Dynamic protected lightpath provisioning in mesh WDM networks

Guolong Zhu (祝国龙)[1], Qingji Zeng (曾庆济)[1], Tian Xu (许 田)[2],
Tong Ye (叶 通)[1], and Junjie Yang (杨俊杰)[1]

[1] *The State Key Laboratory on Fiber-optical Local Area Networks and Advanced Optical Communication Systems, Shanghai Jiao Tong University, Shanghai 200030*
[2] *Guided-Wave Optoelectronics Laboratory, Shanghai Jiao Tong University, Shanghai 200230*

Received September 20, 2004

This paper investigates the problem of dynamic protected lightpath services provisioning in optical mesh networks employing wavelength division multiplexing (WDM). A variety of schemes for dynamic protected services provisioning have been proposed, supporting a range of tradeoffs among restoration speed, capacity efficiency, and scalability. In this paper, we propose a novel scheme, called p-cycles-based maximum protected working capacity envelope (PC-MPWCE), which can offer an attractive combination of features: ring-like speed, mesh-like capacity efficiency, and good scalability. To evaluate the performance of PC-MPWCE, we compare it via simulation with $1+1$ automatic protection switching (APS) and two well-known shared backup path protection (SBPP) on NSFNET. Our simulation results show that PC-MPWCE can achieve much better blocking performance than $1+1$ APS, and perform the similar blocking performance and capacity efficiency as SBPP.

OCIS codes: 060.4250, 060.4510.

The Internet infrastructure is evolving towards the network architecture that employs the wavelength division multiplexing (WDM) technology for providing sufficient transmission bandwidth. Future WDM mesh networks are foreseen to be more dynamic and sensitive to failures. Therefore, dynamic service provisioning and network survivability become two critical issues for network planning and management[1].

In designing a survivable network, the major challenges to be addressed are how to allocate minimal amount of spare capacity using scalable scheme, and in case a failure occurs, it is able to quickly recover by re-routing affected traffic using the spare capacity. These issues are challenging because restoration speed, capacity efficiency, and scalability are often in conflict with each other. A variety of schemes have been proposed for dynamic protected service provisioning, supporting a range of tradeoffs among restoration speed, capacity efficiency, and scalability.

Clearly, it is important to achieve faster restoration after a failure, but schemes achieving this usually do so at the expense of network resource utilization. For example, $1+1$ automatic protection switching (APS) usually uses a large amount of dedicated spare capacity and thus is not a cost-effective solution for most customer applications[2].

Unlike $1+1$ APS, shared backup path protection (SBPP) allows multiple failure-independent connections to share backup links and hence reserves less capacity. However, in SBPP, the path is pre-computed on a demand's arrival but only configured after a failure occurrence. Traditionally, path setups follow a protocol involving signaling, acknowledgements, and cross-connect setups. These operations take much longer than the required 50 ms because of signal transmission delays, slow optical cross connects (OXCs), and signal processing overheads, making the scheme non-viable for many real-time services.

Many studies show that p-cycles can achieve the benefits of both ring-based protection and mesh-based restoration[2,3]. But most previous work only focused on the optimization of p-cycles for static traffic where a traffic demand matrix is known a priori. Here, we focus our attention on using p-cycles to protect dynamic traffic.

Another key issue in WDM networks is the scalability. In SBPP, both working and backup paths must be determined in the service provisioning process, link state information (such as topology, resource availability and sharability) needs to be distributed throughout the network, and an up-to-date sharability database needs to be maintained at each node to reflect the sharability information about local resources. Therefore, if connection requests for setting up lightpaths have high arrival and departure rates, the scalability problem is incurred at once[4]. However, in the new concept of protecting working capacity envelope (PWCE)[5], the physical total capacity is divided into two parts: spare capacity (S_i) and protected working capacity (W_i). An example of PWCE is shown in Fig. 1. The protected working capacity in each span creates a capacity envelope within which a vast number of simultaneously provisioned paths are inherently protected without any further consideration or even checking. In PWCE, service provisioning is simplified to the equivalent of routing a new path in a previously non-protected network of point-to-point transmission systems.

In this paper, we propose a novel scheme, i.e., p-cycles-based maximum PWCE (PC-MPWCE), for provisioning of dynamic protected lightpath services against any single-span failure. The proposed PC-MPWCE performs the following:

1) The maximum PWCE (MPWCE) in a given network is determined by an integer linear programming (ILP) model. This is an offline step.

2) Each lightpath request is routed via its shortest path in the MPWCE. This is an online step.

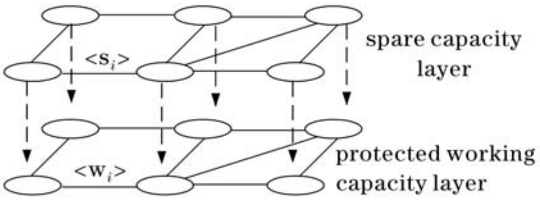

Fig. 1. An example of PWCE.

A WDM network is modeled as a directed graph $G(V, E)$ where V is the set of WDM nodes and E is the set of edges (i.e., spans). Each edge k has F_k unidirectional fibers, and each fiber contains W wavelengths. A unit of capacity is referred to as one wavelength channel. Therefore, edge k has a capacity of $C_k = F_k \times W$. In this paper, we consider unidirectional working demands and unidirectional p-cycles as shown in Fig. 2. The network is assumed to be a virtual wavelength path (VWP) WDM networks where all nodes can perform full wavelength conversion.

Notation of the ILP model are as follows: (1) S: set of spans, indexed by i (failed) or k (surviving); (2) P: set of candidate p-cycles, indexed by j; (3) C_k: total unit of capacity on span k; (4) $\gamma_{j,i}$: equal to 1 if the working capacity on span i is protected by cycle j, 0 otherwise; (5) $\delta_{j,k}$: equal to 1 if span k is an on-cycle span of cycle j, 0 otherwise. The variables of the ILP model are: (1) w_k: number of unit-capacity copies of protected working capacity on span k; (2) s_k: number of unit-capacity copies of spare capacity on span k; (3) n_j: number of unit-capacity copies of cycle j.

The objective function is formulated as

$$\text{maximizing} \sum_{k \in S} w_k, \tag{1}$$

$$\sum_{j \in P} \gamma_{j,i} \cdot n_j \geq w_i, \quad \forall i \in S, \tag{2}$$

$$\sum_{j \in P} n_j \cdot \delta_{j,k} = s_k, \quad \forall k \in S, \tag{3}$$

$$w_k + s_k \leq C_k, \quad \forall k \in S. \tag{4}$$

The Eq. (1) is to maximize the PWCE, which is possible to accommodate future dynamic lightpaths, regardless of the actual traffic pattern. Constraint of Eq. (2) ensures that affected working flows upon a span failure must be fully restored. Constraint of Eq. (3) guarantees that there are sufficient resources reserved on the on-cycle span k of cycle j to protect against any single span failure. Constraint of Eq. (4) ensures that the sum of working and spare capacity on an on-cycle span does not exceed the amount of capacity on the span. All variables are nonnegative integers.

Note that both the working capacity and the spare capacity on a span are variables in our ILP model, which is distinguished from previous work. $\gamma_{j,i} \in \{0, 1\}$ indicates if the unidirectional p-cycle j can protect the working capacity in the span i. $\gamma_{j,i}$ can not be 2 because a unidirectional p-cycle j can only provide one restoration path when a straddling span i fails as shown in Fig. 2(b). However, the straddling span i can be protected by two counter directional p-cycles, so the capacity efficiency of p-cycles can be still maintained[6].

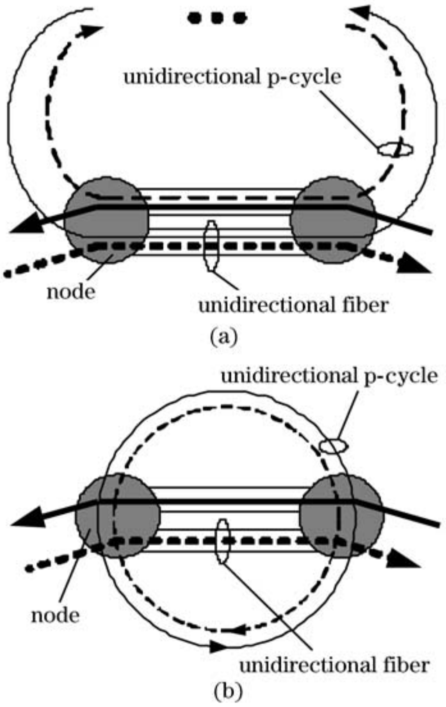

Fig. 2. Use of unidirectional p-cycles to protect on-cycle span (a) and straddling span (b).

A vast number of simultaneously provisioned working paths can be accommodated within the static distributed MPWCE, and be protected by the p-cycles determined by the ILP model. Since the concept of p-cycles breaks the challenging tradeoff between restoration speed and spare capacity efficiency, and the concept of PWCE breaks the challenging tradeoff between scalability and spare capacity efficiency. Therefore, the combination of p-cycles and PWCE can inherently achieve fast restoration and good scalability. But can PC-MPWCE achieve good blocking performance and high capacity efficiency for provisioning dynamic protected lightpath services? In order to answer the question, we will quantitatively evaluate our approach.

We simulate a dynamic network environment with the assumptions that the lightpath arrival process is Poisson and the lightpath holding time follows a negative exponential distribution (whose average value is normalized to unity in this paper). For the illustrative results shown here, 10^6 lightpath requests are simulated, which are uniformly distributed among all node pairs. All the nodes have full wavelength-conversion capability. Each span has two fibers running in opposite directions, and each fiber has $W = 16$ wavelengths. The cost of any span is unity. The NSFNET network shown in Fig. 3 is used in our simulations.

A key measure of performance in dynamic WDM networks is the blocking probability. Figure 4 compares the blocking probability of PC-MPWCE to 1 + 1 APS, the shortest path restoration (SPR), and full information restoration (FIR)[7] on NSFNET. Based on the results, we have several observations as follows:

1) PC-MPWCE has much lower blocking probability

than 1 + 1 APS.

2) When the network load is modest or low, PC-MPWCE can achieve lower blocking probability than SPR.

3) FIR always has the lowest blocking probability.

That is to say that the blocking performance of PC-MPWCE is significantly improved compared to 1 + 1 APS, and is very close to that of SBPP. The simulation results show that PC-MPWCE can even achieve lower blocking probability than SPR when the network load is modest or low. Moreover, the failure traffics are protected by p-cycles in PC-MPWCE, so they could be recovered with ring-like speed (because p-cycles are fully pre-planned and only two nodes do real-time switching when a failure occurs).

One figure of merit for comparing capacity efficiency is restoration overbuild, defined as the ratio of the total backup capacity to the total working capacity[7]. Restoration overbuild implies how much extra capacity is needed to satisfy the network restoration objective for single failure protection. Figure 5 compares the restoration overbuild of PC-MPWCE to 1 + 1 APS, SPR, and FIR in NSFNET. In PC-MPWCE, the amount of backup capacity is determined offline for protecting the maximum potential lightpaths requests. For example, the amount of backup capacity in NSFNET is a constant (i.e., 224). The low bound of restoration overbuild of PC-MPWCE is referred to as the total backup capacity over the maximum potential working capacity as shown in Fig. 5. We observe that the restoration overbuild of PC-MPWCE is high when the network load is low. The main reason is that the amount of backup capacity in PC-MPWCE is overstocked when the network load is low. However, the restoration overbuild of PC-MPWCE is much lower than that of 1 + 1 APS, when the network load is high. PC-MPWCE can achieve similar restoration overbuild as SBPP when the network resource becomes deficient.

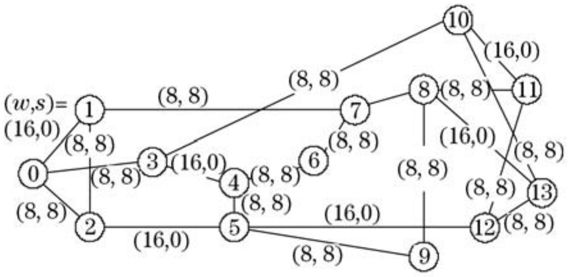

Fig. 3. NSFNET network: 14 nodes, 21 bi-directional spans, 278 candidate unidirectional cycles. The bracket by each span gives the number of PWCE and the number of spare capacity on the unidirectional span.

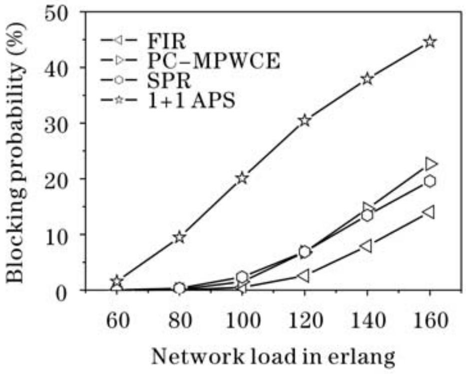

Fig. 4. Network load versus blocking probability in NSFNET.

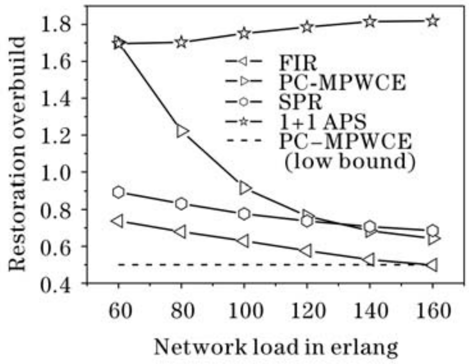

Fig. 5. Network load versus restoration overbuild in NSFNET.

When the network load is low, network has large amounts of excess capacity. In such a case, the restoration overbuild of a scheme is not statically significant. However, when the network load is high, network resource becomes deficient, so the schemes with lower restoration overbuild may achieve better network performance. That is, the restoration overbuild of a scheme becomes more important when the network resource becomes insufficient. Therefore, PC-MPWCE can achieve similar capacity efficiency as SBPP.

In summary, results show that PC-MPWCE can achieve similar restoration speed as 1 + 1 APS, but much better blocking performance and capacity efficiency than 1 + 1 APS. The blocking performance and capacity efficiency of PC-MPWCE are very close to those of SPR and FIR. Nevertheless, SPR and FIR have much slower restoration speed than PC-MPWCE, and may suffer from scalability issues. Thus PC-MPWCE is a fast, capacity-efficient, and scalable scheme for dynamic protected lightpath services provisioning in mesh WDM networks.

This work was supported by the National Natural Science Foundation of China under Grant No. 69990540 and 90304002. G. Zhu's e-mail address is guolongzhu@sjtu.edu.cn.

References

1. P.-H. Ho and H. T. Mouftah, IEEE Communications Magazine **42,** 70 (2004).
2. W. D. Grover and D. Stamatelakis, in *Proceeding of ICC 1998* 537 (1998).
3. G. Zhu, Q. Zeng, T. Ye, and J. Yang, Chin. Opt. Lett. **2,** 508 (2004).
4. P.-H. Ho and H. T. Mouftah, IEEE Network **16,** 29 (2002).
5. W. D. Grover, IEEE Communications Magazine **42,** 62 (2004).
6. D. Schupke, C. G. Gruber, and A. Autenrieth, in *Proceedings of ICC* **5,** 2761 (2002).
7. G. Z. Li, D. M. Wang, C. Kalmanek, and R. Doverspike, in *Proceeding of INFOCOM* **1,** 140 (2002).