Joint Capacity and Spare Capacity Placement with *p*-Cycles

Dale R. Thompson and Khalid Al-Snaie

Abstract— ***Preconfigured protection cycles (p-cycles) provide recovery times for mesh networks that are near the recovery times of SONET ring networks while providing lower spare-to-working capacity ratios. In this work, two methods of assigning p-cycles in a wavelength division multiplexing network are compared over a range of topologies with different average node degrees. The joint capacity placement (JCP) method considers the working traffic and spare capacity jointly. The spare capacity placement (SCP) method assigns traffic to the shortest paths and then assigns p-cycles using the spare capacity. The joint capacity placement method provides ~35% lower spare-to-working capacity ratio than the spare capacity method with ~7% increase in working capacity cost. In addition, a topology with higher average node degree provides lower spare-to-working capacity ratios because more straddling links are possible.***

Index Terms—network reliability, *p*-cycles, *wavelength division multiplexing*

1. Introduction

THE Internet and business functions rely on communication networks. Failures of optical connections, even for small periods of time, cause a large waste of resources. Unfortunately network failures are frequent. According to the Federal Communication Commission (FCC), metro networks annually experience 13 cuts for every 1000 miles of fiber, and long-haul networks experience 3 cuts for 1000 miles fiber [1]. A network with 30,000 route miles of fiber is cut every four days on average [1].

There are two well-known approaches for protecting an optical network: ring-based restoration and mesh-based restoration. Ring protection such as the bi-directional line switched ring (BLSR) can achieve low restoration times (50-60 ms). However, in real networks ring protection requires a spare-to-working ratio between 200% and 300% of resources [2].

In mesh restoration the spare-to-working ratio is lower than the ring protection because many working paths can share one unit of spare path. The required spare-to-working ratio can be as low as 50-70% depending upon the network topology [2]. However, the restoration times of mesh-based restoration are generally higher than ring-based recovery because of the more complex distributed signaling.

In 1998 Grover and Stamatelakis introduced the concept of preconfigured protection cycles (*p*-cycles), which can be an attractive method for span protection in wavelength division multiplexing (WDM) optical networks because it combines the benefits of the recovery speed of ring-based restoration and the efficiency of mesh-based networks [2-4].

2. Problem Statement

There are two methods for assigning *p*-cycles in a network. The joint capacity placement (JCP) method considers the working traffic and spare capacity jointly when assigning *p*-cycles. The spare capacity placement (SCP) method assigns traffic to the shortest paths and then assigns *p*-cycles using the remaining spare capacity. In this work, the spare-to-working capacity ratios of JCP and SCP will be compared on several network topologies with varying node degree. In addition, the required working capacity for JCP and SCP will be compared on the same set of topologies. These comparisons will give network designers guidance for which method to use when assigning *p*-cycles.

3. Literature Review

3.1 The p-Cycle Concept

Two basic types of *p*-cycles exist. Link *p*-cycles protect the individual channels within a link. Node encircling *p*-cycles are routed through all neighbor nodes of a specific node and protect all the connections traversing this node. In this work, we focus on link *p*-cycles, assuming the nodes are reliable.

Fig. 1 illustrates using *p*-cycles for a 6-node network topology with 11 spans (average node degree: $\bar{d} = 2S/N = 3.67$). Like BLSR the *p*-cycle is based on cyclic structures having the property that protection switching decisions can be made quickly. Since only the two nodes on either side of the failure need to perform actions, BLSR-like restoration times can be achieved. For example, the single *p*-cycle shown in Fig. 1 can cover 6 on-cycle working fibers as seen in Fig. 2.

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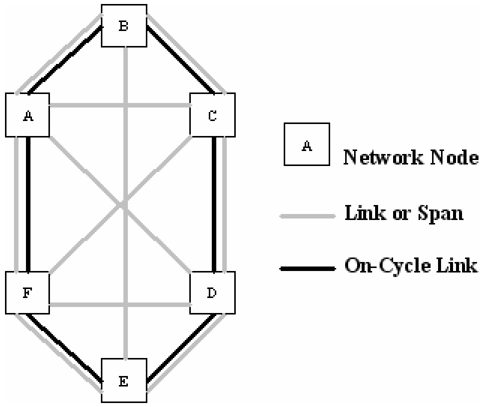

Fig. 1 Network topology with 6 nodes and 11 spans before failure with one *p*-cycle (A-B-C-D-E-F).

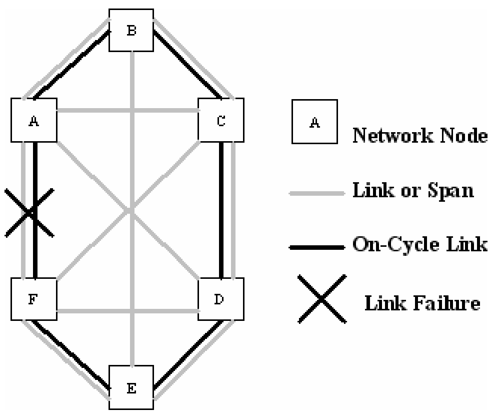

Fig. 2 Network after A-F on-cycle failure with one protection path (A-B-C-D-E-F). Only nodes A and F need to perform real-time action.

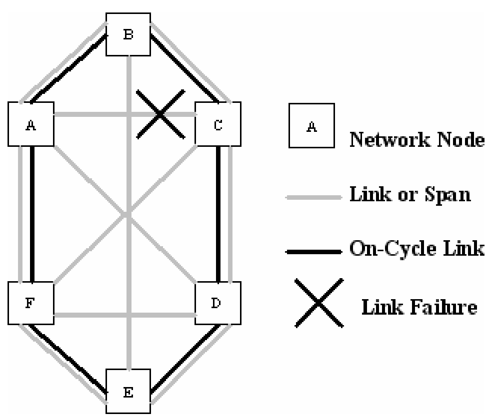

Fig. 3 Network after A-C off-cycle or straddling span failure with two protection paths (A-B-C) and (A-F-E-D-C).

A *p*-cycle can also protect 5 straddling spans providing mesh-like efficiency as seen in Fig. 3. Note that a straddling span can be restored by using capacity from two different paths. We see that a single Hamiltonian *p*-cycle that has 6 spans can protect up to 6+2(5)=16 working fibers with a spare-to-working percentage of 6/(6+2(5))=37.5%, which for this case is a lower bound for a span-restorable mesh network, 1/($\bar{d}$ -1) [1], [5-8].

There are two types of WDM networks: virtual wavelength path (VWP) and wavelength path (WP). The nodes in VWP WDM networks perform full wavelength conversion, i.e., lightpaths can be switched to a fiber output if there is a free wavelength channel. The nodes in WP WDM networks do not have wavelength conversion [4]. In this paper, *p*-cycles are used in VWP WDM networks.

3.2 Mathematical Formulation for the Optimal Combination of p-Cycles

The mathematical formulations for JCP and SCP are shown below [1]. These formulations will be used to find the set of *p*-cycles for a given topology and traffic matrix. The set of elemental distinct simple candidate cycles are limited to a reasonable number to make the problem tractable [1].

Sets:

- S set of spans between mesh cross connection points.
- P set of elemental distinct simple cycles.
- D set of all demand pairs.
- WR set of all candidate working routes for each demand pair *r*.

Parameters:

- c_j cost of a link (working or spare) assigned to span *j*.
- W_j number of working links placed on span *j*.
- $x_{i,j}$ number of paths a single copy of *p*-cycle *i* provides for restoration of failure of span *j* (2 if straddling span, 1 if on-cycle span, 0 otherwise).
- $p_{i,j}$ number of spare links required on span *j* to build a single copy of *p*-cycle *i* (1 if *p*-cycle *i* passes over span *j*, 0 otherwise).
- d_r number of demand units between end-end pair *r*.
- $\zeta_j^{r,q}$ Takes on value of 1 if the q^{th} working route for demand pair *r* uses span *j*, 0 otherwise.

Variables:

- n_i number of copies of *p*-cycle *i* used.
- s_j number of spare links placed on span *j*.
- w_j number of working wavelengths placed on span *j*.
- $wf^{r,q}$ working capacity required by q^{th} working route for demand between node pair *r*.

3.2.1 Spare Capacity Placement (SCP) in VWP WDM Networks

In spare capacity placement (SCP) the demand is first routed using shortest path, and then the optimal capacity algorithm is applied on the spare links to minimize the spare capacity cost as in (1).

Objective function: *Minimize* $\sum_{j=1}^{|S|} c_j \times s_j$ (1)

Subject to:

$$s_j = \sum_{i=1}^{|P|} p_{i,j} \times n_i \quad \forall j \in S \quad (2)$$

$$W_j \le \sum_{i=1}^{|P|} x_{i,j} \times n_i \quad \forall j \in S \quad (3)$$

$$n_i \in \{0,1,2,........\} \quad (4)$$

3.2.2 Joint Capacity Placement (JCP) in VWP WDM Networks

In joint capacity placement (JCP) the working routes are optimized at the same time as restoration routes and spare capacity placement to minimize the total capacity as in (5) [1].

Objective function:

Minimize $\sum_{j=1}^{|S|} c_j \times w_j + \sum_{j=1}^{|S|} c_j \times s_j$ (5)

Subject to:

$$\sum_{q=1}^{|WR|} wf^{r,q} = d_r \quad \forall q \in D \quad (6)$$

$$w_j = \sum_{r=1}^{|D|} \sum_{q=1}^{|WR|} wf^{r,q} * \zeta_j^{r,q} \quad \forall j \in S \quad (7)$$

$$s_j = \sum_{i=1}^{|P|} p_{i,j} \times n_i \quad \forall j \in S \quad (8)$$

$$w_j \le \sum_{i=1}^{|P|} x_{i,j} \times n_i \quad \forall j \in S \quad (9)$$

$$n_i \in \{0,1,2,........\} \quad (10)$$

Constraints (2) and (8) determine the protection capacity allocation, constraints (3) and (9) ensure the working capacity to be protected, and (4) and (10) ensure integer *p*-cycle units. Constraint (6) ensures all demands are routed, and constraint (7) ensures the working capacity on span *j* can accommodate all working flows simultaneously routed over it by all demand pairs.

4. METHOD

SCP and JCP were applied to sets of network topologies with 10, 15, 20, and 25 nodes. Each set had 20 random physical topologies that are similar to real networks with varying average node degree and were generated by GT-ITM[7] using the Waxman method [9], [10]. The number of required wavelengths between each source and destination was generated randomly with a uniform distribution in the range from 1 to 15. Then SCP and JCP were applied to each of the topologies with the same demand. The mathematical models of section 3.2 were formulated in AMPL and solved by CPLEX 8.1.0. The spare-to-working capacity ratio was calculated for each case. The spare-to-working capacity ratio is defined as the number of required spare wavelengths required for all *p*-cycles divided by the total number of wavelengths required for the working traffic.

5. RESULTS

The spare-to-working capacity ratio for the twenty random network topologies with 25 nodes and varying average node degree are shown in Fig. 4 with a polynomial trend line. Similar results were obtained on the network topologies with 10, 15, and 20 nodes, but are not shown.

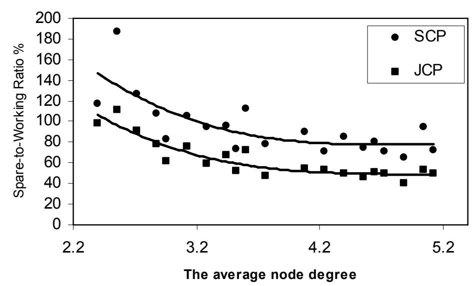

Fig. 4. Spare-to-working ratio vs. average node degree for 20 random topologies with 25 nodes.

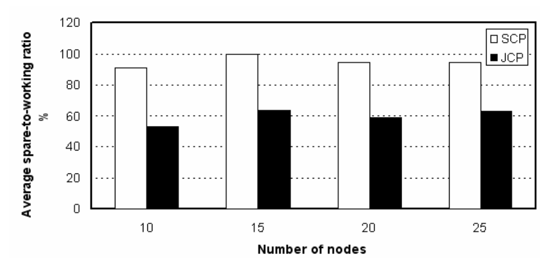

Fig. 5. Average spare-to-working ratio vs. number of nodes for JCP & SCP.

As seen in Fig. 4, jointly considering the working capacity and spare capacity costs provides lower spare-to-working capacity ratios. In addition, a higher average node degree lowers the spare-to-working capacity ratio because there are more straddling links and more possible candidate *p*-cycles. In general, a higher average node degree corresponds to more straddling links that can be efficiently used by *p*-cycles. In addition, *p*-cycles are less suitable for network topologies with average node degree below 3.0.

[7] Georgia Tech Internet Topology Models (GT-ITM) is a package for generating the flat random and hierarchical models. It is publicly available at: http://www.cc.gatech.edu/projects/gtitm/.

For SCP and JCP, the average spare-to-working ratio at a given number of nodes was plotted and is shown in Fig. 5. JCP provides approximately 35% lower spare-to-working capacity ratios than SCP over all tested topologies. However, JCP solutions require an approximate 7% increase in required working capacity.

6. CONCLUSIONS

The joint capacity problem (JCP) and the spare capacity problem (SCP) methods for assigning *p*-cycles were applied to network topologies with 10, 15, 20, and 25 nodes and varying average node degree. JCP provides solutions with lower spare-to-working capacity ratios than SCP. In addition, network topologies with higher average node degrees have lower spare-to-working capacity ratios when using *p*-cycles because more straddling spans are available.

JCP provides solutions with lower spare-to-working capacity ratios than SCP because it jointly considers the working traffic and the spare capacity required by the *p*-cycles during a failure. This provides a solution space with a greater number of possibilities than the more restrictive case of SCP. SCP initially assigns the working traffic to the shortest paths and then uses the remaining capacity for assigning *p*-cycles. A disadvantage of JCP is that the required working capacity is larger than SCP.

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