A Differentiated Reliability (DiR) Approach for Dynamic Provisioning in WDM Networks*

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Abstract

The highly dynamic characteristic of the Internet traffic requires efficient connection set-up and tear down procedures, e.g., lightpaths at the WDM layer must be created and destroyed as needed. Clients of such created lightpaths consist of a variety of upper layers and applications, whose requirements may differ significantly, case by case. Therefore, the WDM layer must be able to provide differentiated levels of service in terms of bandwidth, delay and reliability.

This paper extends the concept of Differentiated Reliability (DiR), introduced for static networks in [1], to dynamic networks. To provide redundancy in the network, the Shared Path Protection (SPP) scheme is used and enhanced to provide multiple degrees of reliability. An on-line two-step algorithm, referred to as *Dynamic SPP-DiR* (DSPP-DiR), is proposed that efficiently reserves network resources to incoming connection requests, while both guaranteeing the required level of reliability and minimizing the blocking probability. Simulation results are shown to illustrate the impact of DiR on the blocking probability and expected length of both working and protection lightpaths.

1 Introduction

Wavelength Division Multiplexed (WDM) networks are evolving to respond quickly and economically to highly dynamic client traffic demands. In general, a WDM network consists of a number of optical switches interconnected by fiber optic links to form a mesh topology. The basic service provided by WDM networks are high speed, high bandwidth all-optical channels, also referred to as *lightpaths* [2], that are created between any node pair in the network to produce the desired logical connectivity. To be created, a lightpath requires one wavelength on every link of the path chosen to connect two nodes.

As any other network, WDM optical networks are prone to failures too. In WDM networks, failures may have severe consequences due to the large amount of traffic carried by the WDM channels. Therefore, it is of paramount importance that WDM networks are made resilient by means of some protection scheme implemented at the WDM layer [3].

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*This research is supported in part by NSF Grants No. ANI-0082085 and ECS-0225528, and CPqD.

A protection scheme requires allocation of spare resources to be used in case of a fault, e.g., a demand is assigned a *working* and a *protection* lightpath. The working lightpath carries the traffic during normal network operations. When the working lightpath is disrupted by a fault, the traffic is re-routed using the protection lightpath until the fault is repaired.

Conventional protection schemes [4] are capable of providing either full protection in the presence of a single fault or no protection at all. However, the growing importance of concepts such as Quality of Service (QoS) and Differentiated Services [5, 6] indicates that different levels of reliability may be required by different applications. With the aim of addressing this trend, the concept of *Differentiated Reliability* (DiR) was introduced in [7, 1] and applied to provide different degrees of reliability in static networks, with ring and mesh topology, respectively. According to the DiR concept, each connection has a guaranteed maximum failure probability (or downtime ratio) that must be met by the protection scheme. The ultimate objective of the DiR design is to satisfy the reliability degree of the traffic demand, while optimizing the network performance, e.g., cost.

This paper extends the DiR concept to networks with dynamic resource reservation. In dynamic reservation networks, each lightpath is set up in real time, without rerouting already existing lightpaths, nor knowing what future lightpath requests are going to be generated. An on-line algorithm, referred to as *Dynamic SPP-DiR* (DSPP-DiR), is proposed that determines what resources must be reserved to each incoming lightpath request. The objective of the proposed algorithm is twofold: 1) to minimize the probability that a lightpath request is blocked and 2) to yield the requested reliability degree.

To simplify the optimization process a two-step approach is adopted. During the first step, the algorithm produces a reliability level with large granularity, i.e., depending on its required reliability level, the newly generated lightpath is either protected or not. The lightpath reliability granularity is then refined during the second step, when the algorithm attempts to provide a reliability degree that closely matches the required value. As shown in the paper, the second step is of paramount importance in reducing blocking probability, as it limits the overprovisioning of spare resources.

Performance of the proposed algorithm is evaluated using the Pan-European network. As illustrated by the presented simulation results, the DSPP-DiR algorithm yields improved blocking probability when compared to the conventional SPP.

2 Network Model

A generic WDM network with arbitrary, i.e., mesh topology is considered. Wavelength conversion is not available in the network. However, working and protection lightpaths of the same lightpath request may use distinct wavelengths. It is assumed that only single-link faults may occur in the network, i.e., the probability that two or more links are failed at once is considered to be negligible [8]. It is also assumed that a link fault disrupts demands in both directions of propagations.

The WDM mesh is modelled as a graph $G(\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ represents the set of networks nodes and $\mathcal{L}$ the set of networks links. It is assumed that each link in the network can accommodate F fibers for each direction of propagation, each one carrying W wavelengths.

Each link in set $\mathcal{L}$ is characterized by the number of available fibers, the number of available wavelengths for each fiber and the value of the conditional link failure probability. Based on the single failure assumption, the conditional link failure probability is the conditional failure probability given that a single link fault has occurred in the network[1]. For example, assuming a uniform distribution of faults among the links, the conditional link failure probability is:

$$P_f(i,j) = \frac{1}{|\mathcal{L}|} \; \forall (i,j) \in \mathcal{L} \tag{1}$$

Connection demands arrive randomly at the network nodes and must be served as they are received. A demand consists of one lightpath that needs to be created between two nodes. A lightpath is a path of light between a node pair whose bandwidth equals the wavelength bandwidth. Splitting of lightpaths that belong to the same demand along multiple working, or protection, lightpaths is not allowed. A connection demand is blocked and discarded when the network does not have enough resources available to guarantee the required level of reliability.

The reliability degree is modelled by assigning each demand a Maximum Conditional Failure Probability ($MCFP$). $MCFP$ represents the maximum acceptable probability that, given a network link failure, the connection will not survive. The protection scheme must satisfy this value for each demand. With the conventional SPP protection scheme, each working lightpath is assigned a route-disjoint protection lightpath ready to be used when the working lightpath is affected by a fault. Based on the single fault assumption, route disjoint working lightpaths can share the same protection wavelengths to increase resource utilization efficiency. Each demand is thus provisioned with resources to be 100% survivable against any single fault, i.e., the conventional SPP supports only $MCFP = 0$.

To yield a wider range of $MCFP$ values, the DSPP-DiR scheme is derived from the SPP scheme as follows. For a demand with a non stringent $MCFP$, the protection lightpath needs not be available for every possible link failure scenario. Thus, it is possible to select a set of links $U^{(D)}$ of the working lightpath for which demand D will not require to resort to the protection lightpath. Set $U^{(D)}$ must be selected while satisfying the required reliability degree, expressed by the $MCFP$ parameter. Notice that, with DSPP-DiR, two working lightpaths having a common link along the working lightpath, can also share protection wavelengths if at least one of the two working lightpaths needs not resort to the protection lightpath in case of a failure of the common working link. Similarly, it is also possible to have a working lightpath completely unprotected if its path failure probability satisfies the reliability requirement given by the connection $MCFP$. Intuitively, the DSPP-DiR scheme achieves a better resource utilization when compared to the conventional SPP scheme, while provisioning to each connection enough resources to satisfy the reliability requirement.

The example in Figure 1 illustrates the provisioning approach based on the DSPP-DiR concept. All links in the network are bidirectional and can accommodate two wavelengths for each direction of propagation. Based on the uniform link failure distribution, the link conditional failure probability is $P_f(i,j) = \frac{1}{7} \; \forall (i,j) \in \mathcal{L}$. Three demands are shown. Demand D_1 arrives first with $MCFP_{D_1} = 0$. The chosen working lightpath is $C - B$. The reliability degree requirement requires full protection against any single fault, the protection lightpath is therefore $C - E - B$. Demand D_2 arrives to the network next with $MCFP_{D_2} = 0$. The chosen working lightpath is $D - E - A$. The reliability requirement mandates that all the links along the working lightpath are protected. The protection lightpath is therefore $D - C - B - A$. Demand D_3 comes last with $MCFP_{D_3} = \frac{1}{7}$. The reliability requirement allows to have demand D_3 protected against any single fault but

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[1] Based on the single fault assumption the link failure probability is the product between the conditional link failure probability and the probability of having a single fault.

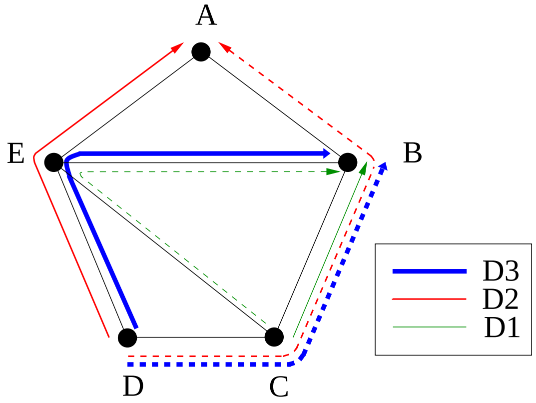

Figure 1: DSPP-DiR provisioning approach.

one. It is therefore possible to route the working lightpath along $D-E-B$ and have link $D-E$ unprotected. The protection lightpath is $D-C-B$ and is used only in 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 lightpaths are not route disjoint. Notice that by changing reliability degree $MCFP_{D_3} < \frac{1}{7}$, demand D_3 is blocked due to lack of resources.

The objective of the next section is to determine the routing for and the resources used by each demand to minimize the blocking probability, while satisfying the reliability degree requirement expressed by $MCFP$.

3 Optimization of the Dynamic SPP-DiR (DSPP-DiR) Scheme

In this section the problem of optimally provisioning reliable connections in WDM mesh networks is formally described. The on-line two-step *DSPP-DIR* algorithm whose aim is to minimize the blocking probability, is described.

3.1 The DSPP-DiR Problem Definition

Let $H_w^{(D)}$ be the set of working links used by the working lightpath to accommodate traffic demand D and $H_p^{(D)}$ be the set of protection links used by the protection lightpath assigned to traffic demand D. To guarantee the availability of a protection lightpath when the working lightpath is affected by a failure, working and protection lightpaths must be route-disjoint:

$$H_w^{(D)} \cap H_p^{(D)} = \emptyset \tag{2}$$

Let $U^{(D)}$ be the set of unprotected links along the working lightpath of connection D, the conditional failure probability of a connection D can be calculated as:

$$P_f^{(D)} = \sum_{(i,j)\in U^{(D)}} P_f(i,j) \leq MCFP_D \tag{3}$$

where $P_f(i,j)$ is the conditional link failure probability. The failure probability of each connection must be smaller than the required value of $MCFP$. Sharing of resources between the protection lightpaths of two demands D and D^* is possible if the following condition is satisfied:

$$(H_w^{(D)} \cap H_w^{(D^*)}) \subseteq (U^{(D)} \cup U^{(D^*)}) \tag{4}$$

Let $H_s^{(D)} \subseteq H_p^{(D)}$ be the set of links, used by the protection lightpath of traffic demand D, that share resources with other protection lightpaths already routed in the network.

Based on the routing for both working and protection lightpaths, a cost function measuring the goodness of the choice for the routing is defined as:

$$C^{(D)} = |H_w^{(D)}| + |H_p^{(D)}| - |H_s^{(D)}| + (MCFP^{(D)} - P_f^{(D)}) \tag{5}$$

The cost function measures the amount of resources provisioned to a demand. In addition it measures the excess of reliability $(MCFP^{(D)} - P_f^{(D)}) \geq 0$ that demand D receives.

3.2 The DSPP-DiR Algorithm

The objective of the DSPP-DiR algorithm is to provision each demand with enough resources to satisfy equation 3, while minimizing the cost function defined in equation 5, which in turn has an impact on the overall blocking probability. The algorithm consists of two steps.

- Step 1: SPP-DiR-FF. The protection lightpath is allocated only if the working lightpath has a failure probability that does not satisfy the reliability requirement expressed by equation 3.
- Step 2: SPP-DiR-SA. This step refines the outcome of the first step when a protection lightpath is allocated by Step 1. The objective is to provide each demand with a reliability degree that closely matches the connection requirement.

3.2.1 Step 1: SPP-DiR-FF

The objective of this step is to solve the Routing and Wavelength Assignment (RWA) problem for each demand D while guaranteeing that the level of reliability requested by each connection is met by the protection scheme. The protection strategy is based on a modified version of the conventional Shared Path Protection (SPP) scheme, i.e., demands can be fully protected or fully unprotected only. The DiR concept is applied here with a larger granularity.

Since the number of possible paths between a source and a destination node grows exponentially with the network size [9], a subset of possible candidate paths is preselected for each node pair to contain the number of possible options and reduce the search complexity.

Let $\mathcal{S}_{K_{s,d}}$ be the preselected set of candidate paths between the source node s and the destination node d. Paths in $\mathcal{S}_{K_{s,d}}$ are sorted by non decreasing number of hops.

A pseudo-code that describes the algorithm is reported in Figure 2. When traffic demand D between source node s and destination node d arrives at the network, the algorithm searches for the first path in set $\mathcal{S}_{K_{s,d}}$ that has enough resources available to route the working lightpath for traffic demand D. Once an available path is found, the algorithm finds the first available wavelength that can accommodate all links along the

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begin SPP-DiR-FF
  $\mathcal{S}_{K_{s,d}} = \{ordered\ set\ of\ candidate\ paths\}$
  for (every $w \in \mathcal{S}_{K_{s,d}}$ ) {
    if (resources are not available)
      continue
    set working_lightpath = w
    $P_f^{(w)}$ = failure_prob(working_lightpath)
    if ($P_f^{(w)} < MCFP$)
      return working_lightpath
    for (every $p \in \mathcal{S}_{K_{s,d}}$) {
      if (p and working_lightpath are not disjoint)
        continue
      if (resources are not available)
        continue
      set protection_lightpath = p
      return working_lightpath and protection_lightpath
    }
  }
end SPP-DiR-FF
```

Figure 2: Pseudo-code of Step 1: SPP-DiR-FF.

chosen path, while satisfying the wavelength continuity constraint — the so called first fit approach. The reliability of the working lightpath alone, without considering any protection lightpath, is then evaluated. If the path failure probability, as is defined in equation 3, is less than the demand $MCFP$, the protection lightpath is not required and only the working lightpath is returned. Otherwise the algorithm searches for the shortest route-disjoint path in the set $\mathcal{S}_{K_{s,d}}$ that has the necessary resources to accommodate the protection lightpath. The algorithm considers both unused wavelength and wavelengths that may be shared[2]. If an available wavelength is found the working and protection lightpath are returned.

If no resources are available to route the working lightpath, the demand is immediately blocked. Conversely, when the $MCFP$ requires the protection lightpath, but no resources are available for such lightpath during Step 1, the demand is still processed by Step 2: SPP-DiR-SA.

3.2.2 Step 2: SPP-DiR-SA

Upon completion of the first step demand D is assigned a working and a protection lightpath. (When the protection lightpath is not assigned by Step 1, Step 2 is not necessary.) The objective of this second step is to reduce the reliability degree of the demand if possible, with the intent of reducing the output of the cost function defined in equation 5. This objective is accomplished by selecting a subset of links along the working lightpath for which protection is not required. A Simulated Annealing (SA) [10]

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[2] Sharing is possible if condition 4 is satisfied. Notice that the set of unprotected links $U^{(D)}$ is always empty at this step.

algorithm is used to choose the subset of unprotected links. The outcome of the SPP-DiR-FF step is used as the initial solution of the SA algorithm. If the solution provided by the SPP-DiR-FF step is unfeasible, i.e., resources (wavelengths) for the protection lightpath were not found and reserved, a high cost is assigned to such initial solution, thus forcing the SA algorithm to search for lower cost solutions.

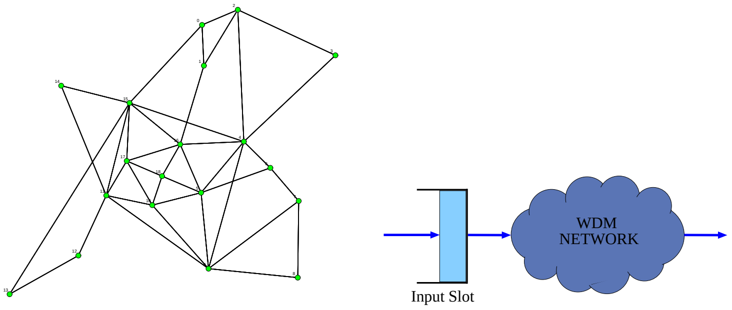
The routing for the working lightpath is left unchanged. Only sets $H_p^{(D)}$ and $U^{(D)}$ are modified by the SA algorithm as follows. Initially, set $U^{(D)}$ is empty and set $H_p^{(D)}$ contains the chosen candidate path for the protection lightpath. At each SA iteration, a neighboring solution is computed as follows. One of the following two moves is equally likely to be chosen:

1. modify the reliability degree of the working lightpath by randomly selecting a link $l \in H_w^{(D)}$
    - if l is not protected, l is removed from set $U^{(D)}$
    - if l is protected, l is chosen to be a candidate to enter set $U^{(D)}$: if $P_f^D \leq MCFP_D$ when considering set $U'^{(D)} = l \cup U^{(D)}$ then $U^{(D)} = l \cup U^{(D)}$. If $P_f^D > MCFP_D$, another move is randomly selected and set $U^{(D)}$ is left unchanged.
2. randomly select a different protection lightpath.

4 Performance Evaluation

The two-step algorithm presented in Section 3 is tested using the Pan-European optical network shown in Figure 3(a). The network comprises 19 nodes and 39 bidirectional links. Each link accommodates 1 fiber for each direction of propagation and each fiber is carrying 32 wavelengths. The conditional link failure probability is obtained assuming a uniform distribution of faults among the links, i.e., $P_f(i, j) = \frac{1}{39}$.

Traffic demands arrive at the network with a Poisson distribution with arrival rate λ. Source and destination nodes are randomly chosen with a uniform distribution. Each demand requires one lightpath and comes with a constant reliability degree requirement $MCFP$. Each established connection is held for a time equal to a random variable with exponential distribution and parameter $\mu = 1$.



(a) (b)

Figure 3: Pan-European optical network (a) and input slot buffer (b).

In order to guarantee fairness, i.e., the distribution of demands that are admitted into the network is the same distribution of the arriving demands, a single-slot buffer (Figure 3(b)) is used to store the demand waiting for service. When an incoming demand can not be satisfied it will be placed in the input buffer until enough resources become available in the network to accommodate such request. When the slot is taken, all arriving demands are blocked.

The set of preselected candidates, $\mathcal{S}_{K_{s,d}}$, is constructed using the $K-th$ shortest path algorithm [11]. For each source-destination pair the $K = 50$ shortest paths are included in the set.

The performance of the two step DSPP-DiR algorithm is assessed in terms of blocking probability, average number of links used by the working and the by the protection lightpaths, and average number of links along any protection lightpath that allow for resource sharing. For comparison, results obtained by both the SPP-DiR-FF step presented in Section 3.2.1 and the conventional SPP scheme are shown.

The simulation time is set to achieve the confidence interval values shown in Figure 4 at 99% confidence level. The SA algorithm requires some parameters to be fine tuned to achieve satisfactory performance in terms of both optimality of the solution found and computational time required to find the solution. It was found that a number of iterations $nrep = 40$, starting temperature $t_0 = 2$, final temperature $t_f = 1$, cooling factor $a = 0.9$ with geometrically decaying temperature represent a good tradeoff in terms of the above objectives.

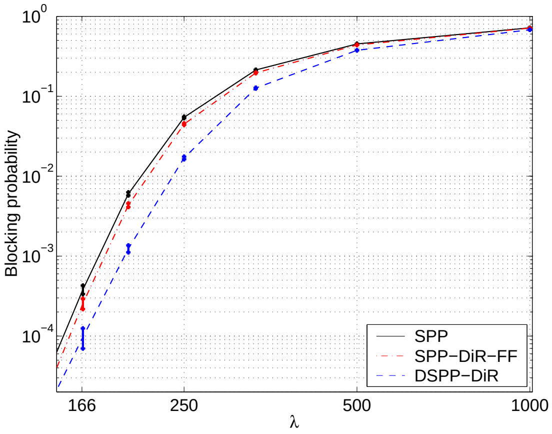
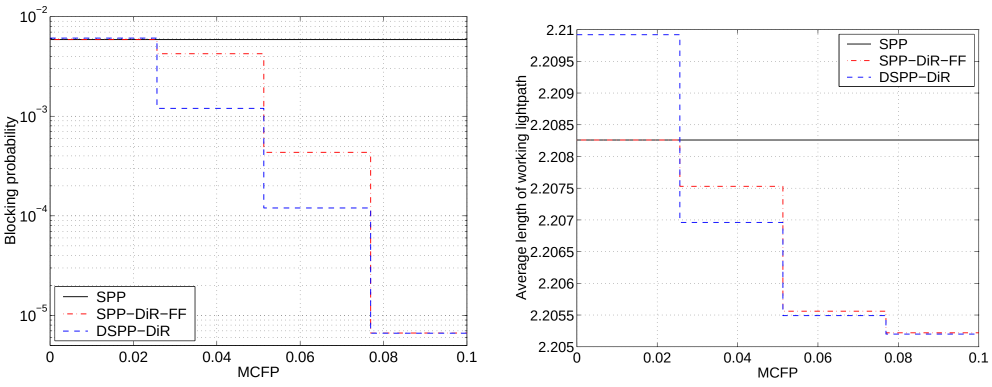


Figure 4: Blocking probability as a function of arrival rate λ.

Figure 4 shows the blocking probability as a function of the arrival rate, λ. Each demand has a reliability requirement of $MCFP = 0.03$. Three curves are shown. The first is the one obtained using the conventional SPP scheme. The second is the result obtained at the end of the SPP-DiR-FF step presented in Section 3.2.1. The third is the curve obtained by the proposed DSPP-DiR algorithm. The percentage of blocked requests increases as λ increases. A comparison with the conventional SPP protection scheme reveals that the DSPP-DiR algorithm reduces the blocking probability by 80% for values of $\lambda \leq 200$, while the incurred reduction of reliability is only minimal. As λ increases, network resources become quickly unavailable and the gaps between the schemes become less visible.

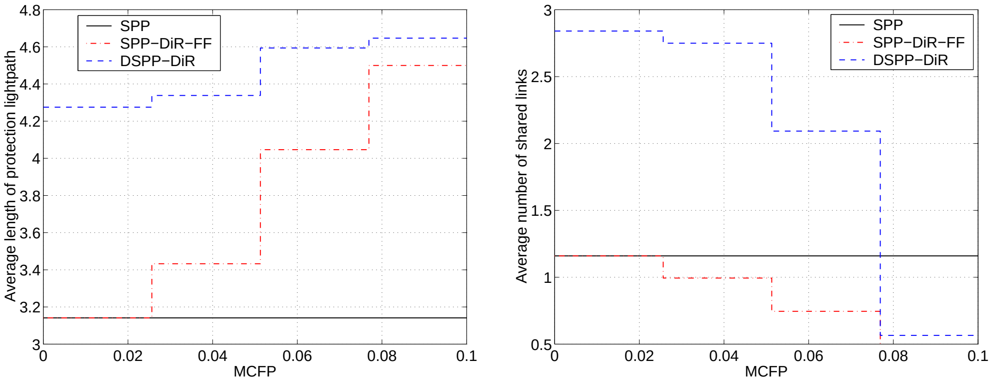
Figures 5(a), 5(b), 6(a), and 6(b) show the blocking probability, the average number of links used by the working lightpaths, the average number of links used by the protection lightpaths, and the average number of links of the protection lightpaths that are shared as a function of the reliability degree ($MCFP$) required by the demands. The arrival rate λ is fixed and equal to 200.



(a) (b)

Figure 5: Blocking probability (a) and average length of working lightpaths (b) vs. $MCFP$.

The blocking probability decreases as the value of $MCFP$ increases for both the SPP-DiR-FF step and the DSPP-DiR algorithm while it remains constant for the SPP scheme. The SPP scheme always guarantees a 100% degree of reliability, i.e., the SPP scheme overprovisions reliability to demands that do not need high degree of reliability. On the other hand, SPP-DiR-FF and DSPP-DiR attempt to closely match the demand requirement[3], thus, provisioning less resources to demands that require lower reliability degrees. Figure 5(b) shows that when $MCFP$ is increased, more resources become available and working lightpaths can be routed on shorter routes rather than longer ones, thus, also decreasing the probability of being disrupted by a fault.



(a) (b)

Figure 6: Average length of protection lightpaths (a) and average number of shared links (b) vs. $MCFP$.

Figures 6(a) and 6(b) show that the DSPP-DiR scheme improves by 60% the number of shared links, trading off an increased 26% in the protection lightpath length.

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[3] Recall that SPP-DiR-FF and DSPP-DiR provision reliability with different granularity.

5 Summary

The on-line DSPP-DiR algorithm was proposed to dynamically reserve network resources to incoming connection requests, with the objective of providing Differentiated Reliability (DiR) by means of Shared Path Protection (SPP). It was shown that when compared to the conventional SPP scheme, the proposed DSPP-DiR algorithm reduces the overall blocking probability by efficiently making use of reusable protection wavelengths, while guaranteeing the required reliability degree of each connection.

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