A Heuristic Method for Design of Survivable WDM Networks With p-Cycles

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***Abstract*—We consider a new heuristic method for design of survivable wavelength-division multiplexing (WDM) networks with preconfigured protection cycles (p-cycles). Numerical studies show that the new heuristic works well for different traffic patterns, and the spare capacity obtained by the new heuristic is very close to that of the optimal solution but with much reduced computational time.**

***Index Terms*—Optical networks, p-cycles, protection and restoration.**

I. Introduction

IN OPTICAL wavelength-division multiplexing (WDM) networks, a failure of a network component can lead to a severe disruption in the traffic. Therefore, protection and restoration are imperative in the design of WDM networks. The method of preconfigured protection cycles (p-cycles), proposed by Grover's group [1]–[4], can achieve ring-like fast protection speed and mesh-like high efficiency of spare capacity. This is because a p-cycle can provide protection not only for on-cycle spans but also for straddling spans [1]–[4]. A straddling span is an off-cycle span having p-cycles nodes as end points.

The p-cycle design problem has been intensively studied and formulated as an integer linear program (ILP), which is very computationally intensive if the number of network nodes is large [4], [5]. To reduce the computational complexity, a method of preselecting a reduced number of candidate p-cycles was proposed in [3], where two preselection metrics, namely topological score (TS) and a priori efficiency (AE) of p-cycles, were reported to preselect p-cycles and then the ILP was applied to the preselected p-cycles to solve the p-cycle design problem. Our study has found that the preselection method may not perform well for certain traffic pattern. In this letter, we consider an attractively simple heuristic to solve the p-cycle design problem without using ILP. Numerical studies show that this new heuristic performs well for different traffic patterns compared with the pure preselection method. The redundancy obtained by this heuristic is very close to that of the optimal solution but with much reduced computational time. The heuristic itself appears to have been independently developed by both ourselves [10] and Grover in [8] and has also been called the "CIDA" algorithm for "capacitated iterative design algorithm" in [9]. The main contribution of this paper is to provide the first systematic study and quantitative results on the performance of this design heuristic.

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II. Heuristic Method for p-Cycle Design

In general, network traffic is unlikely to be symmetric in both directions between two nodes. This means that the number of working and protection wavelengths is not likely to be the same in both directions. Like in [5], we will consider unidirectional p-cycles in this paper without loss of generality. One unit of capacity is defined as one wavelength throughout the paper. We use *unity-p-cycle* to denote a unidirectional p-cycle whose capacity on every span is one unit of wavelength. A unity-p-cycle can protect one working unit in the opposite direction for every on-cycle span, and two working units (one in each direction) for every straddling span. The number of spare units of a unity-p-cycle is equal to the number of spans on the cycle. We define the efficiency ratio (ER) of a unity-p-cycle as the ratio of the number of working units that are actually protected by the unity-p-cycle to the number of spare units of the unity-p-cycle. Note that the ER of a unity-p-cycle is determined by both the topology and the working units that are actually protected by the unity-p-cycle, and hence it represents the *posteriori* efficiency of the unity-p-cycle, whereas the preselection metrics of TS and AE of a p-cycle are decided by the topology only [3]. In the following discussion, this heuristic is called the *ER-based unity-p-cycle design*. An unity-p-cycle with a greater ER means that its spare units are utilized more efficiently than an unity-p-cycle with a smaller ER. The idea behind this heuristic is to identify those unity-p-cycles that can actually protect as many working units as possible, and hence to reduce the total spare units.

For a given network topology and traffic demand, this ER-based unity-p-cycle design algorithm is summarized as follows:

1) Find all candidate cycles according to the algorithm in [6], and determine the working capacity on each span based on certain shortest-path routing algorithm [5]. (Note that this is a preprocessing step, and candidate cycles may be subject to certain constraints such as the maximum cycle length or hop count.)
2) For each candidate cycle, calculate the ER of its unity-p-cycle.
3) Select a unity-p-cycle with the maximum ER. If multiple unity-p-cycles have the same maximum ER, then randomly select one. (Note that in order to improve the

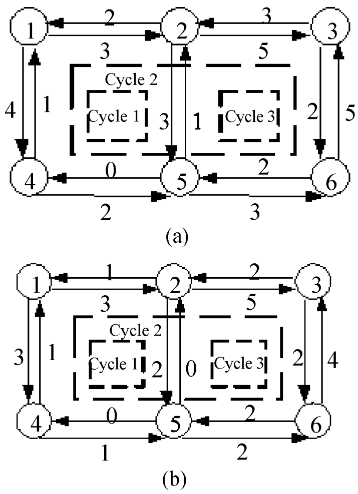

Fig. 1. A simple network showing three cycles and working capacity. (a) Initial working capacity. (b) Remaining working capacity.

speed, multiple unity-p-cycles may be selected at a time so long as they are span-disjoint.)

4) Update the working capacity by removing those working units that can be protected by the selected unity-p-cycle.
5) Go to Step 2 until the working capacity on every span becomes 0.

We now use a simple network in Fig. 1 to show how the algorithm works, where the numbers on the spans indicate the working capacity. The notation "span i $\rightarrow$ j" denotes a directional span from node i to node j. Fig. 1(a) illustrates the initial working capacity on each span. There are three candidate cycles, each of which can be in either the clockwise or counter-clock direction. As cycle 2 has six spans, its unity-p-cycle in the clockwise direction requires six spare units and can protect eight working units (including one unit on each of the two straddling spans $5 \rightarrow 2$ and $2 \rightarrow 5$, and 1 unit on each of the six on-cycle spans $1 \rightarrow 4$, $4 \rightarrow 5$, $5 \rightarrow 6$, $6 \rightarrow 3$, $3 \rightarrow 2$, $2 \rightarrow 1$), and hence its current ER is 1.33. The current ER's for all the unity-p-cycles in Fig. 1(a) are given in Table I. As the clockwise unity-p-cycle of cycle 2 has the maximum ER, it will be selected and the working units that can be protected by this unity-p-cycle will be removed. The remaining working units on each span are shown in Fig. 1(b). We shall see in Section III that, since the ER represents the posteriori efficiency of unity-p-cycles, this heuristic is very effective for the non-joint assignment of working and spare capacity under different traffic patterns, but it is not applicable to the joint assignment of working and space capacity [3], [5].

III. Numerical Results

To examine the effectiveness of this design heuristic, we have chosen the pan-European COST 239 network [5], [7] and three other networks reported in [4] as the test cases. Without loss of generality, we assume that each node performs full wavelength conversion, i.e., a lightpath can be switched to an output fiber at any free wavelength, each span has two fibers for bidirectional transmission, and the number of wavelengths per fiber is 64. Note that a network without wavelength conversion can be considered as a set of parallel networks each with different wavelengths, and hence the heuristic algorithm can be applied to

TABLE I
The ER for All the Unity-p-Cycles in Fig. (1a)

Cycle Number	Efficiency ratio (ER) of unity-p-cycle	
	Clockwise	Counter-clockwise
1	1.00	0.75
2	1.33	1.17
3	1.00	1.00

each of the parallel networks. We consider two different traffic patterns: (i) distributed pattern where the number of lightpaths between any two nodes is selected from 0 to 10 (both inclusive) using an uniform random distribution, and (ii) centralized pattern where each node has lightpath demands from and to a central node only and the number of lightpaths between the central node and any other node is an uniformly distributed random integer between 0 and 10 (both inclusive). The lightpath requests are routed based on the shortest path with metrics reciprocal to the free capacity of the span [5].

Fig. 2(a) compares the redundancy obtained by the ER-based unity-p-cycle design, the preselection method (500 cycles were preselected based on the AE and TS metrics in [3]), and the optimal solution using the ILP [3], [5] for the COST 239 network under both traffic patterns. Here, the redundancy is the ratio of the sum of spare units required on each span to the sum of working units on each span. The results are summarized as follows.

1) The ER-based unity-p-cycle design works well for both traffic patterns. The redundancy obtained by the ER-based unity-p-cycle design is very close to that of the optimal solution with a difference less than 5% for various max. allowed cycle lengths.
2) The preselection method is slightly better than the ER-based unity-p-cycle design for the distributed traffic pattern. However, it does not perform well for the centralized traffic pattern. Its redundancy is about 15% higher than that of the optimal solution, and about 10% higher than that of the ER-based unity-p-cycle design.
3) The redundancy is significantly reduced as the max. allowed cycle length increases for all the methods.

Fig. 2(b) shows the computational time versus the max. allowed cycle length for the COST 239 network for both traffic patterns. As the max. allowed p-cycle length increases, more candidate cycles are selected and hence the computational time for the optimal solution increases dramatically from 1.9 to 55 s for the distributed traffic pattern, whereas the computational time for the ER-based unity-p-cycle design is much lower, increasing from 0.15 to 2 s. For the preselection method, the number of preselected p-cycles is always fixed at 500 and hence the computational time is constant at 0.85 s for the distributed traffic pattern. Similar results for the centralized traffic pattern are also shown in Fig. 2(b). Note that the computing platform used is Intel Pentium IV 2.4-GHz PC running Windows 2000 with 512-MB memory and 24-GB hard disk.

We have also studied three other networks reported in [4] where the candidate cycles are not subject to the length constraint. Table II compares the redundancies obtained by different methods for both traffic patterns described above. As shown in Table II again, the redundancies obtained by the ER-based

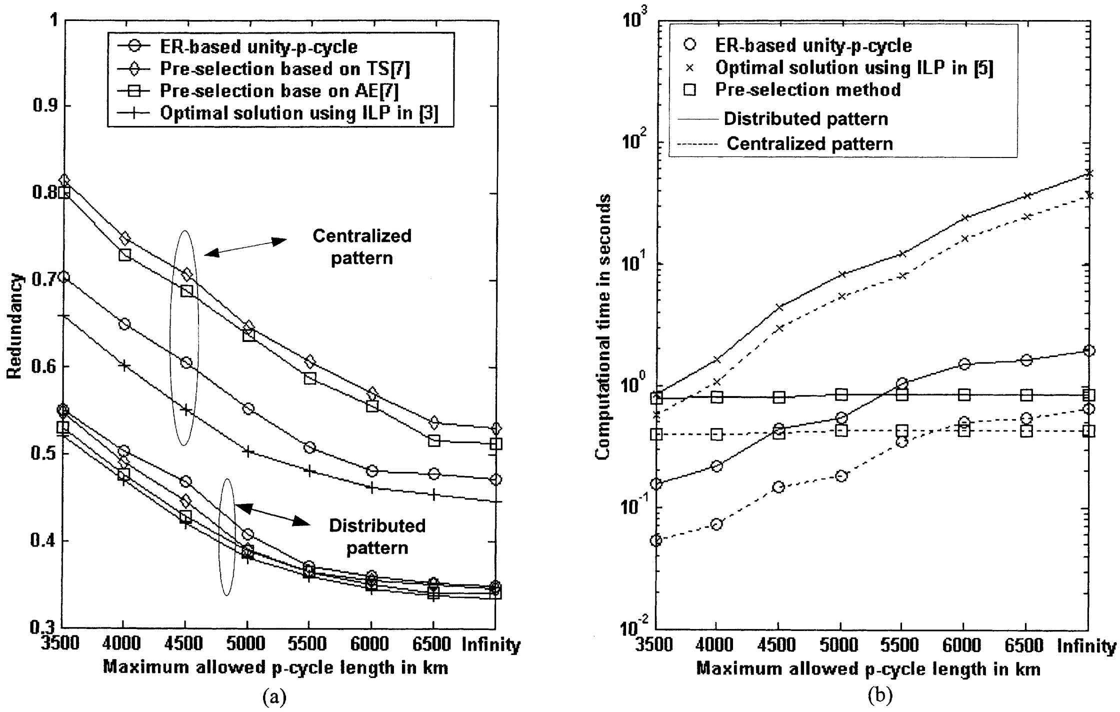

Fig. 2. Performance comparison among different methods for the COST239 network. (a) Comparison of redundancy. (b) Comparison of computational time.

TABLE II
COMPARISONS FOR DIFFERENT NETWORKS IN [4]

Network			Net2	Net3	Net4
Number of nodes			11	15	19
Redundancy	Distributed pattern	Optimal (ILP)	64.7%	52.8%	41.8%
		ER-based unity-p-cycle	72.5%	60.6%	47.1%
		Pre-selection (TS)	71.2%	59.5%	45.8%
		Pre-selection (AE)	68.4%	55.2%	43.2%
	Centralized pattern	Optimal	68.5%	56.5%	45.4%
		ER-based unity-p-cycle	72.5%	60.2%	49.6%
		Pre-selection (TS)	83.2%	70.8%	60.9%
		Pre-selection (AE)	80.5%	68.3%	58.8%

unity-p-cycle design differ from the optimal ones by 5.3% to 7.8% for both traffic pattern; the preselection method is slightly better than the ER-based unity-p-cycle design for the distributed pattern, but it requires 12% to 15% more redundancy than the optimal solution and 8%–10% more than the ER-based unity-p -cycle design for the centralized pattern.

IV. CONCLUSION

We have considered a new design heuristic, i.e., the ER-based unity-p-cycle design, for the construction of survivable WDM networks without using ILP. To evaluate the effectiveness of this new heuristic, we have studied four networks and compared the redundancies obtained by different methods under two different traffic patterns. The study has shown that the new heuristic performs well for both traffic patterns, and the redundancies obtained by the new heuristic are very close to that of the optimal solution with much reduced computational time.

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