Separate Wavelength Pools for Multiple-class Optical Channel Provisioning
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Abstract
Current wavelength routed optical networks serve a vast variety of clients, carrying connections belonging to different Quality of Service (QoS) classes. However, optical channel, i.e. lightpath, requests with different QoS requirements compete for the same network resources. Proper policies are, therefore, necessary to assure the client’s service level requests, e.g. blocking probability, when setting up lightpaths.
In this paper, we propose and evaluate a strategy for multiple-class optical channel provisioning. The separate wavelength pool provisioning (SWAP) strategy logically separates into different wavelength pools the resources available for the allocation of optical channels that carry connections belonging to different QoS classes. In this way the network itself provides different class connections with classes of lightpaths characterized by different service levels, e.g. blocking probability.
Numerical results show that the SWAP strategy, suitably adjusting the pool sizes, inherently differentiates the blocking probability experienced by different class lightpaths, while encouraging backup resource sharing. Moreover it eliminates any impact of low class lightpath requests variation on high class lightpath blocking probability, without significant performance degradation. Finally, with the SWAP strategy the lightpath setup is fast, since a lightpath route is searched in a limited wavelength pool.

1 Introduction
Current trend in communications networks is to utilize the same transport network infrastructure for supporting traditional circuit-oriented voice services as well as packet-oriented data services. However, different services must be carried by connections satisfying different quality of service (QoS) requirements, such as blocking probability and resilience. For example in [1, 2] the concept of Differentiated Reliability (DiR) is proposed, where each connection class is guaranteed a minimum reliability degree. Moreover, the continuously increasing demand for wide bandwidth connections has fostered the adoption of wavelength division multiplexing (WDM). WDM allows to harness the huge fiber capacity providing connection requests with multiple high capacity transparent optical channels, i.e. lightpaths, along the same fiber link. Wide bandwidth connections carrying different service classes might be differentiated at the network edge through policy based admission controls [3, 4] enforced at the connection granularity. Indeed high and low class connections are, usually, routed concurrently, i.e. they exploit the same set of network resources. Therefore low class and less predictable traffic must be carefully loaded into the network to avoid that strict performance constraints (e.g., a constraint on the maximum blocking probability) for high class traffic are violated. In particular, the admission control must assure that low class connections do not overutilize resources necessary to accommodate future high class requests.
In this paper a strategy for multiple-class optical channel, i.e. lightpath, provisioning is proposed. Connections carrying different classes of services are differentiated, directly at the optical layer, by assigning them to different classes of lightpaths. The proposed separate wavelength pool provisioning (SWAP) strategy logically separates the wavelengths available for optical channels carrying connections belonging to different service classes into separate pools. The SWAP strategy provides a relative lightpath differentiation guaranteeing that different class lightpaths experience different blocking probabilities¹. Thus, the network configuration itself provides differentiation by provisioning lightpaths with different service levels, i.e. blocking probabilities.
Numerical results show that with the SWAP strategy several advantages can be obtained at the expense of a small performance loss due to the partitioning of the

¹ The lightpath differentiation is only relative because network resources (i.e., fiber links and wavelengths) are given a-priori, so that under heavy load even high class lightpaths can experience high blocking probability.
network resources. With a suitable choice of the pool sizes the blocking probability of the lightpath classes is differentiated and the sharing of backup resources is favored. Moreover, variations of low class lightpath requests have no impact on high class lightpath blocking probability. Finally, the lightpath set-up complexity is reduced, since the search for a lightpath route is performed only in a wavelength pool of smaller size than the whole wavelength set.

2 Separate Wavelength Pool Provisioning

The SWAP strategy logically partitions the set of available wavelengths to allocate optical channels carrying different class connections. In this study, two connection classes are considered (extensions to multiple-class scenarios are straightforward [4]): SWAP is applied to serve in the same network both premium requests with guaranteed protection in case of any single-link failure, and low priority requests, unprotected and preemptable. Moreover, for simplicity, each connection is assumed to require the amount of bandwidth provisioned by one lightpath. Thus a one-to-one correspondence between connection classes and lightpath classes is present.

High class lightpaths must be guaranteed low blocking probability and be protected against any single link failure. The resilience scheme utilized is shared path protection (SPP) [5]: each high class lightpath is assigned a working path and a Shared Risk Link Group (SRLG) disjoint backup path. With SPP protection resources can be shared among different backup paths if the corresponding working paths have no common SRLG, achieving significant backup resource savings, especially in mesh networks. High class lightpaths are used to carry circuit-oriented services (voice, leased lines, virtual private networks): high class lightpath requests are therefore well predictable and long lasting.

Low class lightpaths have low priority, i.e. they can undergo a higher blocking probability than high class lightpaths, do not require any fault tolerance, and in case of failure can be preempted to recover high class lightpaths [6, 7, 8]. Low class lightpaths may indeed exploit links reserved for protection paths for carrying best effort traffic, which is very variable and difficult to estimate, and do not require resilience at the optical layer since they can be restored at higher layers (e.g., IP).

The SWAP strategy approach is shown in Fig. 1. Available wavelengths are separated into two pools: the first one is devoted to carry working lightpaths of high class optical channel requests only; the complementary one is shared by the backup lightpaths of high class optical channel requests and working lightpaths of low class optical channel requests. Upon link failure, disrupted high class lightpaths are re-routed using the backup path reserved on the "protection wavelength" in the second pool, perhaps preempting resources used by low class lightpaths.

To route both high and low class lightpaths the SWAP strategy utilizes the Shortest Path Algorithm for the Wavelength Graph (SPAWG) [9]. SPAWG adaptively finds a minimum cost path on a layered wavelength graph, built replicating the physical topology of the network on a number of superimposed planes equal to the number of available wavelengths. The SPAWG routing and wavelength assignment (RWA) algorithm has been adapted to cope with the SWAP strategy: since each lightpath must be routed on a specific wavelength pool, SPAWG utilizes only the allowed subset of the wavelength graph, which corresponds to the allowed wavelength pool, to find a path. Within each pool first-fit policy is adopted for breaking ties. When a high class (protected) lightpath is requested, a two-step procedure is performed to determine a pair of SRLG-disjoint paths: first of all a working path is searched within the first wavelength pool; if no path is available the request is blocked. Instead, if a working path is found, a SRLG-disjoint backup path is searched in the second pool, sharing wavelengths utilized for protection of SRLG-disjoint high class working paths. In addition wavelengths occupied by low class lightpaths, besides the free channels, are considered available because they can be preempted for protecting high priority lightpaths. If a backup path cannot be found, the high class lightpath request is blocked.

When a low class lightpath is requested, only a path is searched in the second wavelength pool considering available the free wavelengths and the ones reserved for protection (that may be preempted in case of failure). If a path cannot be found, the low class lightpath request is blocked.
3 Simulation scenario

The study presented in this paper is basically a provisioning problem: thus a network is given and its resource configuration and node capabilities are determined a-priori. The metric considered to evaluate network performance is the blocking probability, defined for each lightpath class and computed as the ratio between the number of blocked lightpath requests and the number of generated requests.

In order to support the proposed SWAP strategy, each network node is equipped with wavelength selection capability, i.e. the possibility to flexibly choose the wavelength of a lightpath in its source and destination nodes [10]. In case of failure, by exploiting wavelength selection capability, the end nodes of a disrupted lightpath quickly switch the transmission from the working wavelength (in the first pool) to the protection one (in the second pool) to restore the communication path. On the contrary, network nodes do not implement wavelength conversion capability, since the necessary equipment is very expensive, while, generally, only a minor improvement [11] of the network performance can be obtained. The SWAP strategy further reduces the importance of wavelength conversion, since it can be performed only among wavelengths within the same pool.

A $4 \times 4$ mesh-torus topology is utilized as test network; links are bidirectional and each of them carries $W=40$ wavelengths. This topology has been chosen because its simplicity and regularity are expected to help grasping the behavior of the proposed strategy.

Simulations follow an approach suitable for networks characterized by low dynamicty: an incremental traffic model is adopted, where requests for permanent optical channels arrive spread in time and space and are served sequentially. With this approach the changes in the resource allocation are not frequent, thus the assumption that all network nodes have an up to date knowledge of the network status, needed by the SWAP strategy, is realistic.

Connections between node pairs are generated with uniform probability, i.e. every node has the same probability to request a lightpath towards any other node. Various distributions of high and low class lightpath requests have been investigated: in the following they are referred to as $(a; b)$, where $a$ is the fraction of generated high class requests and $b$ is the fraction of generated low class requests. Wavelength pool sizes are considered a simulation parameter and are varied to evaluate their impact in the SWAP strategy performance.

The SWAP strategy is compared with the single-pool strategy: in this case the wavelength set is not partitioned, and the routing of low class lightpaths may take resources necessary to accommodate future high class lightpaths. To reduce this problem the re-utilization of resources already reserved for protection or used by low class connections is encouraged through the following link weight policy: if a path for a low class lightpath is searched, the weight on the wavelength graph is reduced for the links already reserved for high class lightpath backup paths; similarly, if a high class lightpath backup path is searched, the weight is reduced for the links booked for protection by SRLG-disjoint high class lightpaths, or used by low class preemptable lightpaths.

4 Numerical results

In this section we present simulation results that compare the single-pool strategy, denoted by 1P, with the proposed SWAP strategy, denoted by 2P$[w_1, w_2]$, where $w_1$ and $w_2$ are the number of wavelengths of the first and second pool, respectively.

Two traffic scenarios have been considered: in the first the lightpath request distribution is set to $(0.5; 0.5)$ and the network is loaded with a variable amount of high class and low class requests; in the second a fixed amount of high class requests is set, and only low class requests are varied.

4.1 Variable high class and low class requests

Fig. 2 and 3 show the blocking probability of high class and low class lightpaths respectively, as a function of the total generated requests, when the network is loaded with half high class and half low class requests $(0.5; 0.5)$.

In Fig. 2 we can notice that the SWAP strategy with the first pool size of about 30 wavelengths allows to greatly reduce the blocking of high class lightpaths compared to 1P or 2P$[20-20]$ strategy. The best results are obtained by 2P$[32-8]$, since a great capacity is available in the first pool for the working paths, and the second pool has enough wavelengths to route the shared backup paths. With 2P$[33-7]$ high class lightpaths begin to be rejected earlier because the second pool is too small, and backup paths cannot be easily found.

In fact, the lower blocking of high class lightpaths obtained through the utilization of SWAP strategy is counterbalanced by low class lightpaths blocking increase. Fig. 3 presents the blocking probability of low class lightpaths: 1P strategy obtains the best results, since low class requests can be routed on the whole range of wavelengths; on the contrary with SWAP the blocking is much higher because this strategy limits the capacity that can be exploited by low class lightpaths, constrained in the second pool. However, since low class connections have less stringent performance.

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2 The SPAWG algorithm has been adopted also for single-pool strategy: first-fit policy is chosen for breaking ties for all lightpath requests.
requirements they can tolerate a higher blocking probability.
Comparing Fig. 2 and 3, it appears that 1P and 2P[20-20] strategies obtain very similar blocking probability for high and low class lightpaths. Therefore the flexibility in the choice of pool sizes is shown to be an important feature of the SWAP strategy in order to provide service differentiation. In addition the poor performance of the 2P[20-20] strategy proves the added value of SWAP with respect to an alternative approach utilizing as separate pools two equal capacity fibers on every link, instead of two variable wavelength pools in a single fiber.

In Fig. 4 and 5 the advantage achieved by the SWAP strategy in terms of backup resource utilization is highlighted. Fig. 4 shows the average number of wavelengths utilized for the routing of high class backup paths. With single-pool strategy, protection resource utilization grows very quickly compared to all two-pool strategies, because working and backup paths interfere on the same wavelength set, and the sharing is less effective. On the contrary, with SWAP the confinement of backup paths allows to better share protection resources, even without reducing the weights of reserved links. This behaviour is confirmed in Fig. 5, which presents the average number of backup paths that share a booked protection channel: only for very low loads single-pool takes advantage of the weight-reduction policy to improve the sharing. However, increasing the number of channel requests the SWAP strategy quickly overcomes the single-pool strategy and achieves much better performance exploiting the confinement of protection paths in the second pool: when this pool is saturated the number of backup paths per channel tends to infinity, because no free resources are available anymore, and a protection path can be allocated only re-using already reserved channels.

4.2 Fixed high class requests and variable low class requests

We also investigated the impact of low class lightpath request variations on high class lightpath blocking performance. The analysis is conducted loading the network with a fixed amount of high class requests and a variable amount of low class requests. This choice relies on the fact that high class requests are usually well predictable and stable on long periods of time; on the contrary low class requests are typically very difficult to estimate and much more variable.
In Fig. 6 and 7 the blocking probability is plotted as a function of the generated low class requests keeping the value of high class requests fixed to 150. The sweep on the generated low class requests starts at a value of 300 connections, yielding a (1/3; 2/3) request distribution. This last connections value depicts a network load where all requests are routed (blocking probability is null). At the extreme side, the sweep on the amount of low class requests is brought to 600. Fig. 6 and 7 compare the single-pool (1P) and the SWAP (2P[14-26]) strategies: in the latter case pool sizes are chosen assigning the least capacity to the first pool for the routing of all high class lightpath working paths, and the greatest capacity to the second pool for the routing of low class lightpaths.

Fig. 6 shows the blocking probability of high class lightpaths, whose amount remains fixed: with the SWAP strategy high class requests experience a null refusal for any amount of generated low class requests; on the contrary with the single-pool strategy a blocking of high class requests appears exceeding 375 generated low class requests. Then, differently from the single-pool strategy, the SWAP solution makes the blocking probability of high class lightpaths independent of the amount of generated low class requests, thanks to a more precise routing of the connections. This advantage again is counterbalanced by low class lightpath blocking probability, presented in Fig. 7: with the SWAP strategy, low class requests begin to be blocked earlier and more frequently than with the single-pool strategy, since the RWA algorithm can span only the second pool to find a suitable path. Comparing Fig. 6 and 7, we can notice that 1P strategy achieves the same blocking for high and low class traffic, showing again that the SWAP strategy is needed to differentiate the service levels for requests belonging to different traffic classes.

A drawback of the SWAP strategy is the performance degradation due to the partitioning of the network capacity. In the following this issue is investigated, choosing as metric the maximum amount of allocated low class lightpaths that can be routed satisfying a typical blocking probability constraint: all high class requests have to be allocated, \( P_{b}^{HIGH} = 0 \), while some low class requests can be blocked under heavy load even in the absence of failures \( P_{b}^{LOW} < 10\% \).

The results are presented in Fig. 8, for different initial request distributions and assigning the greatest possibility.
ble number of wavelengths to the second pool. In spite of capacity splitting, the SWAP strategy achieves a performance similar to single-pool strategy: the latter has a slight advantage when the initial load consists mainly of high class lightpaths ((1;0) and (0.5;0.5)), since in this case the second pool size is small and the loss due to capacity splitting more evident. Nevertheless, when the initial quantity of low class traffic is high, SWAP equals 1P in terms of maximum amount of allocated low class lightpaths. Finally, we present the study of the computational effort required to set up a low class lightpath: the adopted metric is the average number of nodes on the auxiliary wavelength graph visited by the RWA algorithm in order to find a minimum cost path. This quantity is proportional to the time and the amount of information necessary to establish a low class lightpath.

Fig. 9 presents the results for various initial request distributions: the SWAP strategy requires a lower computational effort than single-pool strategy, because with the former the search is performed only in the separate wavelength pool, while the latter must scan the whole range of wavelengths. With the proposed approach the set up of a low class lightpath is faster and needs less network state information: then the SWAP strategy can be more effective than single-pool one to manage low-priority connections, especially in a distributed-control network, where the dissemination of network state information is not instantaneous.

5 Conclusion

In this paper the separate wavelength pool strategy for the provisioning of multiple-class optical channels has been investigated. Numerical results show that, suitably adjusting the pool sizes, the proposed method inherently differentiates the blocking performance of different lightpath classes and allows to effectively exploit the sharing of backup resources. In addition, the analysis conducted with variable low class traffic has shown that the SWAP strategy actually eliminates any impact of low class lightpath requests variation on high class lightpath blocking probability, without significantly reducing the maximum amount of allocated low class lightpaths. Finally, the wavelength set partitioning utilized by the SWAP strategy helps decreasing the computational effort necessary to find a path for low class requests.

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