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p^2-Cycles: p-Cycles with parasitic protection links [☆]

Long Long, Ahmed E. Kamal [*]

Department of Electrical and Computer Eng., Iowa State University, Ames, IA 50011, USA

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The p-cycle and its Failure Independent Path Protection (FIPP) extension are known to be efficient and agile protection strategies. The p-cycle is pre-configured such that if there is a failure, only the switches at two end nodes need to be reconfigured. In this paper, we extend the p-cycle by allowing cycles to have attached links, called Parasitic Protection Links (PPL), in order to protect paths whose source and destination nodes are not only located on the cycle but also connected by a PPL to the cycle. A p-cycle with PPL is named p^2-cycle.

We address the unicast service protection problem against single-link failures by using p^2-cycle in mesh networks for both static and dynamic traffic scenarios. In the static case, the problem is formulated as an Integer Linear Program (ILP). We further propose two p^2-cycle based heuristic algorithms, Strict Routing Protection (SRP) and Flexible Routing Protection (FRP), to address the dynamic traffic case. The numerical results show that the p^2-cycle scheme provides better capacity efficiency than the FIPP p-cycle scheme in all the traffic scenarios considered and achieves only less than 1% extra total cost over the optimum in COST239, provided by Shared Backup Path Protection (SBPP) approach when the traffic load is high. We also study the failure recovery performance in terms of average number of switch reconfigurations (NOR), and show that the performance of the p^2-cycle becomes much better than that of SBPP and gets close to FIPP as the traffic demand increases. In the dynamic case, both SRP and FRP outperform FIPP p-cycle schemes in terms of blocking probability in most scenarios considered. In general, the p^2-cycle protection scheme outperforms the p-cycle based in terms of capacity efficiencies which being slightly slower in terms of traffic recovery speed.

1. Introduction

Network survivability, defined as the ability of networks to continue to function properly in the presence of the failures of network components [1], is an important requirement for WDM optical networks due to their ultra-high capacity. A single failure can disrupt millions of applications and users. Ring-based networks and resilience schemes are prevalent due to the simple manageability and fast recovery mechanism, in which the traffic recovery process can be completed within 50–60 ms, but require 100% capacity redundancy [2]. As mesh-based networks emerged, more capacity efficient protection schemes were proposed which allow backup capacity sharing. These schemes fall into three categories: link-based, segment-based and path-based [3,4].

Link-based protection schemes produce the fast traffic recovery speed but suffer from the worst resource efficiency [5]. As capacity cost is one of key factors in network design [6,7], path-based protection schemes are usually proposed to achieve the best capacity efficiency. Among them, a path protection scheme, namely, Shared Backup Path Protection (SBPP), was shown to be the most capacity efficient protection scheme [3]. However, it suffers from

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[*] Corresponding author. Tel.: +1 515 294 3580.
E-mail addresses: longlong@iastate.edu (L. Long), kamal@iastate.edu (A.E. Kamal).

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long traffic recovery time upon a network failure. Segment-based protection schemes lie between the link-based and path-based schemes, and offer a better combination of bandwidth efficiency and recovery time [8,9].

The pre-configured protection cycle approach, referred to as *p*-cycle, combines the merits of both ring-based and mesh-based protection schemes and achieves the recovery speed of ring-based with the capacity efficiency of mesh protection [10,11]. A thorough study of *p*-cycle-based survivability techniques was conducted by Grover in [12]. Since the concept of *p*-cycle was first introduced in [10], a large amount of work in the literature studied the *p*-cycle design problem with unicast traffic against a single-link failure. The authors in [10,13] introduced a tractable solution by solving the problem in two steps: by first routing the connections, and then selecting the best *p*-cycles candidates from the enumeration of all the cycles to protect the established connections. In [14,15], however, the problem were solved jointly by minimizing the total capacity cost used by both primary paths and protection *p*-cycles.

Besides link protection, *p*-cycles has been extended to protect segments and paths in [16,17]. Ref. [17] proposed a Failure Independent Path-Protecting (FIPP) *p*-cycle which is a more capacity efficient protection strategy than link protecting *p*-cycle. Recently, the author of [19] introduced a new 1+N protection scheme against single-link failures by combining network coding and *p*-cycles. Besides *p*-cycles, other pre-configured structures are also used for fast recovery, such as non-simple *p*-cycle [20,21], *p*-trails [22], *p*-trees [24,25] and Cooperative Fast Protection (CFP) [23]. A cycle is a non-simple cycle if one or more node on the cycle is traversed by the cycle more than twice. The study in [21] reveals that the major capacity gain of non-simple *p*-cycles over simple *p*-cycles lies in small networks with lightly loaded traffic. In [25], the authors extended traditional *p*-tree by adding links to form a more flexible protection pattern, such as cycles, trails or trees. It is a link-based protection scheme and provides higher protection capacity than link-protecting simple and non-simple *p*-cycles. However, the short recovery time cannot always be guaranteed due to the flexibility of the protection structure. The authors in [23] enhanced the protection capacity utilization by solving the backhaul problem, in which the same link is traversed twice in opposite directions by the protection path before reaching the destination after a link failure. However, it suffers from longer switch reconfiguration time due to the fact that all failure-aware nodes need to carry out protection switching after failure detection.

Regardless of the protection schemes, the trade-off between the capacity efficiency and failure recovery speed always exists [26]. Since the *p*-cycle has a good combination of capacity and time efficiency, we attempt to further increase the capacity efficiency of FIPP *p*-cycles without sacrificing too much of its fast recovery property. In this paper, therefore, we extend the FIPP *p*-cycle paradigm to a new one in which each *p*-cycle may be augmented with a number of protection links that are attached to the cycle, called “Parasitic Protection Links (PPL)”.

The rest of the paper is organized as follows: In Section 2, we analyze the p^2-cycle protection scheme in more detail. In Section 3, we consider unicast protection problem with static traffic demands using p^2-cycles as the protection method. The problem is formulated as an Integer Linear Program (ILP). In Section 4, we further consider dynamic traffic scenarios, in which two heuristic algorithms are proposed. Performance evaluation of multiple criteria for both static and dynamic traffic scenarios will be presented in Section 5. Finally, we conclude the paper in Section 6.

2. Overview of p^2-cycles

In this section, we provide an overview of p^2-cycle protection scheme and elaborate the details of protection mechanism and traffic recovery time.

2.1. Concept

An example is shown in Fig. 1 to illustrate the concept of the p^2-cycle. In Fig. 1(a), a *p*-cycle $(A-B-C-D-E-F-A)$ is used to protect two bidirectional paths, P_1 and P_2, where path P_1 traverses on-cycle span (D,E) and (E,F) and is protected by on-cycle segment $(F-A-B-C-D)$ and path $P_2(A-C)$ is a straddling path that is protected by on-cycle segment $(A-B-C)$. Working paths are denoted by solid lines and protection paths are represented by dashed lines. Assuming we have another working path P_3 (shown in Fig. 1(b)) traversing on-cycle span (A,B) and non-cycle span (B,G), the original *p*-cycle cannot protect it, since the end node G is not on the cycle. We then extend the *p*-cycle to have a PPL (C,G) and hence protect P_3 by using the path $(A-F-E-D-C-G)$, which is partly on-cycle and partly on PPL. The idea can also be applied to a path whose two end nodes are not on the cycle, such as path p_4 shown in Fig. 1 (c). Two PPLs (A,H) and (C,G) can be used to construct the protection path $(H-A-F-E-D-C-G)$. Therefore, the augmented *p*-cycle with the two links (A,H) and (C,G) can protect four paths (shown in Fig. 1(d)). Hence, augmenting a *p*-cycle to have PPLs enhances the flexibility of protection and thus may decrease spare capacity redundancy and reduce overall capacity cost.

2.2. Protection mechanism

The protection ability of a p^2-cycle is an enhancement to that of the *p*-cycle by adding attached spans to the cycle, which enables the cycle to provide protection to the connections whose end nodes are one hop away from the cycle. All the nodes on the cycle still remain pre-configured. For the nodes that also connect to PPLs, they only reconfigure the switches when the attached PPLs are activated to provide protection upon a network failure. Given a unicast session, the primary path and its fully disjoint corresponding protection path, which may consist of an on-cycle segment and one or two PPLs, will be determined in advance regardless of the location of the failure. Hence, the p^2-cycle protection scheme is also failure-independent [17].

Upon a link failure, the failure will be detected by the end nodes of the failed span and the corresponding signals will be transmitted to the source and destination nodes of the path. The distinction between a p^2-cycle and an FIPP