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Research paper



Quality Enhancement with Maximum Allowable *p*-Cycle Length and with *m*-Cycle in Optical Mesh Networks

Deo Chandra Jaiswal[1]*, Rachna Asthana[2]

[1]Department of Electronics Engineering HBTU, Kanpur, Uttar Pradesh, India,
(email: deohbti@gmail.com)
[2] Department of Electronics Engineering HBTU, Kanpur, Uttar Pradesh, India,
(email: rachnaasthana@rediffmail.com)
**Corresponding author E-mail: deohbti@gmail.com*

Abstract

In the modern age, fast communication of information is an essential requirement of everyone moreover communication between long distances is mainly provided by optical mesh networks. Network failures of small interval lead to large disruptions in providing service of transferring of data. Therefore, for uninterrupted network services, network survivability plays a vital role. Preconfigured protection cycle (*p*-cycle) combines the advantages of the capacity efficiency of mesh as well as a fast restoration speed of ring based protection schemes which are two fundamental techniques of network survivability. Level of optimal redundancy is assured by selecting Hamiltonian *p*-cycle as it passes through all the nodes of the network. Obviously, the restored path length will be increased due to increased *p*-cycle length that increases the excessive signal degradation and propagation delay which results in decreased level of quality of service (QoS). Priority-based traffic in an optical mesh network can be restored with different levels of QoS. So the maximum *p*-cycle length is made definite up to a certain limit, the lower limit for premium-grade and the upper limit for low-grade traffic is done. The concept of shortest path routing (SPR) is commonly referred in the optical networks with the condition of *p*-cycle length limit when link failure takes place. Monitoring cycle (*m*-cycle) is responsible for fault detection and localization before *p*-cycle protection. In this paper, dynamic path routing (DPR) with maximum *p*-cycle length limitation including *m*-cycle and SPR with only *p*-cycle length limit is compared. An Integer Linear Programme (ILP) is developed to minimize spare capacity for DPR with the maximum *p*-cycle length limit along with *m*-cycle against single link failure. The result of this programme illustrates that DPR with maximum *p*-cycle length limitation and *m*-cycle requires fewer total spare capacity in comparison with SPR where the only length of *p*-cycle is limited and monitoring is not taken in to account.

Keywords: *Dynamic path routing; fault localization; Hamiltonian p-cycle; m-cycle; p-cycle; p-cycle length limit; shortest path routing.*

1. Introduction

Survivable network design becomes crucial issue in optical mesh networks for reliable data transfer and its results are significant in real-time operation [2]. The two main reasons of network failures are span failures and component failures. Span failures are mostly caused by fiber cuts and it is predominant among both the failures. For instance, U.S. carriers reported 136 such failures to the Federal Communications Commission (FCC) in 1997 [3]. Also, FCC published that 3 and 13 cuts for miles of fiber were observed in metro and long haul networks respectively in 2002 [2]. These information illustrates that rate of span failures is taking place thousands times higher than the node failures. Therefore, fault localization and protection to the networks against span failures due to fiber cable cut is acknowledged as the most realistic and challenging task to achieve in current scenario. Another presumption about single span failures is also considered. Single span failures are the most common form of failures in mesh networks [5]. The failure which is repaired before another failure takes place in the network is known as single span failure. It has been widely accepted that when a failure occurs, there is time to repair it before the occurrence of another failure [6]. Single span failure is considered in this paper while there is also probable existence of multiple failures in existed networks. Hence, highly needed network failure recovery arises in single span failure which provides the services to the users without loss of data. The two categories of network failure recovery are Protection and Restoration. In protection category, before the failure occurs, assigned backup paths are pre provisioned over spare resources for recovery. This category achieves fast recovery speed due to the fact that only the end nodes of the failed span require real time switching of the affected traffic. In restoration, after the failure occurs, backup path for the affected traffic is dynamically recovered [9]. The advantage of optical network is high capacity but on the other hand, when a cable breaks, thousands of connections are interrupted which yields the loss of thousands of Gigabits of data. As result the problem of failure location and isolation in optical networks has become important. The major challenge of failure recovery networking is that if span failure occurs, it is not easily and quickly localized. Detection and localization are essential steps for providing continuous and reliable services in all-optical networks (AONs) with ever-increasing data rate as well as increased wavelength number and density in wavelength-division multiplexing (WDM) [12]. Fault detection and localization by *m*-cycle is needed before providing *p*-cycle protection. *m*-Cycle concept was studied in the Ph.D. thesis by Hongquing Zeng[12]. *p*-Cycle protection is a type of protection scheme in which additional resources are reserved.

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Hamiltonian cycles are mostly selected to achieve optimal redundancy and it becomes length wise too long since it is protecting a vast dimension in optical mesh networks. The desired level of quality of service can be insured with maximum *p*-cycle length limit. The maximum *p*-cycle length provide limit on restored path length. Priority basis traffic demands as premium-grade, medium-grade and low-grade are protected by different maximum *p*-cycle length limit. Premium-grade traffic demands should be restored with high level of quality of service because they are most delay sensitive transmission e.g. video conferencing and other delay sensitive transmission. In order to insure desired quality of service when limitation is posed on length of the *p*-cycle the total spare capacity increases at that length limit [1]. Dynamic path routing (DPR) with *p*-cycles length constraint is responsible for decrease in total spare capacity. The joint optimization of traffic routing and *p*-cycle design is the main reason for decrease in total spare capacity.

This paper is organized as follows. In section 2 we recall monitoring of fault detection and localization with *m*-cycles and the protection concept of *p*-cycle. Section 3 explains routing algorithm. Section 4 describes ILP model for spare capacity optimization using DPR with *p*-cycle length limit and with *m*-cycle. In Sections 5 simulations and results are presented. Finally the conclusions are outlined in Sections 6.

2. The concept of *p*-cycles and its function as their own *m*-cycles

Monitoring cycles (*m*-cycles) are those cycles in which all nodes and links of the given network are covered at least by one cycle. In each monitoring cycle, one node is allotted with a transceiver thus a supervisory channel for dedicated loop is formed. The idea behind *m*-Cycles is that, if a network graph has a cycle cover in which the set of cycles covering each span differs by at least one cycle, then, when a span fails, the span can be uniquely identified by the combination of covering cycles which display an alarm state. This assumes one signal monitor per cycle, which can be placed at any node on the cycle. As so far considered, the idea is to use the fault localization as input to a separate protection or restoration scheme [13]. The *m*-cycle scheme itself is agnostic about the survivability mechanism employed, and could be used as the activating input for any span protection scheme. Combined *p*/*m*-cycle is used for the fault localization and protection. *p*-Cycles are one of the most promising techniques of span protection used in optical mesh networks as shown in Fig. 1 (a). Grover and Stamatelakis [8] proposed *p*-cycles which combine the advantages of ring as well as mesh based shared protection schemes. *p*-Cycles are said to have the mesh like capacity efficiency with the ring like fast recovery speed. *p*-Cycles operate for span protection, presuming the failed span is known. When one of the spans on a *p*-cycle fails, the cycle loops back around the body of the cycle similar to the bi-directional line switched ring (BLSR). For any such on cycle link (each link that has both end points and link on *p*-cycle) failure there is one protection path available per unit of spare capacity in the *p*-cycle as shown in Fig. 1 (b). But when a failure span straddling link (each link that has both end points on *p*-cycle but link not on the cycle) there are two protection paths available per unit of capacity in the *p*-cycle. *p*-Cycles are now a well-established approach to fast and efficient survivable network in as shown in Fig. 1 (c). Here *p*-cycles have been used as *m*-cycles for self-fault detection and localization in WDM mesh networks. *p*-Cycle structure of network with properties of *m*-cycle without significant added cost is not initially obvious. *m*-Cycles must cover all the spans of the network as only the on-cycle span while *p*-Cycles also protect straddling links which makes it more efficient. Straddling span relationship increases the efficiency of *p*-cycle as it protects on- cycle spans as well as straddling spans.

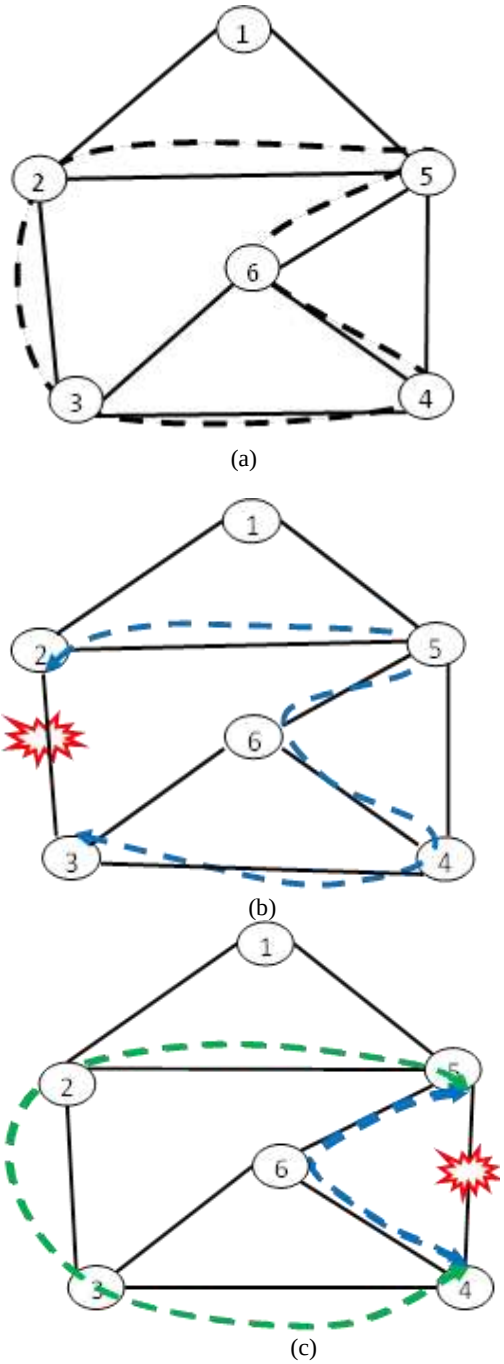


Fig. 1: Protection concept of *p*-cycle for link (a) A *p*-cycle in a network (b) An on-cycle link protection (c) Straddling link protection.

The feature of *p*-Cycle to protect both on-cycle spans and straddling spans makes it more beneficial but the basic issue of reconciliation of two concepts full span protection and failure localisation under the same design model arises while considering the minimisation of total cost. Self- failure isolating survivable network is found as the modern classification when above concept becomes feasible and practical which may make optically transparent networks more advantageous [13].

Hamiltonian *p*-cycle: The *p*-cycle that traverses all the nodes in the network exactly once is called a Hamiltonian *p*-cycle as shown in Fig. 2. The protection concept of Hamiltonian *p*-cycle is same as *p*-cycle discussed above.

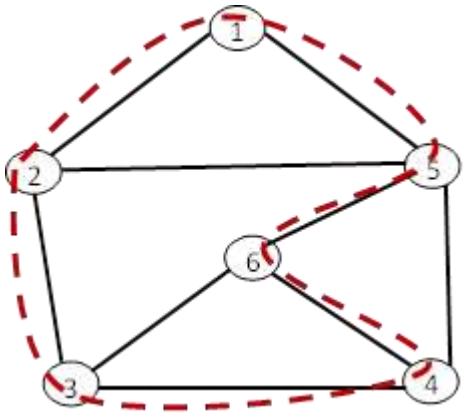


Fig. 2: Hamiltonian *p*-cycle

If Hamiltonian *p*-cycles exist they are most appropriate cycle for better redundancy but provide length wise long restoration path in vast optical networks due to which signal quality drops below the desired threshold.

3. Routing algorithm

Routing is a definite path through which traffic demands are routed from source to destination through intermediate links. In this paper, two different types of routing (a) Shortest Path Routing (SPR) (b) Dynamic Path Routing (DPR) are considered. A brief description about these two routings is as follows.

3.1. Shortest path routing (SPR)

A path from source node to destination node may go through several intermediate links. The objective in SPR is to find path from source node to destination node that has the shortest total length, the total length of path is sum of the link lengths in that path. In SPR, connection is always routed on its shortest path of each demand pair with optimum spare capacity within *p*-cycle length limit and *m*-cycle. Dijkstra's algorithm is one of the methods which determines shortest path from source to destination.

3.2. Dynamic path routing (DPR)

Two or more paths from source node to destination node of each demand pair are taken as shortest to next shorter. The objective of DPR is to find one path from two or more paths from source node to destination node. The total length of path is sum of the link lengths in that path. A connection is always routed on its one path among all paths of each demand pair with optimum spare capacity within *p*-cycle length limit and *m*-cycle. Joint Capacity Optimization (JCO) is used for the selection of one path among all paths of each demand pair with DPR based ILP model. In JCO, load balancing minimizes total spare capacity. Load balancing is as possible as uniform distribution of working capacity on span for all demand pairs.

4. ILP optimization model

An efficient ILP model is used to minimize total spare capacity for network design with objective and constraints. We first present the model for SPR followed by the model for DPR with *p*-cycle length limit including *m*-cycle properties.

4.1. ILP design model for optimized spare capacity using SPR with *p*-cycle length limit and without *m*-cycle

In this part, we applied an ILP model to minimize total spare capacity using SPR with *p*-cycle length limit without *m*-cycle. We have taken only one shortest working route for each demand pair having non zero demand. The related sets, parameters and variables for SPR based model are as follows.

Sets:

S: Set of spans in the network indexed by j.

P: Set of candidate cycles in the network indexed by p.

Parameters:

w_j: The working capacity on span j.

x_j^p: A ternary parameter that equals 1 if *p*-cycle p protects span j as on-cycle span; equals 2 if *p*-cycle p protects span j as straddling span; 0 otherwise.

π_j^p: A binary parameter that equals 1 if *p*-cycle p crosses span *j*; 0 otherwise.

l_j: A length of span j.

L_{max}: Maximum possible length of *p*-cycle to insure desired signal quality.

Variables:

n_p: The number of copies for *p*-cycle p.

s_j: The spare capacity required on span *j*.

The objective of ILP is to Minimize:

$$\sum_{j \in S} s_j \qquad (1)$$

Constraints:

$$w_j \leq \sum_{p \in P} x_j^p \,.n_p \qquad ,\forall\, j \in S \qquad (2)$$

$$s_j = \sum_{p \in P} \pi_j^p \,.n_p \qquad ,\forall\, j \in S \qquad (3)$$

$$\sum_{j \in S} \pi_j^p \,.\, l_j \,.\, n_p \leq L_{max} \,.n_p \quad ,\forall\, p \in P \qquad (4)$$

Objective 1 is minimizing the total spare capacity required to obtain *p*-cycles protection. Constraint 2 ensures that protection provided by all the *p*-cycle of the solution set is sufficient to protect all the working capacity of span. Constraint 3 calculates the spare capacity on each span required by all the *p*-cycle of solution set for single failure. Constraint 4 bounds the maximum length of the selected *p*-cycles to insure the desired level of signal quality.

4.2. ILP design model for optimized spare capacity using DPR with *p*-cycle length limit and with *m*-cycle

In this part, we applied an ILP model to minimize total spare capacity using DPR with *p*-cycle length limit including *m*-cycle properties. We have taken two shorter working routes for each demand pair having non zero demand. The additional related sets, variables and parameters for DPR based model over and above used in SPR based model, are as follows.

Sets:

D: Set of demand pairs in the network indexed by r.

Q^r: Set of equivalent shorter working routes for demand pair r, indexed by q.

Parameters:

$\delta_j^{r,q}$: A binary parameter that equals 1 if the qth working rout for the rth demand passes through span j; 0 otherwise.

d_r: The working demand between demand pair *r*.

Variables:

$f^{r,q}$: A binary variable that equals 1 if the qth working rout for the rth demand chosen; 0 otherwise.

w_j: The working capacity on span j.

The objective of ILP is to Minimize:

$$\sum_{j \in S} s_j \qquad (5)$$

Constraints:

$$\sum_{q \in Q^r} f^{r,\,q} = d_r \qquad ,\forall\, r \in D \qquad (6)$$

$$\sum_{q \in Q^r,\ r \in D} \delta_j^{r,\,q} \cdot f^{r,\,q} = w_j \qquad ,\forall\, j \in S \qquad (7)$$

$$w_j \leq \sum_{p \in P} x_j^p \cdot n_p \qquad ,\forall\, j \in S \qquad (8)$$

$$s_j = \sum_{p \in P} \pi_j^p \cdot n_p \qquad ,\forall\, j \in S \qquad (9)$$

$$\sum_{p \in P : \pi_i^p = 1\ \&\ \pi_j^p = 1} n_p \geq 1 \ ,\forall\, \{i,j\} \in S^2, i \neq j \qquad (10)$$

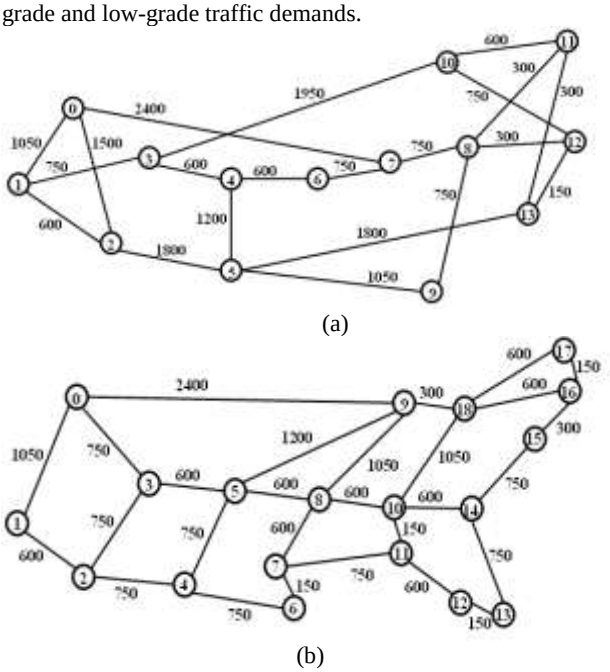
$$\sum_{p \in P : \pi_j^p = 1} n_p \geq 1 \qquad ,\forall\, j \in S \qquad (11)$$

$$\sum_{j \in S} \pi_j^p \cdot l_j \cdot n_p \leq L_{max} \cdot n_p \qquad ,\forall\, p \in P \qquad (12)$$

Objective 5 is minimizing the total spare capacity required to obtain *p*-cycles protection. Constraint 6 ensures that all the demands of demand pair are routed through the single optimum working path among all the permissible paths. Constraint 7 calculates the working capacities of every span in the network after routing. Constraint 8 ensures that protection provided by all the *p*-cycle of the solution set is sufficient to protect all the working capacity of the span. Constraint 9 is to calculate the spare capacity on each span to form the selected *p*-cycles for the single failure. Constraints 10 and 11 combine the requirement *m*-cycle cover to the problem by affirming that the same set of cover cycles cannot be used for two different spans and that at least one cycle covers each span. Constraint 12 bounds the maximum length of the selected *p*-cycles such that signal quality does not drop below the desired threshold.

5. Simulations and results

The simulations for optimized results have been performed on IBM ILOG CPLEX OPTIMIZATION STUDIO 12.7 simulation software on an Intel Core i5 equipped with 2.4 GHz CPU and 4 GB RAM. We evaluated the performance of SPR and DPR with *p*-cycle length limit combining the properties of *m*-cycle by running simulations for two test networks, including (1) the 14 node 21 span (NSFNET) network shown in Fig. 3(a), and (2) the 19 node 28 span network shown in Fig. 3(b). For 14 node 21 span (NSFNET) network from Table 1 the premium-grade traffic demands are restored with the maximum *p*-cycle length 7,000 km, medium-grade traffic demands are restored with the maximum *p*-cycle length 9,000 km and low-grade traffic demands are restored with the maximum *p*-cycle length 11,000 km. Total spare capacity of 06.25%, 9.30% and 5.55% are reduced using DPR with *m*-cycle compared to SPR without *m*-cycle in premium-grade, medium-grade and low-grade traffic demands. For 19 node 28 span network from Table 2 the premium-grade traffic demands are restored with the maximum *p*-cycle length 5,000 km, medium-grade traffic demands are restored with the maximum *p*-cycle length 8,000 km and low-grade traffic demands are restored with the maximum *p*-cycle length 11,000 km. Total spare capacity of 03.03%, 6.89% and 7.40% are reduced using DPR with *m*-cycle compared to SPR without *m*-cycle in premium-grade, medium-grade and low-grade traffic demands.



(a)

(b)

Fig. 3: Test networks (units span length in Kms) used in simulations (a) 14 node 21 span (NSFNET) network (b) 19 node 28 span network.

Table 1: Comparison between SPR and DPR with respect to total spare capacity for 8 different maximum allowable *p*-cycle length with *m*-cycle for 14 node 21 span (NSFNET) network.

Max. Allowable *p*-Cycle Length (in Kms)	Total Spare Capacity		
	SPR without *m*-Cycle	DPR with *m*-Cycle	% Decrease
7,000	48	45	06.25
8,000	45	42	06.67
9,000	43	39	9.30
10,000	39	38	02.56
11,000	36	34	05.55
12,000	33	33	00.00

Table 2: Comparison between SPR and DPR with respect to total spare capacity for 7 different maximum allowable *p*-cycle length with *m*-cycle for 19 node 28 span network.

Max. Allowable *p*-Cycle Length (in Kms)	Total Spare Capacity		
	SPR without *m*-Cycle	DPR with *m*-Cycle	% Decrease
5,000	66	64	03.03
6,000	62	60	03.22
7,000	58	58	00.00
8,000	58	54	06.89
9,000	56	52	08.00
10,000	54	50	07.40
11,000	54	50	07.40

The comparative study of DPR with *m*-cycle compared to SPR without *m*-cycle considering *p*-cycle length limit are shown in Fig. 4 and 5. Comparing the total spare capacity of two routing algorithm with *p*-cycle length limit including *m*-cycle properties, we find the total spare capacity of DPR with *m*-cycle is lesser than SPR without *m*-cycle.

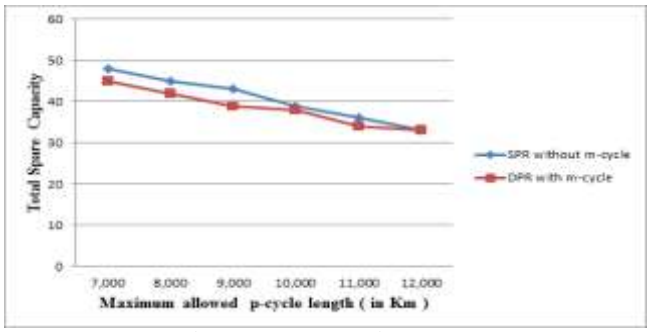


Fig. 4: Comparison of total spare capacity for 14 node 21 span (NSFNET) network.

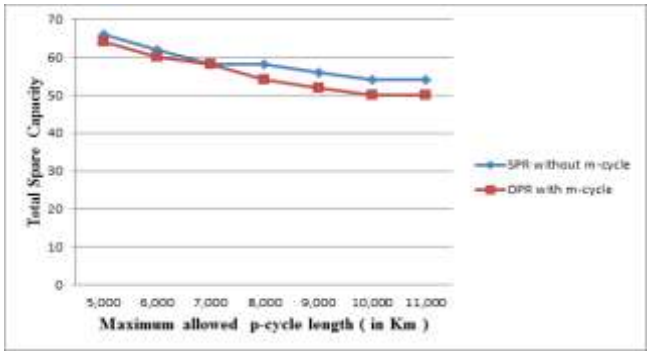


Fig. 5: Comparison of total spare capacity for 19 node 28 span network.

6. Conclusion

We applied DPR with *m*-cycle and SPR without *m*-cycle to WDM mesh networks and developed ILP optimization models to minimize total spare capacity with *p*-cycle length limit. Numerical results indicate that the requirement of total spare capacity for premium-grade, medium-grade and low-grade traffic demands by DPR with *m*-cycle is lesser than SPR without *m*-cycle considering *p*-cycle length limit. They also tell about the requirement of total spare capacity highly depends on routing of traffic demands between each demand pair.

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