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A load-balancing shared-protection-path reconfiguration approach in WDM wavelength-routed networks

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Abstract: We propose a load-balancing shared-protection-path reconfiguration approach for WDM wavelength-routed networks, using which service providers can re-optimize the network utilization to postpone network upgrades, resulting in significant cost savings.

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1. Introduction

Wavelength-routed networks (WRN) are very promising candidates for next-generation Internet and telecommunication backbones. In such a network, optical-layer protection is of paramount importance due to the risk of losing large amounts of data under a failure. To protect the network against this risk, service providers usually provide a pair of risk-independent working and protection paths for each optical connection. However, the investment made for the optical-layer protection increases network cost. To reduce the capital expenditure, service providers need to efficiently utilize their network resources. Among all the existing approaches, shared-path protection has proven to be practical and cost-efficient [1]. In shared-path protection, several protection paths can share a wavelength on a fiber link if their working paths are risk-independent.

In real-world networks, provisioning is usually implemented without the knowledge of future network resource utilization status. As the network changes with the addition and deletion of connections, the network utilization will become sub-optimal. Reconfiguration, which is referred to as the method of re-provisioning the existing connections, is an attractive solution to fill in the gap between the current network utilization and its optimal value [2]. In this paper, we propose a new shared-protection-path reconfiguration approach. Unlike some of previous reconfiguration approaches that alter the working paths, our approach only changes protection paths, and hence does not interfere with the ongoing services on the working paths, and is therefore risk-free.

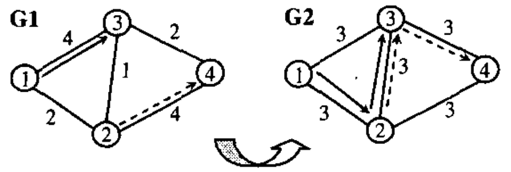
Previous studies have verified the benefits arising from the reconfiguration of existing connections [2] [3] [4]. Most of them are aimed at minimizing the total used wavelength-links or ports. However, this objective does not directly relate to cost saving because minimizing the total network resource consumption does not necessarily maximize the capability of accommodating future connections. As a result, service providers may still need to pay for early network upgrades. Alternatively, our proposed shared-protection-path reconfiguration approach is based on a load-balancing objective, which minimizes the network load distribution vector (LDV, see Section 2). This new objective is designed to postpone network upgrades, thus bringing extra cost savings to service providers. In other words, by using the new objective, service providers can establish as many connections as possible before network upgrades, resulting in increased revenue. We develop a heuristic load-balancing (LB) reconfiguration approach based on this new objective and compare its performance with an approach previously introduced in [2] and [4], whose objective is minimizing the total network resource consumption.

2. Problem statement and heuristic approach

Given a network (denoted by $G(V,E)$), the wavelength availability of the network, and a set of existing connections, the problem is to determine how to reconfigure all the existing protection paths. The objective is minimizing the load distribution vector (LDV) of the network G, denoted by LDV_G. LDV_G is defined as $LDV_G = [m_G^i]$, $(0 \le i \le W)$, where W represents the number of wavelengths on each link and m_G^i denotes the number of links that have a number i of used wavelengths. We define the relationship between two LDVs, LDV_{G1} and LDV_{G2}, as follows:

- $LDV_{G1} = LDV_{G2}$, if $m_{G1}^i = m_{G2}^i$, $\forall i : 0 \le i \le W$.
- $LDV_{G1} > LDV_{G2}$, if $\exists j : 0 \le j \le W$, such that $m_{G1}^j > m_{G2}^j$ and $m_{G1}^i = m_{G2}^i$, $\forall i : 0 \le j < i \le W$.
- $LDV_{G1} < LDV_{G2}$, if $\exists j : 0 \le j \le W$, such that $m_{G1}^j < m_{G2}^j$ and $m_{G1}^i = m_{G2}^i$, $\forall i : 0 \le j < i \le W$.

The above definition ensures that the number of links with a higher load is minimized by distributing some of their load to other links that have a lower load. By reconfiguring the existing protection paths based on this objective, the network becomes less congested so as to enhance the capability of accommodating future connections. Fig. 1 illustrates how to reduce LDV by reconfiguration as well as its benefit. The networks in Fig. 1 have 4 wavelengths on each link. The label on each link represents the number of used wavelengths. By reconfiguring the two paths (1-3) and (2-4) to (1-2-3) and (2-3-4), the network is changed from G1 to G2. Although this reconfiguration increases the total number of used wavelength-links from 13 to 15, it reduces LDV (note that $LDV_{G1}>LDV_{G2}$). After the reconfiguration, another pair of working and protection paths, (1-3-4) and (1-2-4), which could not be provisioned in G1, can be established in G2.



$$LDV_{G1} = \begin{bmatrix} m_{G1}^{0}=0 \\ m_{G1}^{1}=1 \\ m_{G1}^{2}=2 \\ m_{G1}^{3}=0 \\ m_{G1}^{4}=2 \end{bmatrix} > LDV_{G2} = \begin{bmatrix} m_{G2}^{0}=0 \\ m_{G2}^{1}=0 \\ m_{G2}^{2}=0 \\ m_{G2}^{3}=5 \\ m_{G2}^{4}=0 \end{bmatrix} \text{ (because } m_{G1}^{4} > m_{G2}^{4}\text{)}$$

Fig. 1 An illustration on how to reduce LDV by reconfiguration

We develop a heuristic approach to reduce LDV of a network by reconfiguring the protection paths iteratively on each link. We assume that each link supports a fixed number of wavelengths and each node has a full wavelength conversion capability. We only consider single-link failures. The procedure of our heuristic is described as follows:

Step 1. Compute maximum load (denoted by *max_load*) among all the links.

Step 2. Collect the set of links (denoted by *m_list*) that have *max_load* number of used wavelengths.

Step 3. For each link (i, j) in *m_list*, do:

a. Set *repeat*=0.

b. For each wavelength used by protection paths on link (i, j), do:

i. Re-provision all the protection paths that are using this wavelength on the link (i, j) (Note that LDV of the network should be reduced if this step succeeds).

ii. If Step 3.b.i succeeds, remove link (i, j) from *m_list*, set *repeat*=1, and continue Step 3 on the next link in *m_list*.

iii. If Step 3.b.i fails, continue Step.3.b on the next wavelength.

Step 4. If *repeat*=1 and *m_list* is not empty, go to Step 3.

Step 5. Set *max_load*=*max_load*-1

Step 6. If *max_load*=1, then stop. Otherwise, go to Step 2.

In Step 3.b.i, all the protection paths sharing a wavelength-link are re-provisioned one by one. We first release the resources reserved by the protection path and then apply a routing and wavelength assignment (RWA) algorithm to provision a new protection path. The RWA algorithm assigns a weight to each link in the network and finds a shortest weighted path as the new protection path. To ensure that Step 3.b.i can reduce LDV, the weight is assigned according to the following rules: (a) if the traversal of the new protection path through a link will increase LDV, assign infinity to this link; (b) if the traversal of the new protection path through a link will not increase LDV, assign a weight to the link based on a function defined by the wavelength sharing status and the number of free wavelengths on the link; (c) assign infinity to the link that is currently under reconfiguration (i.e., the link (i,j) in Step 3.b); (d) assign infinity to the links on the working path of the current connection to meet the link-diversity constraint. After the new protection path is selected by a shortest path algorithm, the First-Fit wavelength assignment algorithm is used to assign a sharable wavelength (or a free wavelength if no sharable wavelength exists) on each link of the new protection path. If any protection path on a wavelength cannot be re-provisioned, the protection paths that have been previously reconfigured on this wavelength are restored and Step.3.b.i fails. Otherwise, it succeeds.

The above reconfiguration procedure can be triggered on a periodic basis, or by some special events (e.g., an occurrence of blocking or when the number of links with a maximum load reaches a predefined threshold). Service providers can choose the desirable operation policy to trigger the reconfiguration procedure.

3. Illustrative numerical results

We conduct experiments in a mesh USA network, which has 24 nodes and 86 unidirectional links. In our experiments, we provision connection requests one by one until blocking occurs. Then, the reconfiguration procedure is triggered. After the reconfiguration, we continue to provision the connection request previously blocked. If it is still blocked, we upgrade the network by increasing the number of wavelengths on each link from *W* to *2W*. This procedure proceeds from an initial network with 4 wavelengths until the network is upgraded to have 64 wavelengths. Connection requests are uniformly distributed among all node pairs and arrive in a random order. For the simplicity of the experiments, we assume connections are semi-dynamic, i.e., a connection will not be released once provisioned. We conduct the experiments using three different provisioning schemes: minimal-hop, least-congested, and least-cost [4] [5]. Similar results are observed for these three schemes. We only show the results obtained by using the minimal-hop provisioning scheme.

We compare our load-balancing (LB) reconfiguration approach with an approach introduced in [2] and [4], whose objective is minimizing the total wavelength-links (TWL). In addition to the blocking event, we also use another event to trigger the TWL reconfiguration. This event indicates that the number of used wavelength-links reaches a certain percentage of the total number of wavelength-links. We call this approach early triggering (ET) reconfiguration approach. We compare both TWL and TWL-ET reconfiguration with the LB reconfiguration.

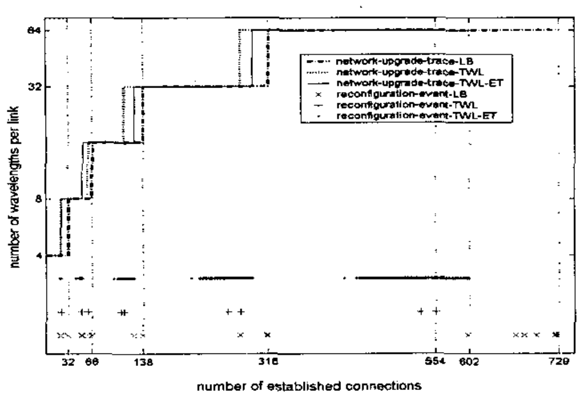


Fig. 2 Network upgrade traces and reconfiguration events.

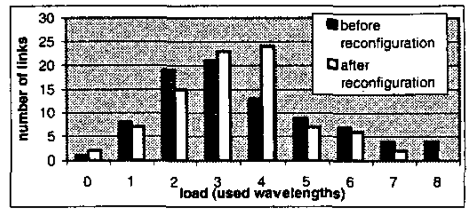


Fig. 3 Load distribution before and after a LB reconfiguration.

Wavelengths	TWL	TWL-ET	LB
4	20	20	32
8	50	50	66
16	110	124	137
32	275	292	302
64	561	601	727

Table 1. The maximum number of connections in networks with different number of wavelengths.

Fig. 2 plots the network upgrade traces and reconfiguration events of the LB, TWL, and TWL-ET reconfiguration approaches. We observe a constant delay of network upgrades by the LB reconfiguration, compared to the TWL and TWL-ET reconfiguration. We set the triggering condition of TWL-ET to be the event of consuming 40% of total wavelength-links. Compared to the TWL reconfiguration, the TWL-ET reconfiguration may delay the network upgrades at the expense of an enormous number of additional reconfigurations. However, its network upgrades still happen earlier than those of the LB reconfiguration. Fig. 3 shows the load distribution before and after one of LB reconfigurations in the network with 8 wavelengths. (Other LB reconfigurations have a similar effect.) We observe a reduction in the number of links with high loads, which corresponds to a reduced LDV.

By using a fixed number of wavelengths in the network (i.e., no upgrades are carried out), we can measure the performance of different reconfiguration approaches from another perspective. Table 1 shows the maximum number of connections that can be established in the networks with different number of wavelengths. In all the networks, the LB reconfiguration approach results in the most number of established connections. For example, the 16-wavelength network using the LB reconfiguration accommodates 25% more connections than using the TWL reconfiguration. These extra connections translate into revenue increase for service providers.

4. Conclusion

We proposed a load-balancing shared-protection path reconfiguration approach for operating WDM wavelength-routed optical networks. This approach has a load-balancing objective which is different from that of minimizing the total network resource consumption. We introduced load distribution vector (LDV) to formulate this new objective and developed a heuristic approach to realize the reconfiguration. Experimental results showed that our approach can significantly postpone network upgrades, thus resulting in revenue increase or cost savings for the network service providers. The LDV introduced in this paper only considers the networks with uniform number of wavelengths on each link. Some service providers may choose to only upgrade the high-load links for economic reasons, resulting in non-uniform link capacity. By slightly changing the definition of LDV, our load-balancing objective and heuristic approach can also be applied in this case.

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