p-Cycle Protection Without Wavelength Converters

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***Abstract*—The wavelength division multiplexing (WDM) networks can be protected using pre-configured protection cycles (*p*-cycles) offering great advantage in terms of speed as well as efficiency. To protect all the wavelengths in a WDM network having single fiber structure, *p*-cycles have to be established on spare wavelengths providing protection to the individual wavelengths carrying working traffic. In this scheme wavelength conversion capability for wavelengths on all links is needed. It will be interesting to investigate *p*-cycles without wavelength converters to reduce the cost. It is observed that the Hamiltonian network can be protected by a single Hamiltonian *p*-cycle by using a separate fiber for protection. Thus on failure, switching can be done to protect the whole fiber link without considering individual wavelengths. A single fiber based protection is therefore sufficient to provide protection to the WDM network without wavelength converters, as only fiber switching will be done. With this approach, we compensate the wavelength converters by additional fiber. The total network cost is expected to reduced as no wavelength converter will required. This is achieved at the cost of one separate fiber on all links for the formation of *p*-cycles.**

***Index Terms*—WDM, *p*-cycles, wavelength converters, protection, Hamiltonian cycle.**

I. Introduction

The significant demand of data services in current day world along with its criticality in all kind of business and governance processes, makes protection mechanisms in networks almost mandatory[13]. The communication between endpoint devices happen via paths created using wavelengths in optical networks, commonly referred to as Lightpaths. The protection of lightpaths from failures due to fiber cuts etc., is very crucial to avoid disruption in data services which may cause tremendous economical losses [9], [12]. Intermediate nodes present in the optical network can switch incoming lightpath to another node with or without wavelength converter. This conversion of wavelength is known as wavelength conversion and the device used for wavelength conversion is known as wavelength converter. Wavelength converters are costly and add to the hardware cost. They also degrade the signal quality during conversion process [6].

In order to protect the optical networks, protection paths are established along with the working paths. The traffic under normal operation is being carried by the working paths while in case of failure the same is switched through the protection paths [16]. There are various protection mechanisms out of which the concept of *p*-cycles have been found to be quite attractive in terms of higher restoration speed and spare capacity efficiency [1], [19], [18], [20].

In most of the studies based on *p*-cycles, availability wavelength conversion without any limit has been assumed. We are investigating the concept of *p*-cycle based protection in WDM networks when wavelength converters are not used. With our approach the *p*-cycle protection can be provided without wavelength converters thus the cost of converters. Although, as some other resources are bound to increase, it will be interesting to find out that what need to be added to compensate the lack of wavelength converters.

The paper is arranged as follows. Section II provides the concept of p-cycle protection. Section III summarizes the conventional approach. In Section IV, we have introduced our work. Section V gives the results followed by the conclusion in Section VI.

II. *p*-Cycles

As mentioned earlier, *p*-cycle is one of the effective protection methods in mesh network[8], [10].

They provide the advantages of being as capacity efficient as mesh protection mechanism and as faster as ring protection mechanism[4]. *p*-Cycles stands for pre-configured protection cycles [9], [11], [14], [15]. There can be many types of *p*-cycles depending on the constraints associated with their formation. Two of the types are as follows.
(i) Link *p*-cycle: It provides protection to the working capacity on a link (Figure(1)).
(ii) Node-encircling *p*-cycle: It provides protection against the node failures by forming cycles keeping the protected nodes enclosed within (Figure(4)).

Whenever configuring a network with *p*-cycles, first we route the connection according to the given demand such that working capacity gets reserved for that requirement. The remaining available capacity apart from working capacity is called as the spare capacity. In this spare capacity p-cycles are formed. The set of *p*-cycles are selected such that all working connections get protection with the associated *p*-cycle. Sometimes, spare capacity may not be sufficient enough for providing protection. Another approach is to find the minimum spare capacity needed by setting up *p*-cycles for providing protection to the working capacity on all the links. The efficacy of this strategy is measured by capacity efficiency which is the ratio of reserved capacity to form *p*-cycles to the total capacity required for working capacities on all links. A *p*-Cycle can provide protection to the links that are on the *p*-cycle also called as on-cycle links, as well as to the straddling links which are not on the *p*-cycle but their end nodes are. The on-cycle and straddling protection together results in higher efficiency. The protection is faster and simpler in *p*-cycles as only end nodes of the failed link need to perform switching action resulting in switching time of the order of 50-150ms. Thus *p*-cycle concept is found to be attractive in providing protection to the WDM networks[2], [7], [8].

Let us consider a network topology as an example with 6 nodes and 9 spans. For providing protection, *p*-cycles i.e. pre-configured cycles are formed. Figure (1) shows the network with a single link *p*-cycle drawn with dashed line. This p-cycle can provide protection to the links associated either on-cycle link or straddling link. Figure (2) shows the failure of on-cycle link BC; *p*-cycle provides protection in the manner as shown by the path BAFEDC and is referred as on-cycle link protection provided by the *p*-cycle. Figure (3) shows the failure in the straddling link BE; two alternate protection paths are provided by the *p*-cycle as shown by the path BAFE and BCDE and is referred as straddling link protection provided by the *p*-cycle.

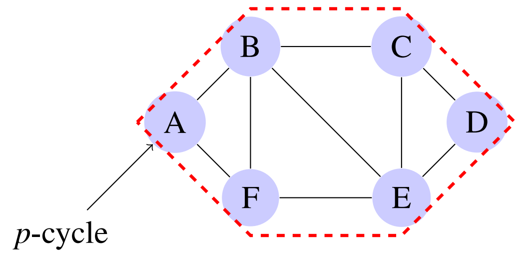

Figure 1: 6 nodes 9 spans network topology with a single link *p*-cycle

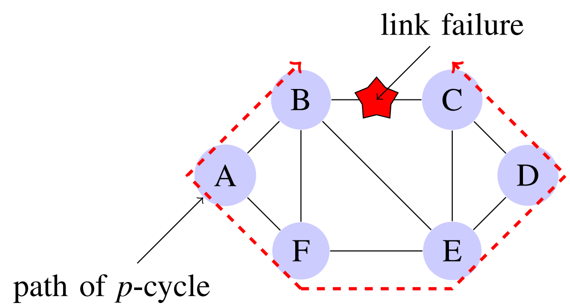

Figure 2: 6 nodes 9 spans network topology with an on-cycle failure

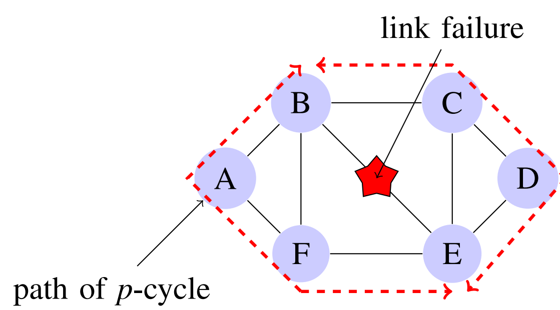

Figure 3: 6 nodes 9 spans network topology with straddling link failure

III. Conventional Approach

The conventional approaches studied so far consider the network topology with working paths as well as protection cycles routed using 100% wavelength conversion at each node [5][9]. This requires wavelength converters to be present at

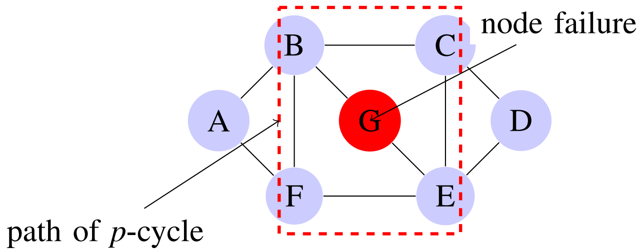

Figure 4: Node-encircling p-cycle

every node. If N is the number of wavelengths used and S is the number of links passing through any particular node then N*S number of wavelength converters will be required at that particular node. In order to protect these networks p-cycles were formed. In an optical mesh network with the following sets, parameters and variables, following integer linear programming (ILP) can be used to achieve minimum spare capacity.

Sets
- S set of spans indexed by j
- P set of p-cycles indexed by p
- L set of wavelengths indexed by l

Parameters
- c_j cost of span j (assumed as 1)
- w_j working capacity on span j
- x_{pj} 1 if p-cycle p protects span j as on-cycle, 2 as straddling 0 otherwise
- δ_{pj} 1 if p-cycle p passes through span j 0 otherwise

Variables
- n_p required number of unit capacity copies of p-cycle p
- s_j spare capacity required on span j

Objective

$$\min \sum_{\forall j \in S} c_j s_j \tag{1}$$

Subject to

$$w_j \leq \sum_{\forall p \in P} x_{pj} n_p \qquad \forall j \in S \tag{2}$$

$$s_j = \sum_{\forall p \in P} \delta_{pj} n_p \qquad \forall j \in S \tag{3}$$

$$n_p \geq \ 0 \qquad \forall p \in P \tag{4}$$

Equation (1) represents the objective of minimizing the total cost of spare capacity required to form the p-cycles. Equation (2) ensures that all the working capacity of every span gets 100% protection for a single failure. Equation (3) gives the required spare capacity on every span to form the p-cycles. Equation (4) ensures that the number of unit capacity copies of p-cycles formed should be an integer greater than zero.

Problem with the conventional ILP.

The conventional ILP assumed 100 percent wavelength conversion. This requires wavelength converters to be used for all working paths as well as for p-cycles. As mentioned above the number of wavelength converters required at any node will be $N * S$. For example, 20 wavelengths are to be used and on an average 5 links passes through a node then that node will require (20*5=100) 100 wavelength converters at a node on an average. This gives an upper limit. In reality, some paths and p-cycles will be setup without using the wavelength converters to the extent possible. As wavelength converters add to the cost, using so many converters e.g. 100 per node is not desirable. Besides cost, wavelength converters also degrade the signal performance. These are the problems with the conventional approach. So we are now exploring an optical mesh network along with p-cycle based protection but without wavelength converters as it will lead to reduced cost of the network.

IV. Our Work

Let us consider a network topology with a unit traffic matrix with a single fiber for every link in each direction. In order to provide protection to the links with a single fiber, p-cycles have to be formed on remaining spare capacity. Obviously the p-cycles can not be formed on the same wavelengths which are used for working paths. Hence wavelength converters are essential. In our approach we are modeling the network with separate fiber for protection, eliminating the need of wavelength converters. This will provide a single fiber for establishing the working paths and another fiber for the protection. p-cycles can be formed on this protection fiber. This will make a fiber based p-cycle. Whenever a failure will occur whole of the fiber present on the failed link will be switched over to the p-cycle formed using protection fiber. This will not require switching at individual working wavelength level. As a whole, the working fiber will be switched over to the *p*-cycle formed in protection fiber capacity independent of wavelengths used in the working fiber. If there is no limit on the length of the *p*-cycle, then Hamiltonian cycle, if feasible, will be the default solution. Hamiltonian cycle is a cycle in the network which passes through all the nodes exactly once[17]. Further, no link should be traversed more than once by the cycle. It is not necessary that a network will always have a Hamiltonian cycle. In that case multiple *p*-cycles will be required for providing 100% protection for all the links. These multiple *p*-cycles can be formed on multiple fibers. If there is a limit on fiber length for the *p*-cycles, then also multiple *p*-cycles will be required depending on the size of the network.

We are considering the Hamiltonian network with working paths established without the wavelength converters. They are provided protection by a single fiber on all the links used for forming the *p*-cycle. In this case, usual on-cycle protection will be provided. However, for straddling protection out of two alternate paths, only one will be used. It is so because we are providing protection to whole fiber alongwith with all its wavelengths. *p*-cycle protection on separate protection fiber will require a single path only as shown in Figure (5) and Figure (6).

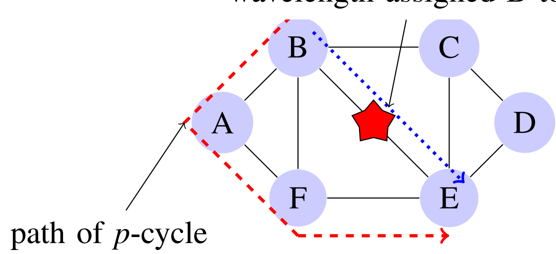

Figure 5: 6 nodes 9 spans network topology with single dashed path BAFE for straddling link failure BE with dotted line showing wavelength assigned

We have formulated the ILP for minimizing the fiber length required without using wavelength converters and with no limit on the fiber length in the *p*-cycles.

Parameters

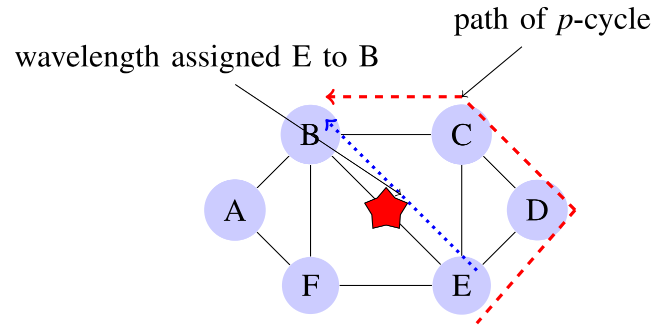

Figure 6: 6 nodes 9 spans network topology with single dashed path BCDE for straddling link failure BE with dotted line showing wavelength assigned E to B

l_j	length metric on span j
δ_{pj}	1 if *p*-cycle p passes span j 0 otherwise
x_{pj}	1 if *p*-cycle p protect span j as on-cycle as well as for straddling link

It implies that for straddling link *p*-cycle will provide protection to all the wavelengths as single fiber is used for working paths. Also our fiber based protection *p*-cycle will be independent of the working wavelengths. So there is no need of specifying working capacity on a span.

Variables

n_p	number of unit fiber copies of *p*-cycles p required

Objective

$$\min \sum_{\forall p \in P} n_p \sum_{\forall j \in S} \delta_{pj}.l_j \tag{6}$$

Subject to

$$1 \leq \sum_{\forall p \in P} x_{pj} n_p \qquad \forall j \in S \tag{7}$$

$$n_p \geq \ 0 \qquad \forall p \in P \tag{8}$$

Equation (6) provides the objective of minimizing the total spare capacity in terms of minimum fiber length required to form the fiber *p*-cycle. Equation (7) ensures that every span will be 100% protected by at least a single fiber based protection. Equation (8) ensures number of unit fiber capacity copies of *p*-cycle should be an integer greater than zero.

V. Results

We have consider two test network topologies, net1 with 19 nodes and 28 spans, and NSFNET with 14 nodes and 21 spans. The link length in km is shown in bracket above all links. We have consider unit traffic matrix and then routing is done following shortest path algorithm. ILPs are solved with ILOG CPLEX 9. p-Cycles are formed using breadth first search algorithm. We have compared the two test network topologies (Figure (7) and Figure (8)) for the conventional case and for our case. The conventional case routing is done using 100% wavelength conversion capability at every node. We estimated the number of converters for the conventional case in worst case scenario, assuming the number of wavelengths to be 10. Hence, for conventional case the total number of converters in a network topology will be sum total of converters at each node. But in the proposed method, routing is done without wavelength conversion thus saving converter cost. We estimated the route km of fiber length required for the proposed algorithm as an alternative to wavelength converters. Since an extra fiber is required to provide protection this fiber cost will required to be invested. It will be much lesser as compared to the wavelength converters' cost. As shown in Figure(7) and Figure(8) hamiltonian cycle is formed passing through the links indicated by dashed line, through which the extra fiber will be needed. For network of Figure(7) extra fiber will be needed on the links passing through the nodes 1,4,6,10,9,11,19,18,17,16,15,14,13,12,8,7,5,3,2,1. For network of Figure(8) extra fiber will be needed on the links passing through node 1,3,2,8,7,5,6,11,10,12,13,14,9,4. For conventional case, no extra fiber cost need to be invested as same fiber will be used for working as well as for protection. Table (I) and Table (II) illustrated the number of converters (A) required and route km of fiber length (B) required for both the test networks.

As shown in Table (I) and Table (II) for both the test networks, conventional case requires large number of wavelength converters but does not requires extra protection fiber as the same fiber is used for working as well as protection. In our case route km of protection fiber length is additonal but with the reduced cost of wavelength converters. As large number of converters are required and converters are costlier devices thus they highly increase network cost. But we have reduced the use of converter with meagre investment in extra fiber.

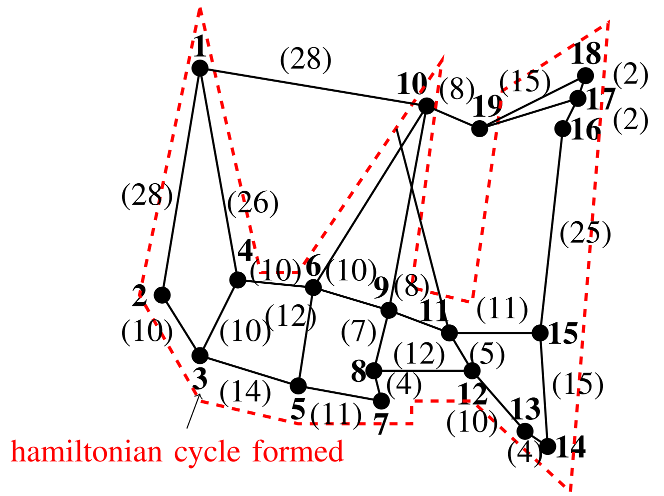

Figure 7: Test network net1 with 19 nodes and 28 spans

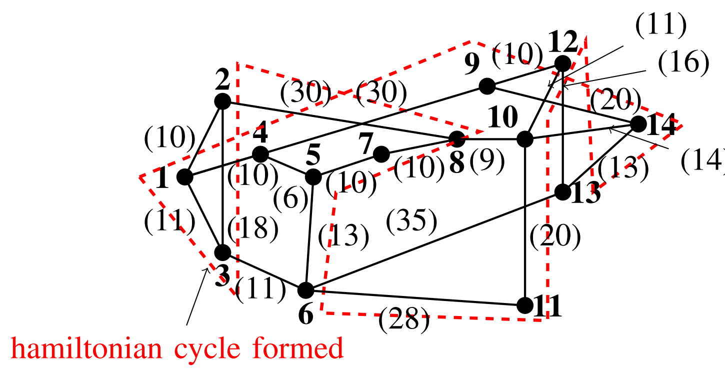

Figure 8: Test network NSFNET with 14 nodes and 21 spans

VI. Conclusion

We have developed an approach by which WDM networks can be protected with very efficient method of p-cycles without the use of wavelength converters. Avoiding wavelength converters reduces the network cost as well as improves signal quality as the signal performance will not degrade. We investigated that Hamiltonian cycle, if feasible, can provide protection by the use of separate fiber on all the links for the formation of p-cycles. Our approach gives reduced cost as compare to the work done so far.

Parameter	Conventional case	Our case
No. of wavelength converters required(A)	560	NIL
Route km of fiber length(B)	NIL	266

Table I: Comparison of net1 with 19 nodes and 21 spans for conventional case and our case

Parameter	Conventional case	Our case
No. of wavelength converters required(A)	420	NIL
Route km of fiber length(B)	NIL	226

Table II: Comparison of NSFNET with 14 nodes and 21 spans for conventional case and our case

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