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Significant Impact of P-cycles on Survivable WDM Optical Network

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ABSTRACT

It is known that Wavelength division multiplexing (WDM) technique enables single fiber to carry huge amount of data but optical WDM networks are prone to failures, therefore survivability is a very important requirement in the design of optical networks. In this paper, a comprehensive review about survivability of WDM networks has been discussed focusing on scalable and efficient p-cycles resilience techniques and a comparative analysis particularly among ring and mesh resilience techniques has been performed. In the context of network survivability, p-cycle based schemes attracted extensive research interests as they maintain balance between recovery speed and capacity efficiency. It is observed that p-cycles are key to obtain mesh-like network efficiency from a ring-like protection.

Keywords: Survivability, WDM, P-cycles, Restoration, Resilience

1. INTRODUCTION

In WDM optical networks, the failure of a network component such as a fiber link can lead to severe disruption in the networks traffic as WDM networks may carry huge amounts of traffic. Hence, providing resilience to failure is very essential in WDM optical networks. Pre-configured protection cycle (p-cycle) resilience techniques are well balanced in terms of recovery speed and capacity efficiency among various optical protection techniques leading to survivable WDM networks [1]. In comparison to conventional techniques, p-cycle protection provides greater resilience and capacity efficiency with less computational time.

The resilience techniques in optical networks are broadly classified into protection and restoration depending on the allocation of spare capacity. They are further divided into link and path-based resilience. Restoration dynamically discovers backup paths in the network after a link fails. It is more efficient in term of capacity utilization than protection.

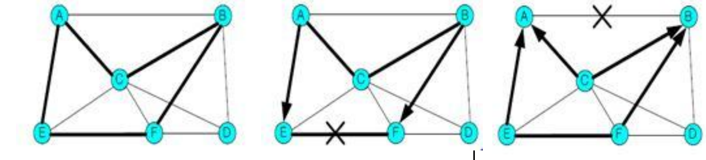
In the dynamic restoration computation time is a challenging problem. As a comparison of computation time between path restoration and link restoration, S. Ramamurthy et al. [2] shows that link restoration is faster than path restoration but in terms of spare capacity utilization path restoration is more efficient than link restoration [3]. In Path restoration, an alternative path is immediately determined from the source node to the destination node when a failure occurs [4]. In link restoration, spare capacity is reserved at the time of failure and it dynamically discovers a backup channel around the adjacent nodes of the failed link. Thus, it offers efficient capacity utilization and thus network failure can be recovered through any number of reserved channels.

In Protection based technique when a network fails, the working path is switched to the reserved path which should be disjoint from the corresponding working path. It is more efficient in capacity utilization compared to link based survivable techniques as it only needs spare capacity for the whole reserved path instead of every link along the path [5]. In link protection, all alternative paths have been already reserved when the working path is computed. Thus, restoration time is faster than path based survivability which requires a longer time to generate a fault notification message [6].

2. PRE-CONFIGURED PROTECTION CYCLE

Pre-configured protection cycle (p-cycle) has been developed as a hybrid of the ring and the mesh protection mechanisms. P-cycle has the advantage of the fast restoration time from ring topology and the high capacity efficiency from mesh topologies [7]. It is based on closed cyclic routes. However, unlike the ring mechanism which only protects the working channels on the ring, the p-cycle method offers useful backup paths for protecting the straddling links as well as the on-cycle links[8]. A straddling link of a p-cycle is a link which does not belong to that cycle but whose end-nodes lie on the p-cycle[9].

Figure 1(a)[5] illustrates a p-cycle (A-C-B--F-E-A). An alternative path for the failure of an on-cycle link provides a single restoration path as shown Figure 1(b)[5] but when straddling link (A-B) fails, the two nodes spanning the failed link are switched to the alternative path and capacities are reserved in both directions along the cycle by the p-cycle and thus the p-cycle method provides two alternative paths for the failure as shown in Figure 1(c)[5].



(a) an individual p-cycle	(b) failure of on-cycle link	(c) failure on straddling link

Figure 1: P-cycle contribution on an alternative path.[5]

2.1 Hamiltonian Cycles

A Hamiltonian cycle is a cycle that traverses each node in the network exactly once. It has the characteristic of having the minimal number of links among all survivable topologies which has two consequences (i) it reduces spare link capacity (ii) it collapses spare resources into a minimal set of links, which facilitates aggregate protection switching upon network element failures[10].

Only two nodes adjacent to the failure are involved in the recovery, so Hamiltonian cycle protection (HCP) is simple and robust. Hamiltonian p-cycles have been investigated by Stamatelakis and Grover [11]. It is a single large p-cycle that travels over every node exactly once as shown in Figure 2[12].

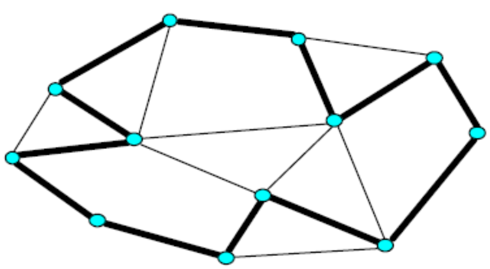
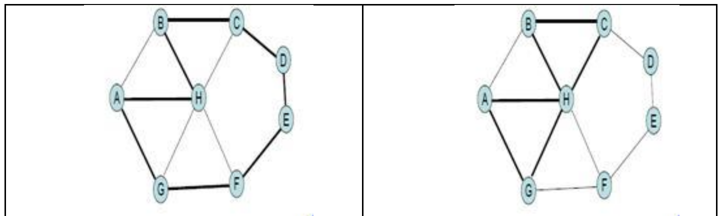


Figure 2*:* A single Hamiltonian p-cycle[12]

That means the circumference is N in a network of N nodes. The Hamiltonian *p*-cycle can achieve lower bounding redundancy by (1/$\bar{d}$ - 1) for any type of span restorable mesh network [12], where $\bar{d}$ is the average nodal degree. Thus, a Hamiltonian *p*-cycle is the most efficient overall solution, theoretically. However, a set of p-cycles including small cycles in general provides better solution for reducing the spare capacity. For example, where there exist two spans with unprotected working capacity in the network, a Hamiltonian p-cycle wastes other spare capacity to protect two spans where these two spans may be protected by a single small cycle. Thus, small cycles are needed to achieve the best performance. Heydari et. al [13] investigates why a Hamiltonian p-cycle is far from optimal and found that a Hamiltonian p-cycle requires over 100% redundancy.

2.3 Non-Simple P-cycles

Non-simple p-cycles have been proposed by Gruber [14]. They are needed in order to achieve good performance when a there is not enough capacity available for full protection. Non-simple p-cycles permit a node to be visited twice.



(a)Convential P-Cycle	(b) Non-Simple P-Cycle

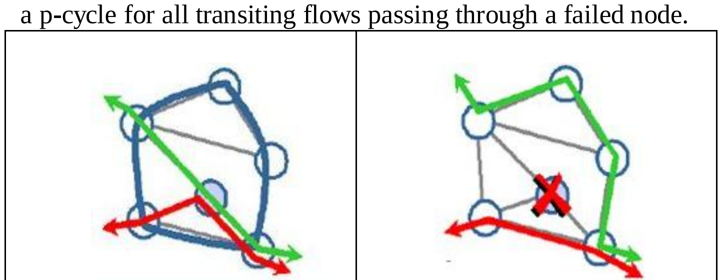
Figure 3: Non-Simple P-Cycle Protection.[15]

Figure 3[15] shows that when link A-B fail, the conventional p-cycle is not the best choice for protection because only the conventional p-cycle (A-H-B-C-D-E-F-G-A) which should traverse every node is available. However, the non-simple p-cycle is able to find a small cycle (A-H-B-C-H-G-A) to cover the failure so that it reduces the spare capacity. Their simulation results show that non-simple p-cycles reduce the redundancy when compared to conventional p-cycles. However, the number of candidate p-cycles needed for protection is increased, therefore the computation time required is longer.

2.2 Node Encircling P-cycles (NEPCs)

Protect against node failures can be provided by encircling all the neighbors of the node to be protected by a node encircling p-cycle. When node fails, all connections passing through that node effectively become straddling spans of the cycle and hence protected. It may not be possible to use simple cycles for node encircling in such a case, thus we can use a non simple cycle to do node encircling.

In Node Encircling P-Cycle all neighbouring nodes (i.e., those directly connected to it with a span) of the protected node are crossed by the *p*-cycle, but the protected node itself is not crossed by p-cycle, as shown in Figure 4(a)[16]. This type of p-cycle offers two routes around which any affected node may be re-routed to survive the failure as shown in Figure 4(b)[16]. Node protection itself inherently involves an effort at restoration only of the affected transiting paths through a failed node. In span protecting models the same set of backup paths residing within a p-cycle are used to provide recovery routes for all working demands affected by a span failure[17]. Node protection involves finding a unique set of backup paths within a p-cycle for all transiting flows passing through a failed node.



(a) Neighbouring Nodes	(b) Route To Survive The Failure crossed By P-Cycle

Figure 4: Node Encircling P-Cycle[16]

2.4 Failure Independent Path- Protection(FIPP) P-cycles

A commonly used method to provide protection in optical networks is shared backup path protection (SBPP). There are however some issues with SBPP, for example when a fault occurs there is signaling time involved to make the required cross connections. FIPP is an improvement over this. Protection paths along FIPP p-cycles are fully pre-cross connected. In case of failure, only the two end nodes of a failed path perform real-time switching. FIPP p-cycles therefore retain the ring-like recovery speed. FIPP p-cycles can protect on-cycle working paths as well as straddling working paths. For each on-cycle working path, a FIPP p-cycle provides one protection path; for each straddling working path, a FIPP p-cycle can offer two protection paths. FIPP p-cycles are therefore very suitable for protection of WDM networks where the detection of light loss is awkward.

A network instance and a FIPP p-cycle is presented in Figure 5(a)[18]. Upon a link failure, e.g., link a-c shown in Figure 5(b)[18], the end nodes of the failed working path i.e. a-c, switch failed connection to protection path a-b-d-c. Upon a straddling path failure, as shown in Figure 5(c)[18], the end nodes of the failed working path i.e. a-e-f-d perform end-to-end switching to protection paths a-b-d and a-c-d. Two units of working paths can thereby be recovered. The basic principle behind FIPP is that we allow a p-cycle in a network to only protect a group of flows that are vertex disjoint in nature[19].

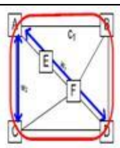
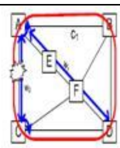
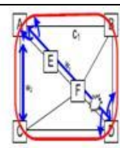
		
(a)Network Instance	(b) On-Cycle Path Failure	(c)Straddling Path failure and FIIP P-Cycle

Figure 5*:* Failure Independent Path-Protection P-cycles[18]

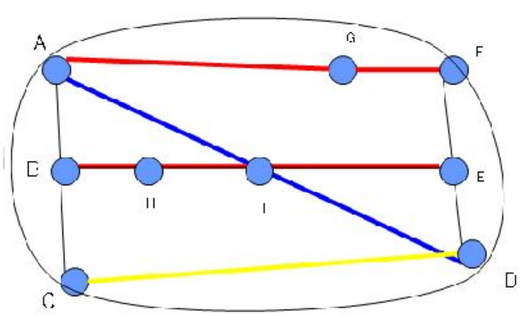


Figure 6: Two different cycles in FIPP[19]

AGFEDCBA and AFDCA are the two cycles shown in the Figure 6[19]. FIPP simply shows that cycle AGFEDCBA can protect all flows on paths AGF, BHIE, CD since these are mutually vertex disjoint. However if later there is a flow A-I-D, it cannot be protected by the same cycle in spite of fact that it is straddling on it, since it is not vertex disjoint So to protect A-I-D we need another p-cycle, AFDCA. In this case assuming single link failure, it is clear that all flows are protected and the failure path is known in advance and hence can be tested

2.5 Flow P-cycles

Shen and Grover in [20] proposed the concept of path - segment protecting p-cycles (flow p-cycles for short) in which a working segment is defined by a sequence of contiguous links on a working path (but not necessarily routed on the same wavelength). Here, a working segment is a set of contiguous links of a working path such that the signal carried on the segment remains in optical domain and undergoes optical-electrical-optical conversion only at end nodes. This suggests that protection switching is only performed at the end nodes of working segments.

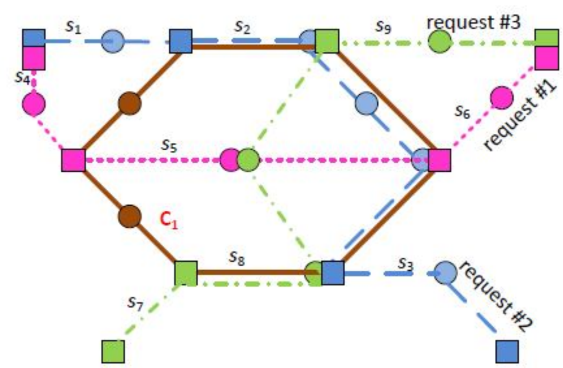


Figure 7: shows Flow p-cycles[20]

Figure 7[20] shows that for segment s2 of request #2 (blue dashed line) all its links and intermediate nodes are protected by its complement part in the *p*-cycle. Straddling segments e.g. segment s5 of request #1 (pink dotted line) have all its links and intermediate nodes protected by the two halves of the *p*-cycle defined by the end points of s5, meaning that one unit of *s*5 is provided two protection units by the p-cycle. Hybrid segments, e.g. s8 of request #3 (green dash-dot line) have all its links and intermediate nodes protected by p-cycle arc delimited by its two endpoints, which does not contain any link of s8.

3. COMPARISON ANALYSIS

P-cycle unlike any ring-based systems that we know of to date protect both on-cycle and straddling failures. This initially seems to be a rather minor difference but when its implications are fully worked through it turns out to be the key to obtaining mesh-like network efficiency from a ring-like protection structure. P-cycles are formed from individual spare links (or channels) of the point-to-point n systems present, whereas rings commit a whole n module of working and spare capacity to the same cycle. The ring protection method uses simple mechanism where only two nodes adjacent to the failure link or node need to perform protection switching and hence is very fast but it is relatively inefficient, as the ratio of reserved spare capacity to working capacity (known as redundancy) is at least 100% [2]. On the other hand the mesh protection method can achieve a much better efficiency in the use of spare capacity, but requires a much longer restoration time due to the complicated signaling process[21].

Table 1[22] summarizes performance metrics of *p*-cycle and comparison among p-cycle, rings and mesh protection.

Table 1. Comparison of Ring, Mesh and P-cycle protection mechanism [22].

Attributes	Protection Mechanism		
	RING	MESH	P-CYCLE
Restoration time	50-60 (msec)	100-150 (msec)	50 - 60 (msec)
Network design	Simple	Complex	Simple
Capacity efficiency	Low	High	High
Cost	Low	High	Low
Redundancy	High	low	low
Multiple services	Hard to accommodate	Easy to design	Easy and efficient to design
Routing techniques	Ring-constrained routing	Shortest-path routing	p-cycle adapted routing
Protection flexibility	Spans on the cycle	Spans on the cycle	On cycle and on cycle-straddling spans

4. CONCLUSION

In this paper an overview of the various approaches for survivability protection have been presented. It is observed that *p*-cycle protection offers excellent performance in terms of optimality of solution and computational complexity. This paper presents main ideas and sub domains behind p-cycle protection in optical WDM Networks. Various extensions to the p-cycle concept have been reviewed and summarized. Pre-selection approach has computational complexity problem but shows good capacity utilization. This paper presents various scalable techniques considering the significance of p-cycle against link failure. It is seen that in comparison to conventional techniques p-cycle protection provides greater resilience and capacity efficiency because of efficient utilization of capacity as well as computational time.

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