_p^{(\hat{d})} = \lambda_p^{(d)})\}. \tag{8}$$

A cost function measuring the goodness of the RWA chosen for both the working and protection paths of demand $\hat{d}$ is

$$C^{(\hat{d})} = |H_w^{(\hat{d})}| + |H_p^{(\hat{d})}| - |H_s^{(\hat{d})}| + (MCFP^{(\hat{d})} - P_f^{(\hat{d})}). \tag{9}$$

The optimal solution of the RWA problem for demand $\hat{d}$ is the one that minimizes $C^{(\hat{d})}$, while satisfying Eqs. (2), (3), (4), and (5). The cost function $C^{(\hat{d})}$ quantifies both the amount of resources that must be reserved to accommodate demand $\hat{d}$ and the *excess of reliability* that is guaranteed to demand $\hat{d}$—defined as $(MCFP^{(\hat{d})} - P_f^{(\hat{d})}) \geq 0$. The reason for choosing such a cost function is twofold. First, each demand is guaranteed to have the working and protection path–pair that requires the least amount of newly reserved resources. Second, over-provisioning of wavelengths is avoided by matching the arriving demand's $MCFP$ as closely as possible.

Note that if $MCFP^{(\hat{d})} = 0$ for all arriving demands $\hat{d}$, then $H_u^{(d)} = \emptyset, \ \forall \ d \in D$. In this case $C^{(\hat{d})}$ becomes the cost function that must be minimized to find the optimum solution of the RWA problem for the conventional SPP.

3. Solving the Online RWA Problem for both the Working and Protection Paths

In this section a two-step approach is presented to find a good sub-optimal solution to the RWA problem defined in Section 2. In step *A*, the DPM (disjoint path–pair matrix) is built for each source–destination pair with only selected disjoint path–pairs, i.e., the path–pair candidates. In step *B*, the RWA problem of the SPP-DiR scheme is solved by running a simulated annealing (SA) [19] algorithm that searches for the best candidate in the DPM. More generally, any optimization algorithm can be used for the latter step to replace SA. The SA approach is chosen here as it was found to provide satisfactory results.

The two steps are described next.

3.A. Step A: Construction of the DPM

One DPM is built for each source–destination pair. The DPM is computed beforehand and is then used to route all the arriving connection requests. The candidates of the DPM are computed from the observation that the space of possible solutions contains only route disjoint path–pairs. Let k_1 be the desired number of candidate working paths. The candidate working paths are the first k_1 paths that are found by the k-shortest loopless paths algorithm [16] applied to graph $G(\mathscr{N},\mathscr{L})$. Let k_2 be the desired number of candidate protection paths for each candidate working path. The candidate protection paths for working path i are the first k_2 paths that are found by the k-shortest loopless paths algorithm applied to graph $G^{(i)}(\mathscr{N},\mathscr{L}^{(i)})$, where $\mathscr{L}^{(i)}$ is the set of links in $\mathscr{L}$ that are not in path i. A $k_1 \times k_2$ DPM of route disjoint path–pair candidates is now available for each source–destination (s,d) pair, i.e.,

$$DPM_{s,d}(i,j):\ i=0,1,\ldots,k_1-1,\ j=0,1,\ldots,k_2-1,\ \forall\, s,d\in\mathscr{N},\ s\neq d, \tag{10}$$

where i identifies the working path candidate and j identifies the associated protection path candidate. Because of the arbitrary topology of the WDM network, it is possible that specific node pairs may have fewer working path candidates than k_1, and/or fewer protection path candidates than k_2.

Let $\mathscr{W}_{s,d}$ ($|\mathscr{W}_{s,d}|=k_1$) and $\mathscr{P}_{s,d,i}$ ($|\mathscr{P}_{s,d,i}|=k_2$) be the set of k_1 candidate working path and k_2 candidate protection paths for each candidate working path $i\in\mathscr{W}_{s,d}$ between source node s and destination node d, respectively. Paths are sorted in each set on the basis of their length, i.e, from the shortest to the longest. A pseudocode that summarizes the algorithm used to construct the DPM for each source–destination pair (s,d) is shown in Table 1.

Table 1. Pseudocode of the Algorithm to Construct DPM

begin *Construction of the DPM*
 for($\forall$ node pairs $(s,d),\ s\neq d,\ s,d\in\mathscr{N}$){
  Compute $\mathscr{W}_{s,d}$ on $G(\mathscr{N},\mathscr{L})$
  for($i=0,1,\ldots,k_1-1,\ i\in\mathscr{W}_{s,d}$){
   $\mathscr{L}^{(i)}=\mathscr{L}-i$
   Compute $\mathscr{P}_{s,d,i}$ on $G^{(i)}(\mathscr{N},\mathscr{L}^{(i)})$
   for($j=0,1,\ldots,k_2-1,\ j\in\mathscr{P}_{s,d,i}$){
    $DPM_{s,d}(i,j)=(\mathscr{W}_{s,d}(i),\mathscr{P}_{s,d,i}(j))$
   }
  }
 }
end *Construction of the DPM*

The computational complexity of building the DPM is related to the computational complexity of the k-shortest path algorithm. In the worst case, the computational complexity of the k-shortest path algorithm in Ref. [16] is $O[K\cdot|\mathscr{N}|\cdot(|\mathscr{L}|+|\mathscr{N}|\cdot\log|\mathscr{N}|)]$, where K, $|\mathscr{L}|$, and $|\mathscr{N}|$ represent the number of computed loopless shortest paths between any given source–destination pair, the number of links, and the number of nodes in the network, respectively. Let $\bar{l}$ be the average number of links that belong to each k-shortest path found. The worst-case complexity of the DPM approach is: $O(|\mathscr{N}|^2\cdot\{k_1\cdot|\mathscr{N}|\cdot(|\mathscr{L}|+|\mathscr{N}|\cdot\log|\mathscr{N}|)+k_1\cdot(2\bar{l}+k_2\cdot|\mathscr{N}|\cdot[(|\mathscr{L}|-\bar{l})+|\mathscr{N}|\cdot\log|\mathscr{N}|]\})=O[|\mathscr{N}|^3(k_1\cdot k_2)(|\mathscr{L}|+|\mathscr{N}|\cdot\log|\mathscr{N}|)+|\mathscr{N}|^2\cdot k_1\cdot\bar{l}]$. By properly choosing the values of both k_1 and k_2, we can arbitrarily prune down the solutions that are available to the optimization process described next.

3.B. Step B: RWA Algorithm

The objective of the RWA algorithm described in this section is to search for the best path–pair candidate that can be found in matrix $DPM_{s,d}$, where s and d are the source and destination of the arriving demand, $\hat{d}$. The best path–pair is the one that minimizes the cost function in Eq. (9), while satisfying the four conditions in Eqs. (2), (3), (4), and (5). Those solutions that do not satisfy all conditions in Eqs. (2), (3), (4), and (5) are called unfeasible.

The RWA algorithm consists of two substeps. In the first substep (Step B.1), the algorithm determines the reliability degree of $\hat{d}$ with coarse granularity. Depending on the reliability degree requested by $\hat{d}$, i.e., $MCFP^{(\hat{d})}$, the chosen working path is either entirely protected, i.e., $H_u^{(\hat{d})} = \emptyset$, or entirely unprotected, i.e., $H_u^{(\hat{d})} = H_w^{(\hat{d})}$. In the second substep (Step B.2), the algorithm attempts to modify set $H_u^{(\hat{d})}$ to closely match $MCFP^{(\hat{d})}$.

3.B.1. Step B.1: First Fit Algorithm

Upon arrival of demand $\hat{d}$, both the working path and wavelength are chosen with the first fit (FF). The first working path $i = 0, 1, \ldots, k_1 - 1 \in DPM_{s,d}(i, *)$ that is found to be able to accommodate $\hat{d}$ is chosen. Let $i^{(\hat{d})}$ be such a path. Set $H_w^{(\hat{d})}$ contains all links in path $i^{(\hat{d})}$. The first wavelength $\lambda = 1, 2, \ldots, |W|$ that is found to be available along path $i^{(\hat{d})}$ is selected to be the working wavelength $\lambda_w^{(\hat{d})}$. (If a working path cannot be found in $DPM_{s,d}$, or no wavelength is found to be available along path $i^{(\hat{d})}$, $\hat{d}$ is blocked.) If path $i^{(\hat{d})}$ does not need to be protected—i.e., condition in Eq. (5) is satisfied given, $H_u^{(\hat{d})} = \emptyset$—Step B.1 terminates, and the algorithm continues to Step B.2.

Conversely, if $i^{(\hat{d})}$ path needs to be protected, set $H_u^{(\hat{d})}$ is set to $\emptyset$ and the algorithm chooses the first path $j = 0, 1, \ldots, k_2 - 1 \in DPM_{s,d}(i^{(\hat{d})}, j)$ that is found to be able to provide a protection path to $\hat{d}$. Let $j^{(\hat{d})}$ be such path. Set $H_p^{(\hat{d})}$ contains all the links in path $j^{(\hat{d})}$. All wavelengths $\lambda = 1, 2, \ldots, |W|$ are, in turn, considered as candidate protection wavelengths. The wavelength $\bar{\lambda}$ that is found able to maximize the value of $|H_s^{(\hat{d})}|$—i.e., the number of protection links of demand $\hat{d}$ in which $\bar{\lambda}$ is shared by at least one other protection path already routed—is set to be the protection wavelength. (Note that sharing of protection wavelengths with the demands already in D is permitted when condition (7) is satisfied given $H_u^{(\hat{d})} = \emptyset$.) If a protection path $j^{(\hat{d})}$ that satisfies the above condition cannot be found, the solution is set to be equal to path–pair $DPM_{s,d}(i^{(\hat{d})}, 0)$ and the protection wavelength λ_p is set to be equal to 0. In this case, the solution found is said to be unfeasible. Regardless of the feasibility of the found solution, the algorithm continues to Step B.2.

The (worst case) computational complexity of Step B.1 is $O(k_1 \cdot k_2 \cdot |W|^2 \cdot \bar{l}^2)$.

3.B.2. Step B.2: SA Algorithm

The objective of this step is to reduce the resources (wavelengths) that must be reserved to satisfy $MCFP^{(\hat{d})}$, if possible at all. For this purpose, a SA algorithm is designed to identify which links must be in the final sets $H_w^{(\hat{d})}$, $H_p^{(\hat{d})}$, and $H_u^{(\hat{d})}$. The cost function to be minimized by the SA algorithm is the one given in Eq. (9) for all feasible solutions. Unfeasible solutions are assigned an arbitrary high cost.

The path–pair found in Step B.1, i.e., $i^{(\hat{d})}$ and $j^{(\hat{d})}$, is used as the initial solution for running the SA algorithm. The initial sets $H_w^{(\hat{d})}$, $H_p^{(\hat{d})}$, and $H_u^{(\hat{d})}$, and the initial wavelengths $\lambda_w^{(\hat{d})}$ and $\lambda_p^{(\hat{d})}$ are those obtained in Step B.1. At each SA iteration, a neighboring solution is obtained by randomly choosing one of the following three moves.

1. Randomly select another working path $i'^{(\hat{d})} \neq i^{(\hat{d})}$ from those in the DPM. If the new path–pair $(i'^{(\hat{d})}, j^{(\hat{d})})$ satisfies all conditions in Eqs. (2), (3), (4), and (5), the solution is said to be feasible, and the first wavelength $\lambda = 1, 2, \ldots, |W|$ that is found to be available along path $i'^{(\hat{d})}$ is selected to be the working wavelength $\lambda_w^{(\hat{d})}$. Conversely, if the new path–pair does not satisfy all conditions in Eqs. (2), (3), (4), and (5), or no available working wavelength is found along path $i'^{(\hat{d})}$, the new path–pair solution is said to be unfeasible and another move is randomly selected.

   The (worst case) computational complexity of move 1 is $O(|W| \cdot \overline{l})$.

2. Randomly select a new protection path $j'^{(\hat{d})} \neq j^{(\hat{d})}$ from those in the DPM. All wavelengths $\lambda = 1, 2, \ldots, |W|$ are, in turn, considered as candidate protection wavelengths for the new path–pair $(i^{(\hat{d})}, j'^{(\hat{d})})$. The wavelength that is found able to maximize the value of $|H_s^{(\hat{d})}|$ is set to be the protection wavelength. If no available protection wavelength is found along path $j'^{(\hat{d})}$, the new path–pair solution is said to be unfeasible and another move is randomly selected.

   The computational complexity of move 2 is $O(|W| \cdot \overline{l})$.

3. Randomly select link $(m, n) \in H_w^{(\hat{d})}$ and

   - if $(m, n) \in H_u^{(\hat{d})}$, (m, n) is removed from $H_u^{(\hat{d})}$ and the working wavelength $\lambda_w^{(\hat{d})}$ is left unchanged;
   - if $(m, n) \notin H_u^{(\hat{d})}$, (i, j) is added to $H_u^{(\hat{d})}$ under the condition that the resulting $P_f^{(\hat{d})} \leq MCFP^{(\hat{d})}$. The working wavelength $\lambda_w^{(\hat{d})}$ is not changed. If the resulting $P_f^{(\hat{d})} > MCFP^{(\hat{d})}$, another move is randomly selected.

   The computational complexity of move 3 is $O(1)$.

Each of the three moves is equally likely to be chosen. Sets $H_w^{(\hat{d})}$, $H_p^{(\hat{d})}$, and $H_u^{(\hat{d})}$, and wavelengths $\lambda_w^{(\hat{d})}$ and $\lambda_p^{(\hat{d})}$ are updated at the end of each move accepted by the SA algorithm.

If a feasible solution is found by the SA algorithm, $\hat{d}$ is added to set D. Otherwise, $\hat{d}$ is blocked.

Let $iter_{\max}$ be the number of iterations performed by the SA algorithm each time Step $B.2$ is executed. Since each of the three moves is equally likely to be chosen, the computational complexity of Step $B.2$ in a worst case analysis is $\frac{\text{iter}_{\max}}{3} O(|W| \cdot \overline{l}) + \frac{\text{iter}_{\max}}{3} O(|W| \cdot \overline{l}) + \frac{\text{iter}_{\max}}{3} O(1) = O(|W| \cdot \overline{l})$. The overall (Step $B.1$ and Step $B.2$) computational complexity for the RWA algorithm is $O(k_1 \cdot k_2 \cdot |W|^2 \cdot \overline{l}^2) + O(|W| \cdot \overline{l}) = O(k_1 \cdot k_2 \cdot |W|^2 \cdot \overline{l}^2)$.

4. Performance Results

This section presents a collection of results that are obtained by means of the RWA algorithm and the DPM pruning technique that are presented in Section 3. Both SPP and SPP-DiR schemes are considered.

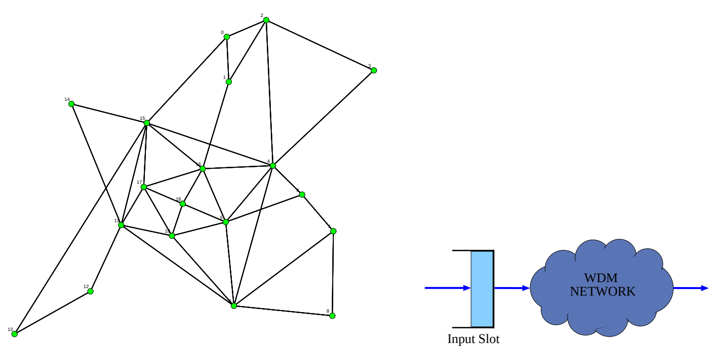
To provide a comparison benchmark for the DPM technique, results that are obtained with the path pruning technique based on the k-shortest loopless paths are also shown. This benchmark pruning technique is referred to as linear based (LB). For LB, candidate path–pairs are computed as follows. For any possible node pair, only the first k-shortest loopless paths are considered. All the possible route-disjoint path–pairs that can be generated from the considered k candidate paths are then used to create the LB matrix. The LB matrix is then used by the RWA algorithm described in Section 3.B. The computational complexity of the LB solution in a worst case analysis is $O(|\mathscr{N}|^3 \cdot K \cdot (|\mathscr{L}| + |\mathscr{N}| \cdot \log|\mathscr{N}|) + |\mathscr{N}|^2 \cdot K \cdot \overline{l^2})$.

Solutions are found for the topology of the European optical network, that is shown in Fig. 3(a). This network comprises $|\mathscr{N}| = 19$ nodes and $|\mathscr{L}| = 39$ bidirectional links. It is assumed that each link accommodates $|F| = 1$ fiber for each direction of propagation. Each fiber carries $|W| = 32$ wavelengths. The conditional link failure probability is obtained assuming a uniform distribution of failures over all links in $\mathscr{L}$. Hence, $P_f(i,j) = \frac{1}{39}\ \forall (i,j) \in \mathscr{L}$.

The demand arrivals form a Poisson process with rate λ. Source and destination nodes of each demand are randomly chosen using a uniform distribution over all possible node pairs. Unless otherwise specified, each demand is assigned a reliability degree requirement of $MCFP = 0.03$. With this value and in the network topology under consideration, each demand may be able to have up to one working link that is unprotected. Once established, a demand remains in the system for a time that is exponentially distributed with parameter $\frac{1}{\mu} = 1$. It is assumed that the signaling latency in the network is negligible, and the correct network status information is available at all nodes.

To provide results that are not dependent upon any specific call admission control, all arriving demands are first stored in a virtual centralized buffer, as shown in Fig. 3(b). At most one demand can be stored in the buffer at once. A demand that upon arrival cannot be established in the network because of lack of available resources is stored in the buffer until it can be established. Demands that arrive while the buffer is busy are blocked and dropped. Let P_b be the probability of blocking and dropping a demand.

For all results, the simulation time is set to achieve a confidence interval value of 5% or better, at 98% confidence level.



(a) (b)

Fig. 2. (a) European topology and (b) the virtual single-slot input buffer.

4.A. Comparison Between Pruning Techniques

Table 2 shows some statistics that are collected on the route-disjoint pair–paths obtained by both the DPM and LB pruning techniques. From left to right the table reports the pruning technique used, the value of k_1 and k_2 used for building the DPM, N_W defined as the average number of candidate working paths per source–destination pair, N_P defined as the average number of candidate protection paths associated with each working path, N_{pp} defined as

Table 2. Statistics on Candidate Paths

Scheme	k_1	k_2	N_W	N_P	N_{pp}	H_{c_w}	H_{c_p}
LB	$k = 20$		20	6.512	130.24	4.157	3.778
LB	$k = 60$		60	15.868	952.1	5.008	4.646
LB	$k = 100$		100	22.594	2259.4	5.536	5.063
DPM	30	10	30	9.282	278.5	4.507	4.435
DPM	30	5	30	4.685	140.5	4.507	3.803
DPM	20	10	20	9.289	185.8	4.157	4.438
DPM	20	5	20	4.688	93.8	4.157	3.819
DPM	10	10	10	9.338	93.4	3.604	4.459
DPM	10	5	10	4.709	47.1	3.604	3.875

the average number of candidate route disjoint path–pairs per source–destination pair, H_{c_w} defined as the average hop length of the candidate working paths, and H_{c_p} defined as the average hop length of the candidate protection paths.

The values reported in Table 2 support the earlier claim that by using the DPM pruning technique the size of the solution space may be reduced when compared with the LB solution space. In some instances, e.g., when comparing LB with $k = 60$ and DPM with $k_1 = 20$ and $k_2 = 5$, the DPM approach is able to reduce the solution space by one order of magnitude. Table 2 also shows that with the DPM pruning it is possible to better control the hop length of both the working and protection paths.

Table 3. LB Solutions Found by the SA Algorithm

$Rep = 100,\ \lambda = 300,\ MCFP^{(\hat{d})} = 0.03$										
k	T_0	T_f	a	P_b	$\lvert H_w\rvert$	$\lvert H_p\rvert$	$\lvert H_s\rvert$	RCT	RCT_{FF}	RCT_{SA}
20	6	1	0.9	4.38E-3	2.315	4.019	3.801	7.41E-3	2.09E-4	7.19E-3
60	6	1	0.9	1.94E-3	2.370	4.597	4.359	1.12E-2	5.69E-4	1.06E-2
100	6	1	0.9	3.13E-3	2.412	4.801	4.501	1.18E-2	8.92E-4	1.09E-2
$k = 60,\ \lambda = 300,\ MCFP^{(\hat{d})} = 0.03$										
Rep	T_0	T_f	a	P_b	$\lvert H_w\rvert$	$\lvert H_p\rvert$	$\lvert H_s\rvert$	RCT	RCT_{FF}	RCT_{SA}
100	3	1	0.9	4.03E-3	2.407	4.539	4.237	6.56E-3	5.81E-4	5.97E-3
25	6	1	0.9	5.73E-3	2.446	4.387	3.944	2.90E-3	4.73E-4	2.42E-3
50	6	1	0.9	3.41E-3	2.412	4.513	4.192	5.34E-3	5.02E-4	4.82E-3
100	6	1	0.9	1.94E-3	2.370	4.597	4.359	1.12E-2	5.69E-4	1.06E-2
1000	6	1	0.9	9.89E-4	2.290	4.634	4.510	9.56E-2	5.84E-4	9.50E-2
100	25	1	0.9	1.50E-3	2.341	4.633	4.438	1.75E-2	5.40E-4	1.69E-2
100	100	1	0.9	1.18E-3	2.327	4.640	4.467	2.52E-2	6.13E-4	2.46E-2
100	300	1	0.9	1.03E-3	2.318	4.641	4.475	3.18E-2	5.65E-4	3.12E-2
500	50	1	0.9	1.10E-3	2.289	4.629	4.508	9.60E-2	5.47E-4	9.54E-2
100	6	1	0.99	1.15E-3	2.292	4.634	4.508	1.07E-1	6.27E-4	1.06E-1
100	25	1	0.99	7.46E-4	2.282	4.620	4.507	1.98E-1	6.54E-4	1.98E-1
100	6	1	0.999	7.42E-4	2.259	4.605	4.508	9.75E-1	5.18E-4	9.75E-1

The top part of Table 3 shows results that are collected for the LB technique, with $k = 20, 60,$ and 100. The best blocking probability is obtained when $k = 60$. This value is chosen to obtain all the subsequent results. Statistics collected from various solutions found by the SA algorithm are reported in the bottom part of Table 3 (LB) and in Table 4 (DPM). Simulations are run using Linux boxes with Athlon_XP 2200 processors. The compiler used is g++, version 3.2.2. Simulation time is measured in seconds. Statistics refer to arriving demand $\hat{d}$ with $MCFP^{(\hat{d})} = 0.03$. For DPM $k_1 = 20$ and $k_2 = 10$. From left to right, both tables report Rep defined as the number of iterations performed by SA at any given temperature, T_0 defined as the starting temperature, T_f defined as the final temperature, a defined as the cooling factor, P_b, $|H_w|$ defined as the average hop length of the chosen working path, $|H_p|$ defined as the average hop length of the chosen protection path, $|H_s|$ defined as the average number of shared links, RCT defined as the average running time of the RWA algorithm, RCT_{FF} defined as the average running time of FF algorithm, and RCT_{SA} defined as the average running time of the SA algorithm. The cooling function is geometric. The DPM technique outperforms the LB technique in terms of $|H_w|$, $|H_p|$, and $||H_p| - |H_w||$ with any set of SA parameter values shown. Table 3 also shows that when the computational time is limited, e.g., RCT in the order of few milliseconds, the DMP technique is better than the LB technique in terms of P_b.

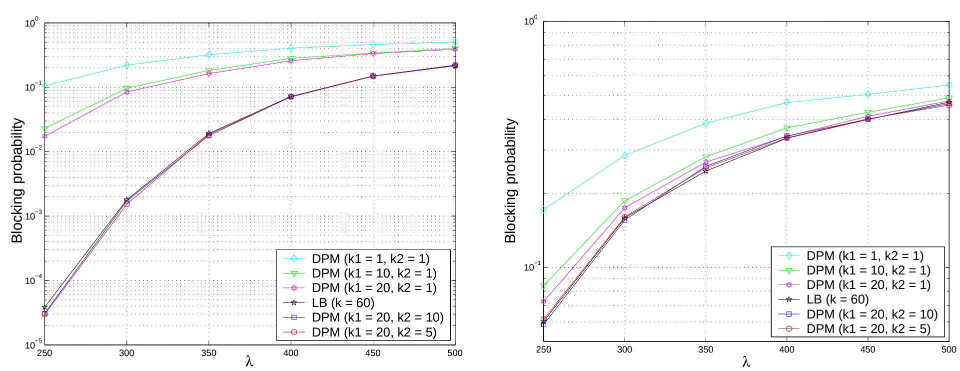
For the rest of the paper, the following SA parameter values are chosen: $Rep = 100$, $T_0 = 6$, $T_f = 1$, $a = 0.9$.

Table 4. DPM Solutions Found by the SA Algorithm

$k_1 = 20,\ k_2 = 10,\ \lambda = 300,\ MCFP^{(\hat{d})} = 0.03$										
Rep	T_0	T_f	a	P_b	$\lvert H_w \rvert$	$\lvert H_p \rvert$	$\lvert H_s \rvert$	RCT	RCT_{FF}	RCT_{SA}
100	3	1	0.9	2.11E-3	2.323	4.271	4.058	5.84E-3	2.03E-4	5.64E-3
25	6	1	0.9	3.43E-3	2.366	4.237	3.934	2.65E-3	1.88E-4	2.46E-3
50	6	1	0.9	2.03E-3	2.332	4.267	4.038	4.76E-3	1.72E-4	4.58E-3
100	6	1	0.9	1.72E-3	2.307	4.271	4.089	1.19E-2	2.33E-4	1.16E-2
1000	6	1	0.9	1.12E-3	2.270	4.246	4.125	1.12E-1	2.91E-4	1.11E-1
100	25	1	0.9	1.45E-3	2.295	4.262	4.102	1.66E-2	2.22E-4	1.64E-2
100	100	1	0.9	1.21E-3	2.287	4.258	4.113	2.31E-2	1.88E-4	2.29E-2
100	300	1	0.9	1.26E-3	2.284	4.249	4.106	2.91E-2	2.59E-4	2.89E-2
500	50	1	0.9	9.14E-4	2.268	4.228	4.100	9.21E-2	1.82E-4	9.19E-2
100	6	1	0.99	1.20E-3	2.270	4.249	4.128	9.09E-2	2.25E-4	9.06E-2
100	25	1	0.99	9.17E-4	2.261	4.245	4.129	1.63E-1	2.01E-4	1.63E-1
100	6	1	0.999	1.16E-3	2.243	4.242	4.142	8.94E-1	2.30E-4	8.94E-1

4.B. Comparison of SPP and SPP-DiR Schemes

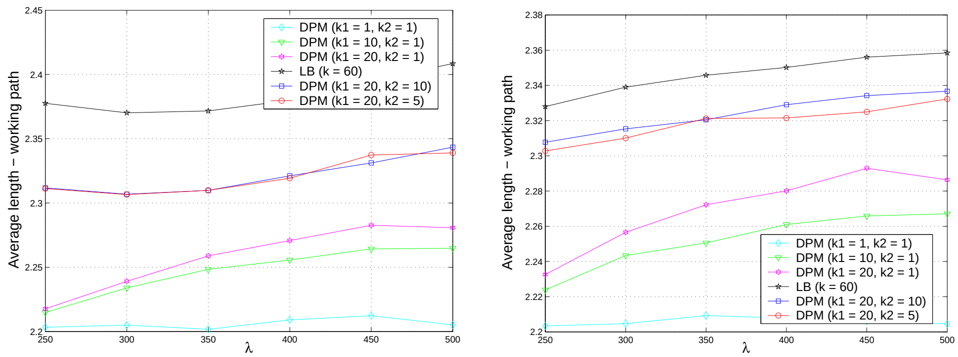
The results shown in this section provide a performance comparison between the SPP-DiR and the conventional SPP schemes. As already mentioned, the SPP scheme can offer only $MCFP^{(\hat{d})} = 0$.



(a) (b)

Fig. 3. P_b versus λ: (a) SPP-DiR and (b) SPP.

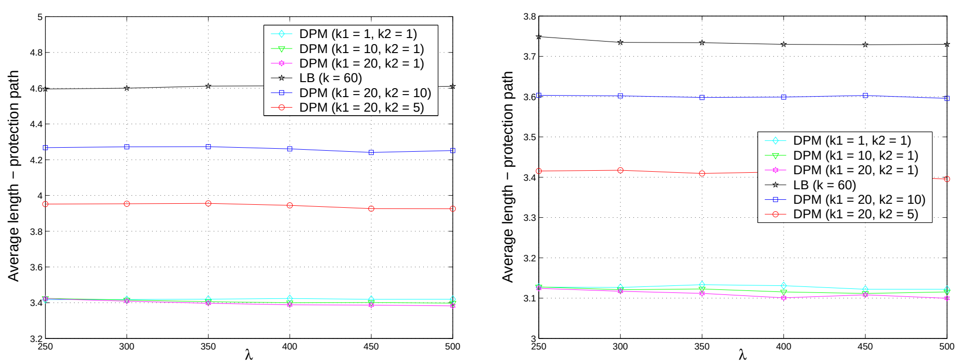
Figure 3 shows P_b (blocking probability) versus λ (arrival rate). The plots show that with a mild reduction of the offered reliability degree ($MCFP^{(\hat{d})} = 0.03$), the SPP-DiR scheme may strongly reduce P_b when compared with the SPP scheme. Moreover, the plots show that the DPM technique better solves the RWA problem when compared with the LB technique, due to the reduced size of the solution space in both the SPP-DiR and SPP schemes. The figure highlights also the importance of making use of multiple candidate path–pairs in obtaining satisfactory performances. If the values of k_1 and/or k_2 are too small, P_b is negatively and significantly affected.



(a) (b)

Fig. 4. $|H_w|$ versus λ: (a) SPP-DiR and (b) SPP.

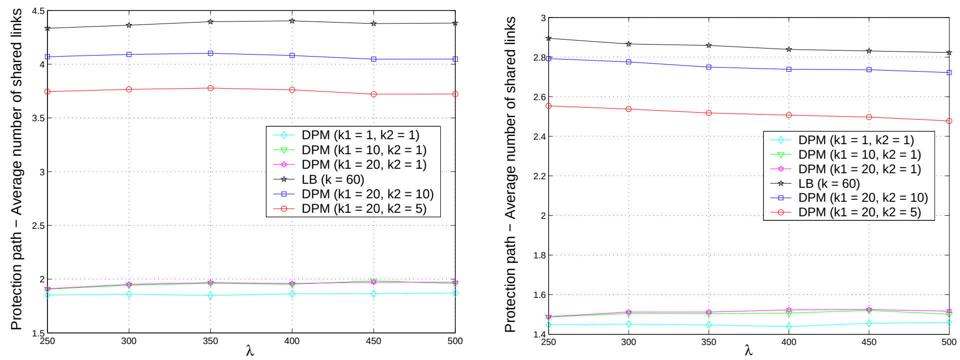
Figures 4 and 5 plot $|H_w|$ (the average hop length of the working path) and $|H_p|$ (the average hop length of the protection path) versus λ, respectively. Results obtained for both the SPP-DiR and SPP schemes are shown. The DPM technique is effective in reducing both $|H_w|$ and $|H_p|$ under any traffic load.



(a) (b)

Fig. 5. $|H_p|$ versus λ: (a) SPP-DiR and (b) SPP.

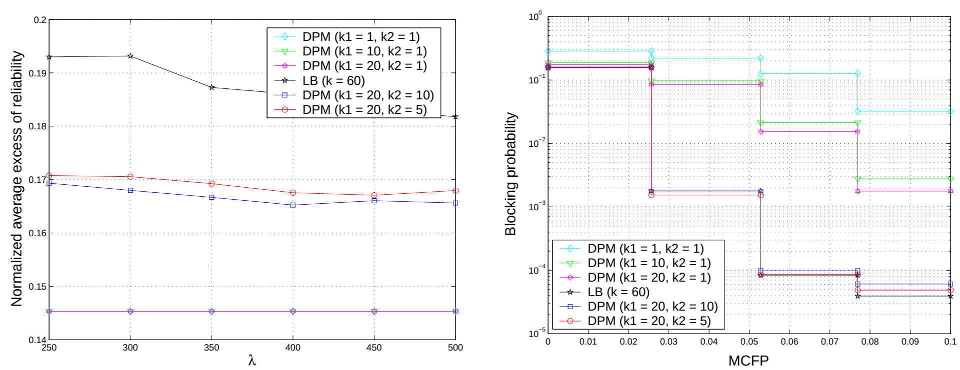
Figure 6 plots $|H_s|$ (the average number of shared protection links) versus λ. Results obtained for both the SPP-DiR and SPP schemes are shown. In the case under study, it is



(a) (b)

Fig. 6. $|H_s|$ versus λ: (a) SPP-DiR and (b) SPP.

found that by closely matching the demand's reliability requirement, the SPP-DiR scheme improves the number of shared protection links by 49% when compared with SPP.



(a) (b)

Fig. 7. (a) Normalized average excess of reliability versus λ and (b) P_b versus $MCFP^{(\hat{d})}$.

Figure 8(a) shows the normalized average excess of reliability versus λ. The excess of reliability, defined in Eq. (9), is averaged over all the serviced traffic requests, and normalized to $MCFP = 0.03$. The obtained excess of reliability is below 20%. The DPM solution appears to yield slightly smaller values of excess of reliability when compared with the LB solution. Simulation results show that the excess of reliability obtained by the DPM solutions with $k_1 < 20$ and $k_2 = 1$ is equal to the excess of reliability obtained by the DPM solution with $k_1 = 20$ and $k_2 = 1$.

Fig. 8(b) shows P_b versus $MCFP^{(\hat{d})}$. Clearly, the plots indicate the existing trade-off between the demand's guaranteed reliability degree and the blocking probability. Values shown at $MCFP^{(\hat{d})} = 0$ represent the blocking probability of the SPP scheme. These results confirm that by attempting to closely match the demand's reliability requirement, the SPP-

DiR scheme is successful in reducing the average amount of network resources that must be reserved to establish a newly arrived demand. In turn, this fact may reduce P_b significantly.

5. Conclusion

We have proposed an approach for dynamically creating reliable demands in WDM networks keeping in mind two objectives: (1) to guarantee the desired demand reliability level while minimizing the required network resources, and (2) to produce satisfactory solutions under constrained computational time.

The first objective was pursued by generalizing the SPP scheme to the SPP-DiR scheme. The SPP-DiR scheme is applied for the first time to create demands dynamically with the desired reliability level. The main advantage of this scheme is the ability to guarantee the demand reliability level, independently of the network topology and size, source–destination distance, and MTBF of the network elements. In some circumstances, the use of an SPP-DiR scheme was found to significantly reduce the amount of network resources that must be reserved for the incoming demand. In turn, this fact was shown to yield a remarkable reduction of the demand's blocking probability.

We pursued the second objective by proposing the use of the disjoint path–pair matrix, which contains a number of preselected candidate path–pairs for both working and protection routes. The solution produced by the DPM approach was compared with the solution produced by the widely used k-shortest paths approach. To provide satisfactory results, the DPM approach was found to require up to one order of magnitude fewer candidate path–pairs than the k-shortest paths approach does. For this reason, the DPM approach is best suitable when the computational time available for choosing each demand routing is constrained. The DPM solution was also found to require reduced average hop length for both the working and protection paths (up to 3% and 14% respectively) when compared with the k-shortest paths solution. This paper shows only the SPP and SPP-DiR schemes; it is expected that similar advantages of the DPM approach will be found when other path protection switching schemes are used.

Acknowledgments

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