Protection switching schemes of multi-granularity p-cycles in survivable WDM networks

Guolong Zhu (祝国龙), Qingji Zeng (曾庆济), Tong Ye (叶 通), and Junjie Yang (杨俊杰)

The State Key Laboratory on Fiber-optical Local Area Networks and Advanced Optical Communication Systems,
Shanghai Jiao Tong University, Shanghai 200030

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In this paper, a novel concept of multi-granularity p-cycle is proposed. In conventional p-cycle concept, all on-cycle spans have the same capacity. However, in multi-granularity p-cycle, each on-cycle span could have different capacity. Results show that multi-granularity p-cycles are much more capacity-efficient and cost-effective than conventional p-cycles. We also propose two protection switching schemes for all types of p-cycle networks. One is wrapping protection, in which only two end nodes do real-time switching when a span failure happens. The other is steering protection, in which at most four nodes do real-time switching when a span fails. In steering protection switching scheme, the restoration path for the failure traffic demand has the least hops.

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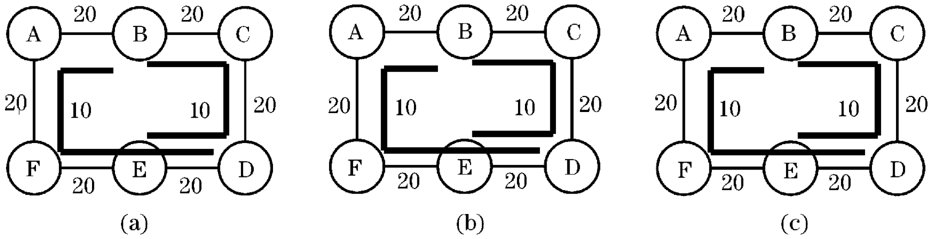
Up to the p-cycles concept was introduced by Grover and Stamatelakis in 1998[1], it seems that 100% redundancy is the inherent "price" that one has to pay to support 50 ms switching. Only rings, ring covers, or 1+1 automatic protection switch (APS) can support that type of fully preconfigured switching, and they are all at least 100% redundant. p-cycles are remarkable and interesting because they combine the real-time switching simplicity and speed of rings with mesh-like efficiency and the flexibility and freedom of a mesh in the routing of working paths. p-cycles offer a promising approach to network survivability, which are applicable to a great variety of network types such as IP, multiprotocol label smtching (MPLS)[2], synchronous optical network (SONET), automatic switched optical networks (ASON) and wavelength division multiplexing (WDM) networks[3]. There are many ongoing research activities to study network survivability using p-cycles. However, there is no formal protection switching scheme has been proposed. It is just suggested that, when a span failure happens, only two end nodes do real-time switching[1−6]. Based on past work, we propose a protection switching scheme, "wrapping protection", in which only two end nodes do real-time switching when a span failure happens. Here we also propose a new scheme, steering protection. There are at most four nodes do real-time switching for a traffic demand in the scheme. Another contribution of this paper is that a novel concept of multi-granularity p-cycles is proposed. Unlike conventional p-cycles, each on-cycle span of multi-granularity p-cycles could have different capacity. The concept of multi-granularity p-cycles can be used in span-protecting (SP) p-cycles[1] using wrapping protection and flow p-cycles[4] using steering protection. The former is called as multi-granularity span-protecting (MS) p-cycles. The latter is called as multi-granularity flow (MF) p-cycles.

There exist three basic types of p-cycles. SP p-cycles can protect on-cycle spans and straddling spans. Node-encircling p-cycles[3] can protect a node failure by providing an alternate path among all of the nodes which are adjacent to the failed node. Flow p-cycles[4] can provide path protection or protection of any flow segment along a path, as well as the original span protecting use of p-cycles.

In conventional p-cycles, each on-cycle span has the same capacity. However, in multi-granularity p-cycles, each on-cycle span could have different capacity. In Fig. 1, there are two traffic demands, one is between node B and D, and the other is between node B and E. Both of two traffic demands have 10 capacity units. Figure 1(a) displays a conventional SP p-cycle, whose each on-cycle span has the same capacity of 20. However, the capacity of each on-cycle span of MS p-cycle (Fig. 1(b)) and MF p-cycle (Fig. 1(c)) is different. Note that the on-cycle span D-E will not be used for restoration in Fig. 1(c), so its capacity could be zero. We call such span as a virtual span of p-cycle.



(a) (b) (c)

Fig. 1. Comparison of conventional p-cycle (a), MS p-cycles (b), and MF p-cycles (c).

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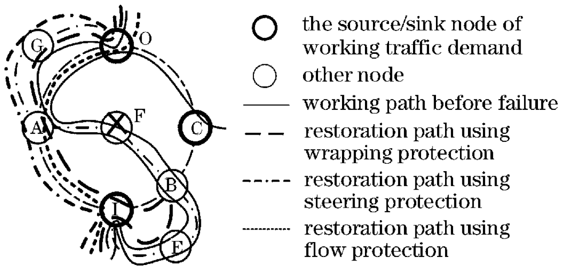


Fig. 2. Comparison of flow protection, wrapping protection and steering protection.

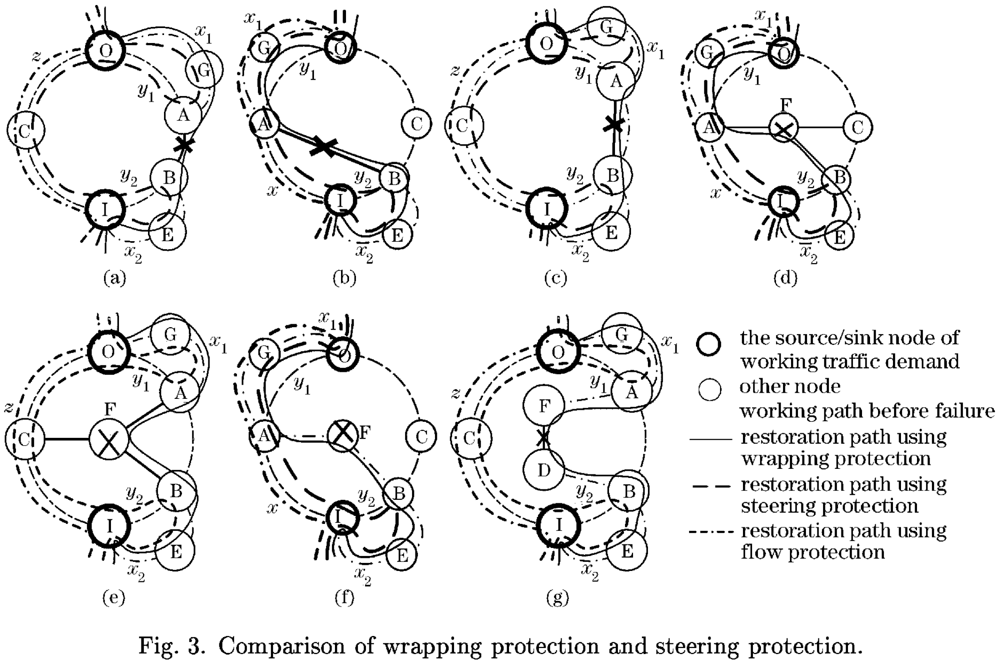
Comparing with conventional p-cycle, the total capacity of MS p-cycle is reduced by 8.3%, and that of MF p-cycle is reduced by 58.3%. Note that, comparing with SP p-cycle, MS p-cycle is more capacity-efficient, but has the same protection speed because the same protection scheme is used.

In this paper, the node where the traffic flow first enters a cycle is defined as source node (node I in Figs. 2 and 3). The node where the traffic flow last leaves a cycle is defined as sink node (node O in Figs. 2 and 3). The end node of the failure straddling span or the failure straddling flow[4], is defined as before node (node B in Figs. 2 and 3) if it is close to the source node, while as after node (node A in Figs. 2 and 3) if close to the sink node. It is possible that the before node happens to be the source node and the after node happens to be the sink node.

A switching method is suggested in Ref. [4], which is called as flow protection here. The scheme suggested that the source node and the sink node should be responsible for the restoration. In fact, more than two nodes may need to do protection switching, because different traffic flow may have different source node and sink node. Figure 2 shows a comparison of wrapping protection, flow protection, and steering protection. In the figure, there are two flows, one is I→E→B→F→A→G→O, and the other is I→E→B→F→A→O→C. We assume that node F fails. While using flow protection, nodes I and O are responsible for doing switching for recovering flow I-O, and nodes I and C are responsible for doing switching for recovering flow I-C. That is, more than two nodes need to do switching. Therefore, the method is not consistent with that in SP p-cycles and node-encircling p-cycles[3] where only two nodes do switching for a failure. In order to develop a protocol for all existing types of p-cycles conveniently, we propose a wrapping protection switching scheme, which is fit for all types of p-cycles. In the wrapping protection, only the end nodes (nodes A and B) of straddling flow should be responsible for doing switching for recovering both flow I-O and I-C. While using steering protection, nodes I, O, A and B will be responsible for doing switching for recovering flow I-O, and nodes I, A, B and C will be responsible for doing switching for recovering flow I-C.

In sum, wrapping protection is the simplest one to operate. Given flow is routed via its shortest path, path segment A-G-O will not be longer than path segment A-O, so the restoration path using steering protection will have the least hops. That is, steering protection can reduce time delay for those real-time application services, and improve the quality of optical signal in WDM networks. In the next section, we will focus on wrapping protection and steering protection only.

Figure 3 illustrates the difference between wrapping protection and steering protection in SP p-cycle (Fig. 3(a) protecting an on-cycle span failure, and Figs. 3(b) and (c) protecting a straddling span failure), node-encircling p-cycle (Figs. 3(d) and (e)), and flow p-cycle (Figs. 3(a)−(g)). Briefly, in Figs. 3(b), (c), (d), (e), (f) and (g), only one of the two alternative restoration paths is illustrated. For example, in Fig. 3(b), there are two restoration paths (I-A-G-O and I-E-B-C-O) for the traffic demand passes through the failure straddling span (A-B) using steering protection. In the figure, the former is illustrated, but the latter not.



(a) (b) (c) (d) (e) (f) (g)

Fig. 3. Comparison of wrapping protection and steering protection.

In Fig. 3, the failure traffic demand passes nodes I, E, B, D (in Fig. 3(g)), F (in Figs. 3(d), (e), (f) and (g)), A, G, and O, sequently. Nodes I, B, A, O, and C are on-cycle node. Nodes E and G (F and D in Fig. 3(g)) may be on-cycle node, but node F (Figs. 3(d) and (e)) must not be on-cycle node. The number of on-cycle hops between nodes I and B is $y2$. That is $y1$ between nodes O and A. That is z among nodes I, C, and O. That is x between nodes A and I (Figs. 3(b), (d) and (f)). The number of hops of the failure traffic demand among nodes I, E, and B is $x2$. That is $x1$ among nodes A, G, and O.

For those real-time application services, time delay is required not exceeding a certain value, and for transparent optical networks, a lightpath can be attenuated too much if the p-cycle length becomes too long after protection switching. Therefore, p-cycles length restriction is important, and the impact of physical length limits of cycles has been evaluated in Refs. [2, 3]. Comparing with wrapping protection, the number of hops reduced by steering protection is defined as RHops. For a failure traffic demand, RHops $= x1 + y1 + x2 + y2$, as shown in Fig. 3. The number of hops of the p-cycle is defined as CHops. Let the number of hops of the straddling flow between nodes A and B be N. In Figs. 3(a), (b), and (c), $N = 1$. In Figs. 3(d) and (e), $N = 2$. We will find that the upper bound of RHops in different type p-cycles is RHops $\le$ CHops $- 2 \cdot N$. To limit the length of the paper, the proof is skipped here.

To be simple and clear, we assume that traffic demands are routed via their shortest paths. Our objective is to minimize total spare capacity in the p-cycles and reduce the hops of restoration paths. An integer linear programming (ILP) model is formulated for design of multi-granularity p-cycles in virtual wavelength path (VWP) WDM networks. The nodes in VWP WDM networks perform full wavelength conversion. Where S is set of spans in the network. P is set of candidate p-cycles. D_i is set of end-node pairs affected by failure of span i. cost_k is cost of adding a unit capacity to span k. s_k and w_k are the number of working and spare units on span k, respectively. c_k denotes capacity of span k. d^r is number of demand units on node pair r. $\gamma^r_{i,j}$ is 0 if flow r can not be protected by cycle j upon span failure i. It is 1 if the failure span i is both in intersecting flow r and cycle j, and 2 otherwise. $\delta^r_{i,j,k}$ is 1 if span k is an on-cycle span of cycle j which is used to protect the failure span i of demand pair r, and 0 otherwise. $n_{j,k}$ is number of unit-capacity copies of on-cycle span k of cycle j. $n^r_{i,j}$ is number of copies of cycle j that are needed specifically for protection of path r against the failure of span i. The model is formulated as follows:

$$\text{Minimize} \sum_{k\in S} \text{cost}_k \cdot s_k, \tag{1}$$

subject to

$$d_r \le \sum_{j\in P} \gamma^r_{i,j} \cdot n^r_{i,j} \qquad \forall i \in S; \forall r \in D_i, \tag{2}$$

$$n_{j,k} \ge \sum_{r\in D_i} n^r_{i,j} \cdot \delta^r_{i,j,k} \qquad \forall i \in S; \forall j \in P; \forall k \in S, \tag{3}$$

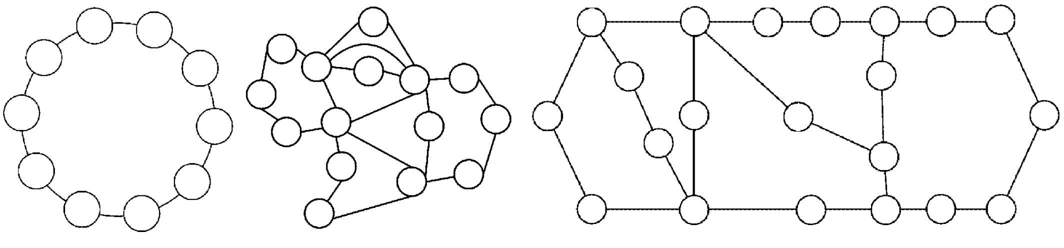
$$s_k = \sum_{j\in P} n_{j,k} \qquad \forall j \in P; \forall k \in S, \tag{4}$$

$$c_k \ge w_k + s_k \qquad \forall k \in S. \tag{5}$$

The objective (1) is to minimize the total cost of spare capacity. Constraint (2) ensures that affected working flows upon a span failure must be fully protected. Constraint (3) says that the number of copies of on-cycle span k of cycle j to build is set by the largest failure-specific simultaneous use for unit copies of on-cycle span k of cycle j. Constraint (4) determines the spare capacity allocation. Constraint (5) introduces the capacity restriction on a span.

To compare different p-cycle designs, we select a 10-node ring, pacific bell, and ARPA2 as test cases. The names for reference and other characteristics are shown in Fig. 4. We assume that each node performs full wavelength conversion, each span has 8 fibers for bi-directional transmission, and the number of wavelengths per fiber is 128. The cost for each wavelength channel on each span is 1. The number of lightpaths required is generated for all node pairs from a uniform random distribution on Refs. [1−10]. The ILP is solved by LP Solver. The simulation results are shown in Table 1. For each test network, column 1 describes the SP p-cycle designs, column 2 shows the MS p-cycle design, column 3 details the design of flow p-cycle using wrapping protection, column 4 shows the design of flow p-cycle using flow protection, and column 5 displays the MF p-cycle designs. All designs for each network have the identical working capacity and demand routing.

Results show that MS p-cycles can improve a little comparing with conventional SP p-cycles, but MF p-cycles are more capacity-efficient and cost-effective than SP p-cycles and flow p-cycles[4], especially, in the ring or some



N=10, S=10, |P|=1
10-node Ring

N=15, S=21, |P|=40
Pacific Bell

N=14, S=21, |P|=18
ARPA2

Fig. 4. Network topologies for simulation.

Table 1. Summary of Results for Capacity Comparisons

	10-Node Ring					Pacific Bell					ARPA2				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Spare Capacity	1	98.4%	1		78.4%	1	98.2%	1		86.3%	1	1	85.4%		78.8%
Number of p-Cycles Chosen	1	1	1		1	6	8	11		18	9	10	9		12
Average Number of Hops of Restoration Paths	11.4	11.4	11.4	6.60	6.60	10.63	10.20	9.94	7.13	6.67	15.08	15.49	14.58	10.37	9.72

other networks (i.e., Pacific Bell). Results also show that MF p-cycles can yield significant reductions in average number of hops of restoration paths relative to conventional p-cycles.

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