A New *p*-cycle Based Survivable Design for Dynamic Traffic in WDM Networks

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Abstract—**Achieving both high capacity efficiency and fast restoration speed is a primary goal of survivable design in WDM network. p-cycle method uses cyclic preconfigured closed paths of spare capacity to provide protection. It aims to benefit from the fast restoration of ring-like protection and high capacity efficiency of mesh protection. The research on p-cycle design has been limited to static traffic. In this paper, we develop a new p-cycle based method to deal with dynamic traffic in survivable WDM network design. In this method, we first find an optimal set of p-cycles for the given network topology. Next, we propose three routing strategies for accommodating dynamic requests upon their arrival time. The performance of our p-cycle based design using different routing strategies are compared with that of the** ***Shared Backup Path Protection*****. The results show that proposed p-cycle based design method achieves fast restoration while having comparable capacity efficiency as the shared backup path protection.**

I. INTRODUCTION

Wavelength-division multiplexing (WDM) technology allows building of very large capacity, of the order of terabits per second wide area networks. Such networks provide low error rates and low delay and offer a viable solution to meet the bandwidth demand ever increasing. Wavelength division multiplexing divides the available bandwidth of a fiber into many non-overlapping channels, each channel carried on a different wavelength on the same fiber. All the channels can be used simultaneously.

Survivability is a critical part of WDM network design due to high traffic speed and high vulnerability. Two radical different approaches are widely adopted in survivable network design: protection and restoration. In protection method, spare resources are pre-allocated when a light path is established. The preplanning feature ensures fast recovering from possible failure. In contrast, restoration method does not allocate spare capacity in advance. Instead, the network searches for resources to recover from the failure in real time. Restoration method has the potential of improving resource utilization, but has the drawback of not having 100% restoration guarantee. We only consider protection for single link failure in this paper.

Capacity efficiency and restoration speed are two important aspects in survivable network design. There are two general protection methods: link based and path based methods. Link based methods employ *local detouring* while the path based methods employ *end-to-end detouring*. Link based methods generally have lower fault detection and recovering time than path based methods, but path based methods tend to use spare resources efficiently. Backup multiplexing is a technique that allows backup capacity to be shared when the corresponding primaries do not subject to a failure simultaneously. Therefore path based protection using backup multiplexing is capacity efficient. However, it often requires more restoration time because the nodes along backup route must reconfigure to establish the backup path corresponding to the working path that failed.

There has been research on protection methods using preconfigured cyclic form of spare capacity in mesh network. The motivation is to benefit from the advantage of fast restoration of ring-like protection. Notable among these is *Double Cycle Cover* and *p-Cycle* concept. They are both link based methods. In the double cycle cover [1], the network is represented by a directed graph. A set of cycles are embedded on the given topology. The links of the digraph are covered by two directed cycles such that each link is covered by a cycle in each direction exactly once. For planar graphs, the required set of protection cycles can be found in polynomial time, but no known polynomial-time algorithm for non-planar graphs. The model uses fiber-based recovery in which working fibers are backed up by a set of protection fibers. On each link, half of the capacity are reserved for backup and the other half are used for working traffic. The traffic on fibers in one direction on a cycle is backed up by protection fibers in opposite direction on another cycle. Since the protection switches can be preconfigured, and no signaling is required upon failure of a link, this method can achieve fast restoration. However, the capacity redundancy is at least 100%.

P-cycle protection method [2] also uses cyclic layout of spare capacity to provide protection. when a link fails, only the nodes neighboring the failure need to perform real-time switching. This makes p-cycle comparable to SONET/SDH line-switched rings in terms of speed of recovering from link failures. The key difference between p-cycle and ring protection is that p-cycle protection not only protects the links on the cycle, as in ring protection, it also protects straddling links. A straddling link is an off-cycle link whose two end nodes are both on the cycle. This important property effectively improves the capacity efficiency of p-cycles. Figure.1 depicts an example that illustrates p-cycle protection. In Figure.1 (a), A-B-C-D-E-A is a p-cycle formed using spare capacity. when

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an on-cycle link A-B fails, the p-cycle can provide protection as shown In Figure.1 (b). When a straddling link B-D fails, each p-cycle protects two working paths on the link by providing two alternate paths as shown in Figure.1 (c) and (d). This straddling link protection is important, because all the capacity on straddling link can be used for carrying working traffic.

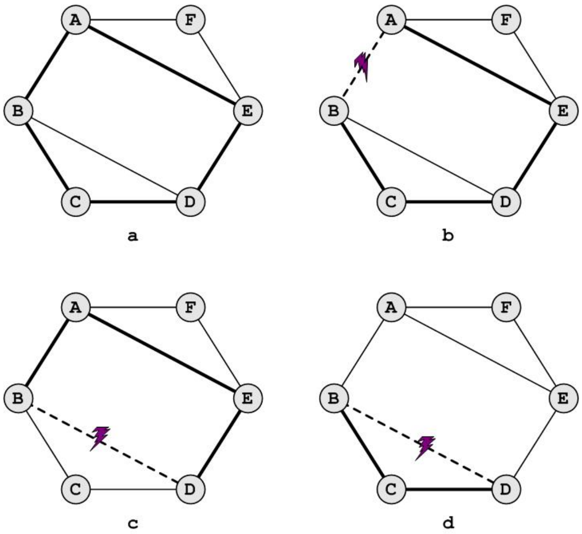


Fig. 1. (a) An example of p-cycle. (b) protecting on-cycle links. (c) (d) protecting straddling links.

The design of p-cycle restorable network is generally formulated as an Integer Linear Programming problem [2], [3]. First a set of all simple distinct cycles up to some upper bounded size is generated. The ILP solution identifies the optimal set of p-cycles in spare capacity of network by choosing the number of copies of each elemental cycle to be configured as a p-cycle. To reduce the computation complexity, an idea of pre-selecting a subset of cycle was proposed in [4]. A subset of cycles that have "high merit" are pre-selected and then provided to an otherwise unchanged optimal solution model. The joint optimization for a p-cycle design was considered in [4]. In joint optimization design, one attempts to optimize the choice of routing working connections in conjunction with the p-cycle selection so that the total capacity is minimized. Survivable design in WDM network with or without wavelength conversion using p-cycles were studied in [5]. Integer linear programs were formulated for both cases.

The research on p-cycle design has been limited on static traffic. In this paper, we consider survivable design for dynamic traffic and propose a new mechanism using the p-cycle concept. To evaluate the performance of proposed method, we compare it with shared backup path protection. The paper is organized as follows: Section II describes the survivable design model. The problem of finding a optimal set of p-cycles to cover network topology is formulated in Section III. The simulation design is described in Section V, and the results are discussed in Section VI. Section VII presents our conclusions and discusses possible future work.

II. NETWORK MODEL

The research on p-cycle has been limited on static traffic, i.e. the set of demands is given a priori. The objective is to identify an optimal set of p-cycles for a given traffic matrix so that all the demands can be met with restoration capability and the spare resources required is minimal. In a dynamic environment, the demands arrive at a network one by one in random manner. We do not have all the information of demands in advance. As reviewed in section I, a p-cycle protects both the links on the cycle and straddling links of the cycle. For on-cycle links, up to half of the capacity has to be set aside for protection, whereas for straddling links, there is no need to reserve spare capacity. To use p-cycle concept for protection in dynamic scenario, we need to consider the following two aspects.

- Selecting a set of p-cycles. Since we don't have all information about the demands, we must provide protection for each link, as every link may carry traffic in the future. In order to do this, we need to select a set of cycles in such a way that every link is either on at least one cycle or is a straddling link of a cycle, i.e. the end nodes of every link is on at least one same cycle. This set of cycles will serve as p-cycles.
- Capacity allocation. Again, as information of demands is not fully known in advance, to provide 100% protection against any single link failure, half of the capacity on the selected cycles needs to be reserved for protection.

To minimize the total reserved capacity, it is desired to minimize the total length of selected set of p-cycles. Thus, the propsed p-cycle design for dynamic traffic scenario can be summarized as following:

1. Compute a set of cycles so that the two end nodes of each link in the network is at least on one same cycle, and the total length of all cycles is minimum. These cycles will serve as p-cycles.
2. For each link on a cycle, reserve half of the capacity for protection purpose.
3. For each arrived connection request, route the request using remaining capacity in the network.

A. Performance Matrix

We define two redundancy metrics to characterize the capacity utilization: network redundancy and instant redundancy. Network redundancy (NR) is defined as ratio of total reserved capacity for protection over total available capacity for working traffic. It is determined by network topology and total available capacity when the network is built. Instant redundancy (IR) is defined as ratio of total used capacity for protection over total used capacity for working traffic at an instant time. IR characterizes the capacity utilization for the traffic that has arrived. NR can be computed by

$$NR = \frac{\sum_{k=1}^{L'} 0.5 \times C \times length(k)}{\sum_{j=1}^{L} C \times length(j) - \sum_{k=1}^{L'} 0.5 \times C \times length(k)} \quad (1)$$

Where j and k are link IDs, L is the total number of unidirectional links in the network, and L' is the total number of links that are on any of cycles that are selected as p-cycles. Assume that every link in the network has equal length, and initial available capacity on every link is same, denote as C, then

$$NR = \frac{0.5 \times C \times L'}{L \times C - 0.5 \times C \times L'} = \frac{L'}{2 \times L - L'} \quad (2)$$

We assume the network is bidirectional (each edge in the graph is considered as two simplex links operating in opposite directions). It is necessary that the set of selected cycles covers all the nodes in the network, then $L' \geq 2N$, N is the number of nodes in the network. Therefore,

$$NR \geq \frac{N}{L - N} \quad (3)$$

This provides a lower bound for NR under the assumptions that every link in the network has equal length, and initial available capacity on every link is same.

III. FINDING AN OPTIMAL SET OF P-CYCLES

The problem of finding an optimal set of p-cycles is the first step of design model discussed in section I. It can be defined as follows: *Given a network topology, represented as a directed graph $G(N, L)$, where $|V| = N$ and $|E| = L$, to identify a set of cycles with minimum total length so that for $\forall j \in E$, the two end nodes of j is at least on one same cycle.* The problem can be formulated as Integer Linear Programming (ILP) problem. Assume the set of all simple distinct cycles in the graph is P. P is precomputed using algorithm developed in [6]. The solution of ILP gives the set of selected cycles. As network size increases, the number of elemental cycles increases exponentially. A lot of research has been performed on Minimum Cycle Cover Problem (MCCP) in which the objective is to find a minimum cost set of cycles to cover all the edges of a graph). In [7], it is shown that MCCP is NP-complete. We suspect the problem of finding a minimum cost set of p-cycles is NP-complete. Proving this claim and finding heuristic algorithm for larger network is one of our future work. We define the notations and formulate the problem in the following.

- $j = 1, 2 \ldots, P$: Number assigned to a cycle.
- L_l: length of link l.
- ω_j^l: Link indicator, which takes a value of one if link l is on cycle j; zero otherwise (data).
- σ_j^l: Protection indicator, takes a value of one if link l is on cycle j or is a straddling link of cycle j; zero otherwise(data).
- δ_j: Takes a value of one if cycle j is chosen as a p-cycle in the design, zero otherwise. (binary variable)

A. ILP Formulation

- Objective: Minimize total length of all p-cycles.

$$min \sum_{l=1}^{L} \sum_{j=1}^{P} \delta_j \times \omega_j^l \times L_l \quad (4)$$

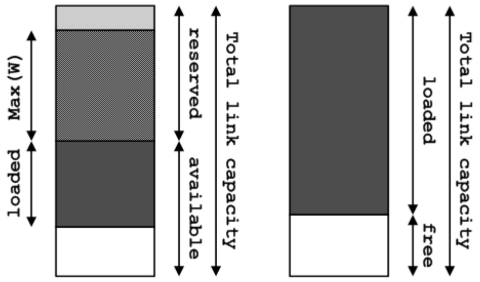
- Constraints: The end nodes of each link are at least on one same ring.

$$\sum_{j=1}^{P} \delta_j \sigma_j^l \geq 1 \qquad \forall l \in L \quad (5)$$

IV. ACCOMMODATING CONNECTIONS

A. Routing Strategies

Three routing strategies are used in step three of design model discussed in Section II, namely, $Shortest-Path-Routing(SPR)$, $Least-Loaded-Routing(LLR)$, $Most-Free-Routing(MFR)$. Three edge-disjoint shortest paths are pre-computed for each node pair. Figure. 2 describes the notations on link capacity usage. The loaded capacity on a link at an instant time is the capacity allocated to carry working traffic on the link. For every link on the p-cycles, half of total capacity has been reserved for protection, as shown Figure 2(a). At an instant time t, the actual used spare capacity on every link of p-cycles is same, denoted as $Max(W)$, as shown in Figure 2(a). It can be calculated as follows. At time t, we first find maximum number of wavelengths used for carrying working traffic on any of the links on p-cycles, denoted as $Max(W_{cycle})$, and the maximum number of wavelengths used for carrying working traffic on any of the straddling links of p-cycles, denoted as $Max(W_{straddling})$. $Max(W)$ is the number of wavelengths required on every link of p-cycles to provide 100% protection at time t. Therefore $Max(W) = Max(Max(W_{cycle}), \frac{1}{2}Max(W_{straddling}))$. There is no reserved capacity on straddling links. The rest of the capacity



(a) on-cycle link (b) straddling link

Fig. 2. Notations on link capacity usage.

is called free capacity on a link. Three routing strategies are defined as following.

- *Shortest-Path-Routing (SPR)*: A connection is always routed on its first shortest path of the node pair of this connection.
- *Least-Load-Routing (LLR)*: We define a maximum-load-link on a path is the link that has maximum load among all the links on the path. Load here is in terms of number of wavelengths used. The load on a path is defined as the load on the maximum-load-link on the path. When a call arrives, the load on three alternate paths of the node pair are compared. The path that has the least load is chosen for routing.
- *Most-Free-Routing (MFR)*: We define a least-free-link on a path is the link that has least free capacity among all the links on the path. The free capacity on a path is defined as free capacity on the least-free-link on the path. When a call arrives, the free capacity on three alternate routes of the node pair are compared. The path that has the most free capacity is chosen for routing. Note that although we assume initial capacity on every link in the network is same, after half the capacity on every link of selected p-cycles is reserved for protection, the available capacity for routing working traffic on every link is not same. Therefore, LLR and MFR are not same, as shown in Figure 2.

B. *Wavelength Continuity Constraint*

We assume that no wavelength conversion is available in the network. Therefore wavelength continuity constraint needs to hold for primary path. Since p-cycle protection is link-based protection method, in the absence of wavelength conversion, the p-cycle has to use same wavelength as the working traffic for protection. We assume that every link in the network has two fibers, one in each direction. We reserved half of capacity on every fiber in such way that working traffic using a wavelength on one fiber in one direction can always be backed up by same wavelength on another fiber in another direction. Figure 3 is an illustrative example. Suppose two cycles $1-4-3-2-1$ and $1-2-3-4-1$ are p-cycles. Assume every link has four wavelengths $\lambda_1 - \lambda_4$. We reserve λ_1 and λ_2 on every link of cycle $1-4-3-2-1$, λ_3 and λ_4 on every link of cycle $1-2-3-4-1$, for protection. λ_3 and λ_4 on the links of cycle $1-4-3-2-1$ can be used for carrying working traffic, which can be backed up by same wavelengths on cycle $1-2-3-4-1$. Similarly, λ_1 and λ_2 on the links of cycle $1-2-3-4-1$ can be used for carrying working traffic, which can be backed up using same wavelengths on cycle $1-4-3-2-1$. In Figure 3, the set of wavelengths reserved on a link for protection is denoted as $\{\lambda_i\}_b$, the set of wavelengths can be used for carrying working traffic on a link is denoted as $\{\lambda_i\}_w$.

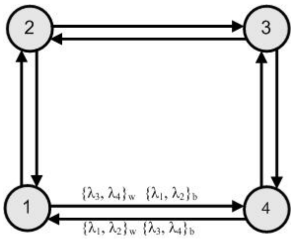


Fig. 3. An illustrative example of wavelength continuity constraint in p-cycle design

C. *Shared Backup Path Protection (SBPP)*

To evaluate the performance of proposed model, we use simulation of shared-backup-path-protection for the same set of connection request sets. For each node pair, three edge-disjoint shortest paths are precomputed. As a call arrives, a pair of paths from three alternate paths of the node pair are selected as primary and backup paths in such a way that the total increase in capacity due to routing this connection is minimum. The backup capacity is always shared when it is possible and not violating 100% protection. Wavelength continuity constraint applies to both primary and backup paths. First-Fit policy is used for wavelength assignment.

V. SIMULATION DESIGN

We evaluate our proposed design model by carrying out simulation experiments on Pan- European COST 239 network [8] with 11 nodes and 26 links as shown in Figure 4. The length of a link is the real distance between the two cities in km.

The dynamic traffic is generated based on a traffic matrix shown in Table I, which is obtained by dividing every entry of the traffic matrix in [8] by 2.5 Gbits/s. The demand unit in the matrix is one wavelength. We randomly pick a request from the traffic matrix and assume that service time of every request is infinite, i.e. the connections are not released once they are established. Dynamic here means that the network has no future information on which request is arriving at a particular time. That is, upon the request arrival time, only the information on existing lightpaths for previous requests is available, and it is not allowed to reroute the existing lightpaths for allocating the current arrival request. The network would select the best route for the current arrived request at the time of arrival, depending on the current network status.

A request is routed using routing algorithms defined in Section IV. We first study the capacity utilization performance under the assumption that initial capacity of network is enough to accept all connection requests. We then study the blocking performance, assuming that the network has limited resources.

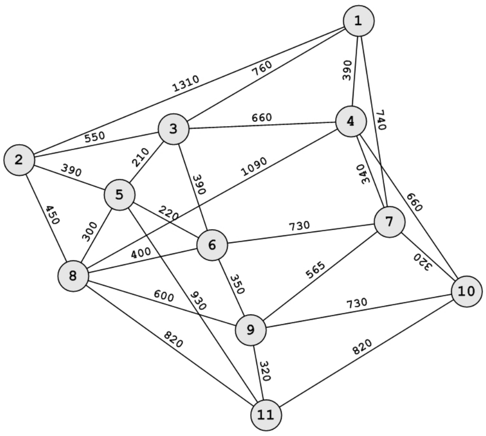


Fig. 4. Pan-European COST 239 network.

TABLE I

REQUEST MATRIX FOR COST 239 NETWORK

Node	1	2	3	4	5	6	7	8	9	10	11
1	0	1	1	3	1	1	1	1	1	1	1
2	1	0	5	8	4	1	1	10	3	2	3
3	1	5	0	8	4	1	1	5	3	1	2
4	3	8	8	0	6	2	2	11	11	9	9
5	1	4	4	6	0	1	1	6	6	1	2
6	1	1	1	2	1	0	1	1	1	1	1
7	1	1	1	2	1	1	0	1	1	1	1
8	1	1	5	11	6	1	1	0	6	2	5
9	1	3	3	11	6	1	1	6	0	3	6
10	1	2	1	9	1	1	1	2	3	0	3
11	1	3	2	9	2	1	1	5	6	3	0

VI. RESULTS AND DISCUSSION

A. *Finding an Optimal set of p-cycles*

Assuming the network is bidirectional, a total of 7062 simple distinct cycles are computed. This entire cycle set was provided as candidate cycles for optimal p-cycle selection. The ILP is solved using Cplex software. On a 2.5GHz SUN machine, the total running time for Cost 239 network is about 5 minutes. The ILP solution identifies two p-cycles, one in each direction: $1-4-7-10-11-9-6-8-2-5-3-1$ and $1-3-5-2-8-6-9-11-10-7-4-1$. Total length of two cycles is 9500 km.

B. *Capacity Utilization*

Assuming every link in the network has 60 wavelengths. The total length of all links in the network (considering bidirectional) is 30090 km. The total capacity in the network is then 1805400 *wavelength*× *km*. 30 wavelengths on the links of two cycles are reserved for protection. The total reserved capacity is thus 285000 *wavelength*× *km*. The network redundancy is 18.8%, computed using Equation 1 in Section II.

Ten dynamic request sequences are generated using the method described in section V. The requests are routed one by one using the three algorithms defined in SectionV. Table II and III list the capacity utilization using LLR and MFR. Working capacity on a link is the capacity used for carrying working traffic on a link, computed by multiplying number of wavelengths with the length of the link. Working capacity in column II is the total of working capacity required on all links. Column III is the total spare capacity used on the p-cycles after last request is routed. It is calculated using following equation

$$Total\ spare\ capacity = \sum_{k=1}^{L'} length(k) \times Max(W) \tag{6}$$

Where $Max(W)$ is defined in Section IV. Column IV in Table II and III is instant redundancy, defined in Section II. Column V is $Max(W)$. Column VI is the total capacity used after last request is routed. The unit for capacity is $(wavelength \times km)$ here and after. Figure 5 and Figure 6 show the total working capacity and total spare capacity of LLR and MFR, respectively.

TABLE II

LEAST-LOADED ROUTING

Simulation Index	Working Capacity	Spare Capacity	IR (%)	Max(W)	Total Capacity
1	316750	161500	51	17	478250
2	316980	161500	51	17	478480
3	328930	190000	58	20	518930
4	330410	180500	55	19	510910
5	350900	171000	49	18	521900
6	323470	171000	53	18	494470
7	328785	171000	52	18	499785
8	339430	199500	59	21	538930
9	310620	199500	64	21	510120
10	334585	171000	51	18	505585
Average	328086	177650	54	19	505736

.

TABLE III

MOST-FREE ROUTING

Simulation Index	Working Capacity	Spare Capacity	IR (%)	Max(W)	Total Capacity
1	332530	152000	45	16	484530
2	334625	180500	53	19	515125
3	334970	171000	51	18	505970
4	333600	142500	43	15	476100
5	341320	171000	50	18	512320
6	326925	133000	41	14	459925
7	348500	171000	49	18	519500
8	342980	161500	47	17	504480
9	341955	171000	50	18	512955
10	344150	171000	50	18	515150
Average	338155	162450	48	17	500605

Since we assume that all calls stay in the network, total working capacity and total spare capacity for SPR is the same

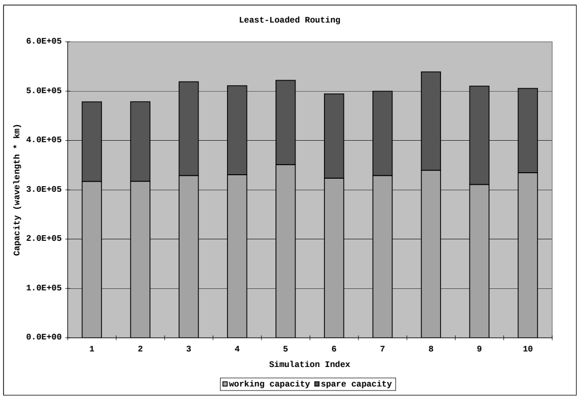


Fig. 5. Total working capacity and total spare capacity of Least-Loaded-Routing

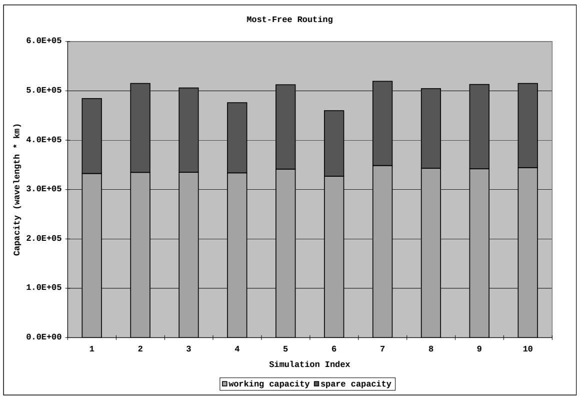


Fig. 6. Total working capacity and total spare capacity of Most-Free-Routing

for each of ten request sequences. Total working capacity is 270230, and total spare capacity is 247000. IR is 91%.

SPR uses least working capacity, as each request is always routed on the shortest path, and the most spare capacity among three routing algorithms. On the other hand, MFR uses the most working capacity and the least spare capacity. The reason is that MFR distribute the load most evenly. Hence $Max(W)$ is the least among all three. On average, MFR uses least total capacity after the last request is routed, and SPR uses the most total capacity.

For comparison purpose, we conducted simulation for SBPP for the same ten request sequences. The results are listed in Table IV. Figure 7 shows the total working capacity and total spare capacity of SBPP. On average, SBPP uses less working capacity than LLR and MFR, and more working capacity than SPR. SBPP uses almost same spare capacity as SPR. Among all schemes, SBPP uses most total capacity. Therefore, in terms of total used capacity, proposed p-cycle design using above routing algorithms performs better than SBPP.

TABLE IV
PATH PROTECTION WITH BACKUP MULTIPLEXING

Simulation Index	Working Capacity	Spare Capacity	IR (%)	Total Capacity
1	300720	225905	75	526625
2	306080	208660	68	514740
3	295200	237635	80	532835
4	304170	244135	80	548305
5	305505	217170	71	522675
6	296375	265120	89	561495
7	309995	238010	76	548005
8	298090	261385	87	559475
9	301135	242635	80	543770
10	295520	261570	88	557090
Average	301279	240222	79	541501

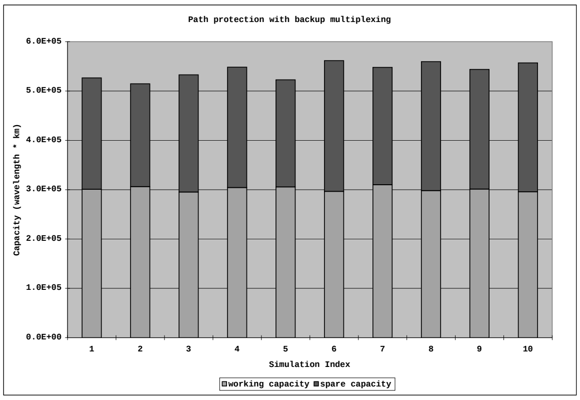


Fig. 7. Total working capacity and total spare capacity of Least-Loaded-Routing

C. Blocking Performance

To study the performance under the condition of non-enough resources in the network, we assume every link only has 30 wavelengths. The total capacity in the network is then 902700 *wavelength*×*km*. 15 wavelengths on the links of two cycles are reserved for protection. The total reserved capacity is 142500 *wavelength*×*km*. As the network load increases, some of requests are blocked. Table V presents the results for same 10 request sequences.

TABLE V

BLOCKING (ASSUME 30 WAVELENGTHS PER LINK)

Simulation	Number of blocked requests			
Index	SPR	LLR	MFR	SBPP
1	9	2	0	4
2	10	0	1	2
3	9	1	0	3
4	9	3	3	4
5	8	1	4	3
6	8	2	0	3
7	10	1	1	3
8	10	1	1	3
9	9	0	1	7
10	8	1	2	4
Average	9	1	1	4

Proposed p-cycle design with SPR has the most number of blocked requests. This is expected, as there is only one route is allowed for each request in SPR. The p-cycle design with LLR or MFR have average 1 blocked request, which is less than average 4 blocked requests in SBPP scheme. This is consistent with the result in Section VI-B where sufficient capacity is assumed. As we observed, under the assumption that there is enough capacity in the network, after all 110 requests are routed, SBPP uses more total capacity than p-cycle design. Therefore, when the network capacity is limited, SBPP leads to more number of blocked requests than LLR or MFR.

VII. CONCLUSION

The p-cycle concept is a type of cycle protection method in mesh network. The design goal of p-cycle protection is to retain the capacity efficiency in a mesh-restorable network, while approaching the speed of ring protection. We developed a new p-cycle based protection method for dynamic traffic in WDM network.

We first find an optimal set of p-cycles based on the given network topology, where the design goal is to minimize the weighted cycle length so that the reserved capacity in terms of wavelength-links in minimized. By using p-cycles to cover a network and reserving capacity on the links that are on p-cycles, the design can achieve 100% protection against single link failure for dynamic traffic. The next step is to route requests upon their arrival time. Three routing algorithms are hence proposed, namely Shortest-Path-Routing (SPR), Least-Load-Routing (LLR) and Most-Free-Routing (MFR). The numerical results obtained for a representative network indicate that Most-Free-Routing has best performance in terms of total capacity used. On average, Least-Load-Routing and Most-Free-Routing have almost the same blocking performance, and they are both performs better than Shared-backup-Path-Protection. It can be concluded that the proposed p-cycle based design for dynamic traffic can achieve fast restoration while having comparable capacity efficiency as Shared Backup Path Protection.

Developing efficient heuristic algorithm for finding minimum-length p-cycles is one of our future work. Studying the performance of propose p-cycle based design in sparser topologies and comparing with SBPP is another future work.

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