P-cycle Design for Translucent Elastic Optical Networks

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***Abstract*—This paper considers the protection of translucent elastic optical networks (EONs) through p-cycles. Such networks improve spectrum efficiency by employing regenerators and using advanced modulation formats for transmission. P-cycles provide fast restoration and high protection efficiency, and have been studied for conventional fixed-grid WDM networks as well as EONs. In this paper, we consider the design and selection of p-cycles for translucent EONs with 3R regenerators in a network. We propose two novel link-protection p-cycle evaluation methods in translucent EONs: individual p-cycle selection and p-cycle set selection. Based on these two metrics, Traffic Independent P-cycle Selection with 3R regenerator (TIPS-3R) and Traffic-Oriented P-cycle Selection with 3R regenerator (TOPS-3R), are designed to find the best set of p-cycles under a given 3R regenerator placement. We evaluate our algorithms using both static traffic and dynamic traffic. Simulation results indicate that the proposed algorithms have a lower spectrum usage and lower blocking ratio compared with baseline algorithms.**

***Index Terms*—Translucent elastic optical network, survivability, p-cycle, 3R-regenerator.**

I. Introduction

Elastic optical networks (EONs) are considered potential candidates to satisfy the future Internet bandwidth requirements due to the flexibility in resource allocation and spectrum assignment [1]. Different from conventional WDM network, the resource in EON is allocated as frequency slot (FS). EONs that allow optical signal regeneration of the lightpaths are named translucent EONs [2]. Compared with transparent EONs, translucent EONs have high spectrum utilization efficiency for increasing the transparent transmission reach by deploying 3R regenerators (devices with re-amplification, re-shaping and re-timing function).

Survivability is an important issue for optical networks, and there are many methods for protection [3]–[6]. P-cycle protection is very attractive due to high protection efficiency and high restoration speed. Protection from p-cycle is achieved by pre-connected ring-like structures. There are many p-cycle protection designs for EONs. In [7], p-cycles are evaluated with a metric called A Priori Efficiency (AE). In [8], a heuristic p-cycle protection algorithm is designed with spectrum sharing and defragmentation. In [9], a path-based protection p-cycle approach in transparent EONs is designed. In our previous work [10], two p-cycle selection algorithms for transparent EONs are proposed. However, all of these p-cycle approaches are designed for transparent EONs. This paper considers p-cycle protection for links in translucent EONs, and proposes metrics for designing and evaluating a set of p-cycles.

We aim to provide 100% failure-dependent protection against any single link failure. Two evaluation metrics are proposed: individual p-cycle cost and p-cycle set cost. These methods consider the 3R regenerator impacts. Based on our metrics, two selection methods are proposed: Traffic-Independent P-cycle Selection with 3R regenerator (TIPS-3R) and Traffic-Oriented P-cycle Selection with 3R regenerator (TOPS-3R). The p-cycle set generation algorithms are presented along with the routing and spectrum assignment algorithm. Our contributions are:

- We propose evaluation methods for a single p-cycle and a set of p-cycles with 3R regenerator consideration. To the best of our knowledge, this is the first paper that considers p-cycle evaluation in translucent EONs.
- We propose two heuristic algorithms to select p-cycles with and without traffic information.
- Based on the proposed metrics, we propose a cycle generation algorithm with a novel routing and spectrum assignment algorithm.
- We show the effectiveness of our metrics and algorithms for both static and dynamic traffic through simulation results.

II. Motivation and Problem Statement

A. Motivation

Compared with transparent EONs, 3R regenerator in translucent EONs is able to relax the transmission distance limitation and reduce the transparent transmission distance by cutting a long lightpath into short segments, over which higher levels of modulation can be used. The performance of a set of p-cycles is determined by the relative positions among links, cycles, and regenerators. Given the placements of 3R regenerators, a p-cycle set can be generated and customized for that placement. On the other hand, the placement of 3R regenerators is not the only factor that determines the p-cycle set performance. The physical length, load balance, and sharing backup possibility should be considered as well. For instance, a p-cycle with higher physical length has to be assigned a lower level modulation format for protection due to the transmission distance limitation. However, a larger p-cycle may provide a higher protection efficiency with more straddling links. A large p-cycle implies more resources are needed to protect from a single link failure, but the protection capacity can be shared among many links. However, there

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is a higher risk of "load imbalance", which is explained as follows. The protection bandwidth on every link of a p-cycle equals the largest working bandwidth of all the links protected by the cycle; therefore, if the load is not balanced, i.e., if the working bandwidth on the cycle links vary widely, then there is more capacity on the protection fibers that will be wasted because it cannot be shared.

B. Problem Statement

We formally define the problem as follows. Consider a network $G(N, E)$ with 3R regenerators, where N denotes the node set and E denotes the link set. On each link e, a pair of working fibers is used for working path, and a pair of protection fibers is used for the p-cycle protection path. A set of unidirectional lightpath request R is given, where each lightpath is denoted as $r(s, d, w)$, where s and d represent the source and destination nodes, and w represents the lightpath data rate. Suppose there are several modulation formats for different spectrum efficiencies and different distance limitations. The number and placement of 3R regenerators are assumed to be given, and we also assume that the regenerators at a node are available for all lightpaths passing through that node. The objective is to select a set of p-cycles that provides 100% link-protection with the minimum possible spectrum utilization in static traffic and minimum blocking ratio in dynamic traffic. This problem includes the routing and spectrum assignment problem (assign links and FSs) for each request r, and the assignment of a protection path for each link along the working path of request r with a set of p-cycles. While it may be possible to use 3R regenerators for spectrum conversion and/or modulation conversion, in this work, we assume that 3R-regenerators can only be used to extend the transmission distance.

III. P-CYCLE EVALUATION

In this and the next section, we present our methods to evaluate and generate p-cycles in a translucent EON network. In the evaluation section, we propose two approaches: Traffic-Independent P-Cycle Selection with 3R Regenerator (TIPS-3R) and the Traffic-Oriented P-Cycle Selection with 3R Regenerators (TOPS-3R). In TIPS-3R, the p-cycles are designed without a priori knowledge of the traffic requests. In TOPS-3R, the set of lightpath requests is known a priori. By using this information, a set of p-cycles that is tailor-made for this set of lightpaths is selected. For each approach, cost metrics are proposed to evaluate a single p-cycle as well as a set of p-cycles. Compared with the p-cycle selection algorithms in [10], these evaluations take 3R regenerators into account and use the potential working paths to achieve a more specific evaluation of both individual p-cycles and p-cycle sets.

A. Traffic-Independent P-cycle Selection with 3R Regenerator (TIPS-3R)

Here, assuming that the 3R regenerator placement is known while the information of traffic request is not known ahead of time, we aim to evaluate a set of p-cycles that is able to provide 100% protection. An individual p-cycle cost metric and a p-cycle set cost metric are proposed.

1) Individual Cycle Protection Cost: In order to evaluate the efficiency and cost of cycles with different modulation formats and 3R regenerator placements, the novel metric Individual Cost for TIPS ($IC_{TIPS-3R}$) is proposed as follows:

$$IC_{TIPS-3R} = \frac{AM \times L}{S} \times AP \qquad (1)$$

where L is the number of links on the p-cycle, and S is the number of links that can be protected by this p-cycle. The ratio L/S is a measure of the protection bandwidth needed per protected link of the p-cycle since every on-cycle link is allocated protection bandwidth but straddling links are not. AP is the average protection distance (in hops). AP is calculated by finding the number of hops on the p-cycle for each potential failed link, and then calculating the average number of hops. AP is designed for the risk of unshareable protection due to load imbalance. If the working capacity on a link is higher than on other links, the "extra" backup capacity cannot be shared by the other cycle links which have a lower working capacity. The risk of unshareability increases with the cycle length; thus, a p-cycle with larger AP corresponds to a higher unshareable backup resource cost for individual link failure. AM is the average modulation index of links that can be protected by the p-cycle. the modulation index of a link that can be protected by the p-cycle is calculated as follows:

For a link that can be protected by this p-cycle, we find all the potential[1] working paths that cross this link. Potential working paths are generated as follows: k-shortest paths (based on physical distance; we use $k = 5$ in the evaluation) are computed for each pair of network nodes. For each potential working path, the lightpath is cut into segments based on regenerator locations. The path that has the shortest longest segment among these paths is selected as the working path. The modulation format of the lightpath is determined by its longest segment.

Assume that all the links that can be protected by this p-cycle are protected by this cycle.[2] By failing a link, we can calculate different potential protection paths corresponding to different potential working paths respectively. Due to the existence of 3R regenerators, these potential protection paths are cut into several transparent segments. Then the modulation index of a protection path is determined by the physical distance of the longest segment. The modulation index of a link is determined by the average modulation index of all the potential protection paths. (For BPSK, QPSK, and 8QAM, the corresponding spectrum efficiencies are 1, 2, and 3 bits/s/Hz; therefore we choose the corresponding modulation index as 1, 0.5, and 0.34, respectively [5]. The modulation index represents the required spectrum resource normalized by that for the lowest modulation level, to support the same transmission bandwidth as its corresponding protection cycle.)

Here is an example for average modulation index calculation: Fig. 1 shows an example to calculate the average modulation index of link A-D in p-cycle A-B-C-D-A. Assume that link A-D has 2 potential working paths (Path 1 is Src 1 to Des 1 in blue and Path 2 is Src 2 to Dec 2 in red). There are

[1]These are called "potential" because the traffic is not known.

[2]In actuality, this need not be the case, since a link may be able to be protected by more than one cycle, but is actually protected by only one of those.

four 3R-regenerators placed at E, B, D, and F. The potential protection path for path 1 (Src 1 - E - A - B - C - D - Des 1) is cut into 4 segments (s1, s2 + A-B, B-C + C-D, and s6) by 3R-regenerators at E, B and D, while potential protection path 2 (Src 2 - F - D - C - B - A - Des 2) is cut into 4 segments (s5, s4, D-C + C-B, and B-A + s3) by 3R-regenerators at F, D, and B. Assume that the longest segment of potential protection path 1 is s1 and the longest segment of potential protection path 2 is B-A + s3. If the physical distance of s1 corresponds to QPSK with modulation index 0.5, and B-A + s3 corresponds to BPSK with modulation index 1, the average modulation index of link A-D is calculated as $(1 + 0.5)/2 = 0.75$.

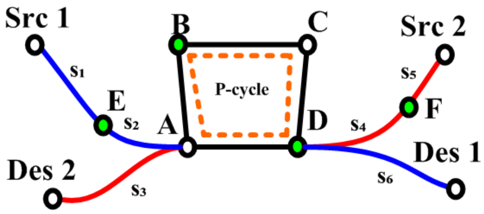

Fig. 1: Example for average modulation index calculation.

2) Cycle Set Protection Cost: Under the failure-dependent protection assumption, p-cycles may overlap with each other. However, a link is only protected by one p-cycle. Therefore, the accumulation of individual cycle's IC is not an effective cost metric for a group of p-cycles. The evaluation of a set of p-cycles is based on p-cycle Set protection Cost (SC). Due to the cycles overlapping, we assume that every link is protected by the lowest IC p-cycle that can provide protection to this link. If a link can be protected by more than one p-cycle which have the same lowest IC, which is unlikely to happen, the link will be assigned to one of them at random. The SC is calculated as follows:

$$SC_{TIPS-3R} = \sum_{p \in \mathbf{P}} \sum_{l \in \mathbf{p}} AM_l \times P_l \times N_p \tag{2}$$

where $\mathbf{P}$ is the set of candidate cycles that provides full protection for the network, p is an individual p-cycle in the set, and l is the set of links that are protected by p. N_p is the number of links that are protected by p. We need to emphasize that not all the links on the cycle are protected by the cycle. AM_l is the average modulation index for the link l protected by p, as calculated above. P_l is the protection distance in hops of l.

B. Traffic Oriented P-cycle Selection (TOPS)

1) Individual Cycle Protection Cost: In TOPS, the p-cycle evaluation and selection are based the 3R regenerator placement as well as the traffic. Given a set of lightpath requests with data rate in Gbps and 3R regenerator placements, we first route all the lightpath requests without any spectrum assignment. As before, we select the path with the shortest longest segment among the k shortest paths for a node-pair, and we use $k = 5$ in the evaluation. We use the total data rate on each link to evaluate an individual p-cycle and a set of p-cycles. The IC and SC for TOPS are calculated as follows:

$$IC_{TOPS-3R} = \frac{AM \times D_{\max}}{D_{\text{total}}} \times AP \tag{3}$$

where $D_{\max}$ is the maximum data rate over all the links that can be protected by this cycle, AM is the modulation index of the p-cycle, AP is the average protection distance of the cycle in hops, and D_{total} is the total amount data rate over all links that can be protected by this p-cycle. For the calculation of AM, we use following method: For a link that can be protected by this p-cycle, we find all the working paths that cross this link. Since the traffic is known, the working path pool in TOPS consists of the actual working paths instead of potential working paths. Assume that all the links that can be protected by this p-cycle are actually protected by this cycle. By failing a link, we can calculate different protection paths correspondent to different working paths. Then the modulation index of a protection path is determined by the physical distance of the longest segment. The modulation index of a link is determined by the average modulation index of all the protection paths. $D_{\max}$ and AP are used to evaluate the cost of protection capacity. D_{total} represents the total amount of data rate than can be protected by the cycle.

2) Cycle Set Protection Cost: In TOPS, the cycle set evaluation is based on data rate as well. The SC is calculated as follows:

$$SC_{TOPS-3R} = \sum_{p \in \mathbf{P}} AM_p \times D_{p,\max} \times AP_p \times N_p \tag{4}$$

where $\mathbf{P}$ is a set of cycles that provide full protection, AM_p is determined by the average modulation index of links that are protected by p, $D_{p,\max}$ is the maximum data rate over all the links that are protected by p, AP_p is the average protection distance of p in hops, and N_p is the number of links that are assigned to be protected by p. AM_p, $D_{p,\max}$ and AP_p are used to measure the cost of protection, and N_p is used to measure load imbalance and unshareable protection capacity, as in $IC_{TOPS-3R}$

C. Examples for TIPS and TOPS

Fig. 2 shows an example to calculate both IC and SC for TIPS and TOPS. Consider p-cycle 1 and p-cycle 2, namely A-B-D and B-C-E-D. P-cycle 1 has a shorter physical distance while p-cycle 2 has a longer physical distance. The total data rate of all working paths on each link is shown on the link in the unit of Gbps. In TIPS-IC calculation, assume that link

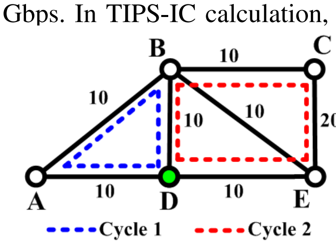

Fig. 2: Example for IC and SC in TIPS and TOPS.

A-B, B-D, A-D, B-E, D-E have average modulation index of 0.34 while link B-C and C-E have average modulation index of 0.5. Thus p-cycle 1 has an average modulation index of $(0.34 + 0.34 + 0.34)/3 = 0.34$, and p-cycle 2 has an average modulation index of $(0.34 + 0.34 + 0.34 + 0.5 + 0.5)/5 \approx 0.4$. The numbers of links that can be protected by p-cycle 1 and p-cycle 2 are 3 and 5 respectively, while the length (in hops) of p-cycle 1 and p-cycle 2 are 3 and 4 respectively. For p-cycle 1, the average protection distance (in hops) of on-cycle links is 2. For p-cycle 2, the protection distance (in hops) of on-cycle links is 3 and the protection distance of straddling link B-E is 2. The total protection distance is 14, therefore the average protection distance is 14/5. Finally, the $IC_{TIPS-3R}$ of p-cycle 1 is $0.34 \times 3 \times 2/3 = 0.68$. Using the same approach, the $IC_{TIPS-3R}$ of p-cycle 2 is $0.4 \times 4 \times 14/(5 \times 5) = 0.896$. Therefore cycle 2 is encouraged to be used due to a lower individual cycle cost.

Suppose now that p-cycle 1 and p-cycle 2 are regarded as a p-cycle set that provides 100% protection. The $IC_{TIPS-3R}$ of p-cycle 2 is higher than the $IC_{TIPS-3R}$ of p-cycle 1, therefore link B-D is protected by p-cycle 1. For p-cycle 1, assume that links A-B, B-D, A-D, B-E, D-E have average modulation index of 0.34 while link B-C and C-E have average modulation index of 0.5. The $SC_{TIPS-3R}$ of this cycle set is $(3 \times 0.34 \times 2 \times 3) + (2 \times 0.34 \times 3 \times 4 + 0.34 \times 2 \times 4 + 2 \times 0.5 \times 3 \times 4) = 29$.

Fig. 2 shows an example for$IC_{TOPS-3R}$ as well. Consider p-cycle 1 and p-cycle 2. For p-cycle 1, $D_{\max}$ is 10 while $D_{\max}$ is 20 in p-cycle 2 since it goes across link B-E. Therefore the IC_{TOPS} of p-cycle 1 is $0.34 \times 10 \times 2/(10 + 10 + 10) = 0.226$ while the IC_{TOPS} of p-cycle 2 is $0.4 \times 20 \times 14/5/(10 + 10 + 10 + 20 + 10) = 0.373$. Thus p-cycle 1 is determined to be better that p-cycle 2.

Now consider p-cycle 1 and p-cycle 2 as a set of p-cycles in TOPS. The $D_{p,\max}$ of p-cycle 1 is 10 while the $D_{p,\max}$ of p-cycle 2 is 20. The lengths of p-cycle 1 and 2 are 3 and 4 respectively. Since links are assigned to be protected by the p-cycle with lowest IC that can protect the link, N_p of p-cycle 1 and 2 are 3 and 4 respectively. The AP of p-cycle 1 is 2. In p-cycle 2, only link B-C, C-E, D-E and B-E are protected by p-cycle 2, thus the AP of p-cycle 2 is $(3 + 3 + 3 + 2)/4 = 2.75$ So the SC_{TOPS} of this cycle set is $(0.34 \times 10 \times 2 \times 3) + (0.4 \times 20 \times 2.75 \times 4) = 108.4$.

IV. Static P-Cycle Set Generation and RSA

A. Cycle Generation

In this paper, we use a similar algorithm to the one proposed in [10] for finding a set of p-cycles based on IC, SC, and 3R regenerator placement. This algorithm is used in both TIPS and TOPS. In this algorithm, we start by randomly finding a basic p-cycle and keep on expanding this p-cycle until the p-cycle cannot be expanded further. The p-cycle with the lowest IC will be selected as a candidate p-cycle. The links that can be protected with this p-cycle are marked as covered. Then we find a second random p-cycle that can provide protection to at least one uncovered link. Continue to expand the second p-cycle as the first p-cycle, and then we get the second candidate p-cycle. By randomly selecting p-cycles again and continuing in this manner, we generate a set of p-cycles that can be provide 100% protection after all the links in the network are marked as covered.

The above procedure produces a good p-cycle set since all the p-cycles selections are based on IC, but the p-cycle set is also somewhat random because since the initial p-cycle and p-cycle expansion are random. Thus, we generate a large number of such random p-cycle sets and choose the best p-cycle set among these as the set with the lowest SC. Later, the performance of such a p-cycle set will be compared with some baseline algorithms for selecting p-cycle sets.

B. Routing and Spectrum Assignment

This section presents the routing and spectrum assignment for the working paths and p-cycle protection. Both TIPS and TOPS use Algorithm 1 for RSA.

Algorithm 1 Routing and Spectrum Assignment

Input: Network topology, traffic requests, a set of P-cycles
Output: The working and protection spectrum assignment
for Each $LR(s, d, B) \in A$ **do**
  Use Shortest Longest Segment Algorithm among k-shortest paths with physical distance to find the working lightpath LP.
  for Each $l \in LP$ **do**
    Assume failure occurs in l
    Calculate the longest segment of protection path
    Determine the modulation with distance as M
  end for
  Select the modulation format that has the lowest modulation index
  Determine the number of FSs F
  Set $SI_{start} = 1$
  while $SI_{start} \leq SI_{max} - FS + 1$ **do**
    for every link $l \in LP$ **do**
      if FSs with index SI_{start} to $SI_{start} + F - 1$ are available **then**
        Assign SI_{start} to $SI_{start} + F - 1$ as working and protection FSs of LP.
        BREAK
      else
        $SI_{start} = SI_{start} + 1$
      end if
    end for
  end while
end for

In TIPS-3R, the *Best* p-cycle set can be found based on network topology and 3R regenerator placement. In TOPS-3R, the working paths are first routed without spectrum assignment by using the Shortest Longest Segment algorithm, and the total data rate on links is recorded. Then the IC and SC for TOPS are used to find the *Best* p-cycle set.

In the spectrum assignment step, first we use the Shortest Longest Segment algorithm among the k-shortest paths (where $k = 5$) to route the working path. After that, we fail the links on this working path one by one. For each failed link, we select the p-cycle with minimum IC to protect this link. The total physical distance of the protection path can be calculated by adding up the length of the working path (excluding the failed link) and the length of the protection path on the p-cycle for the failed link. Note that we use the shorter of the two cycle paths for protecting straddling links. For each protection path, the highest modulation level is determined by the longest transparent segment and the physical length of the working path (note that the protection path segments may be shorter than the working path). The minimum of these modulation indices (over all failed links) is then chosen as the modulation index for this lightpath and the corresponding modulation is selected. The lowest modulation index ensures that the distance constraint is satisfied no matter which link fails. After the modulation format is selected, the spectrum assignment along the working and protection paths are completed by using the first fit lowest FS index method if slots are available.

For the dynamic traffic model, the p-cycle set is generated with TIPS-3R since the lightpath requests are not known in advance. Therefore, a set of p-cycles based on IC and SC are selected in advance, and when a new lightpath request arrives, only RSA is performed and a modulation index is selected as described above. If FSs are not available for the request, the request is blocked.

V. Simulation Results

In this section, simulation results for the proposed p-cycle evaluation methods and RSA are presented. The COST239 network (consisting of 11 nodes and 26 links, shown in Fig. 3) and the pan-European network (consisting of 28 nodes and 44 links, shown in Fig. 4) are used for simulations. We consider three different types of traffic requests with

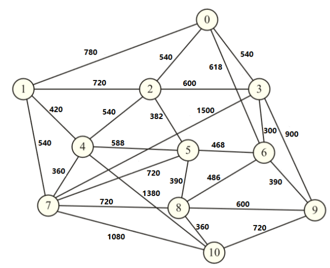

Fig. 3: 11-node COST239 network.

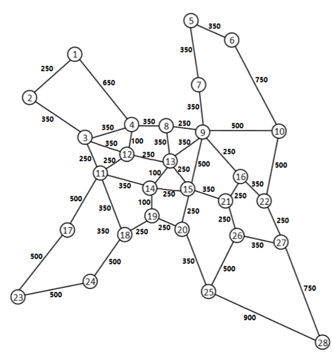

Fig. 4: 28-node pan-European network.

TABLE I
Number of required FSs for various data rates and modulations [5].

Modulation \ Date Rate	40	100	400
8QAM	2	3	11
QPSK	3	5	17
BPSK	4	9	33

data rate 40/100/400 Gbps with probability 0.2, 0.5, and 0.3, respectively. The source and destination nodes for each traffic request are uniformly randomly selected from the physical nodes of the network. The number of required FSs for a lightpath is determined by its data rate and assigned modulation format. Table I shows the number of FSs corresponding to different data rates under different modulation formats. For each modulation format, the physical distance limitations are shown in Table II. The modulation index in p-cycle evaluation and selection are also determined by this limitation. In static model, we assume that there is no physical distance limitation for BPSK in order to guarantee that all the traffic demands can be assigned. In order to show the effectiveness of our algorithm, we compare the *Best* p-cycle set with a random

TABLE II
Physical distance limitation for different modulation formats [5].

Modulation	Transparent Reach
8QAM	1000km
QPSK	2000km
BPSK	>2000 km

cycle set, Hamiltonian cycle [11], [3] and top A Priori Efficiency p-cycle set (TopAE) as the baseline p-cycle sets [10]. For Random Cycle Set, we generate all the cycles through an offline depth-first-search algorithm. The cycle set is formed by selecting p-cycles one by one at random from the pool of all cycles until the network is fully protected. In TopAE, we sort all the cycles with AE in non-decreasing order, then the cycles are selected one by one in this order until the network is 100% protected. We need to emphysize that, in Random cycle set and TopAE cycle set, only cycles that protect at least one unprotected link will be selected to the final p-cycle set.

The 3R regenerators are placed randomly, and all presented results are averages over 100 random placements for static traffic and 10 random placements for dynamic traffic. We assume that there are 3 3R regenerators in the COST239 network and 6 3R regenerators in the pan-European network.

For both TIPS-3R and TOPS-3R, the *Best* p-cycle set is found in advance by generating a large number of (≈ 3000) p-cycle sets and selecting the one with the lowest SC. While the p-cycle sets in TIPS are based only on topology, the sets are also based on the traffic and data rate in TOPS, as explained earlier.

A. Static Traffic

In static traffic model, we assume that there is no limit on the number of FSs on each fiber, thus requests are not blocked due to slot unavailability. The performance is evaluated in terms of spectrum utilization per link (the total number of used FSs for both working and protection on all fibers divided by number of links in the network). For each p-cycle set, we generate 100 sets of lightpath requests. In each set, there are 100 to 600 lightpath requests respectively. Fig. 5 shows the

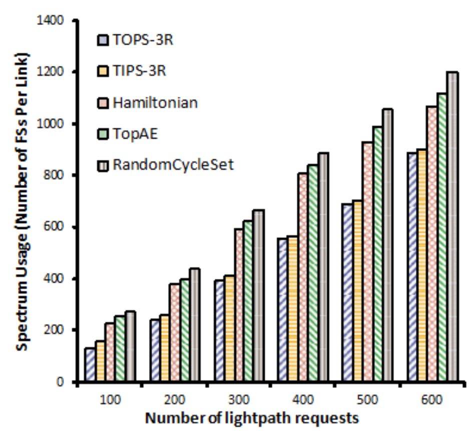

Fig. 5: Spectrum usage in COST239.

results for spectrum utilization for COST239, while Fig. 6 shows the results for pan-European network. TOPS-3R and TIPS-3R denote the *Best* p-cycle set generated by TOPS-3R and TIPS-3R. We make several observations from the

[3]Both the topologies in this paper have a Hamiltonian cycle.

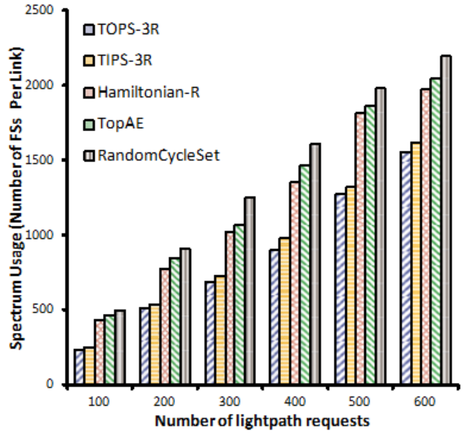

Fig. 6: Spectrum usage in pan-European.

results. TOPS-3R and TIPS-3R are better than the baseline algorithms in terms of spectrum utilization, pointing to the fact that careful p-cycle design considering all relevant parameters yields good results. Moreover, since TOPS-3R is based on traffic information as well, it is better than TIPS-3R.

B. Dynamic Traffic

In dynamic traffic model, 1 million lightpath requests arrive to the network according to a Poisson process with different arrival rates. Each request has a mean duration time of 1 (arbitrary time unit) with exponential distribution. Different from the static traffic model, the highest FS available on each fiber is assumed to be 352. If there is not enough available FSs, an arriving request will be blocked. The blocking ratio is calculated as the number of blocked requests divided by the total number of requests. Fig. 7 and Fig. 8 show the result of blocking ratio under dynamic traffic for the COST239 and Pan-European networks, respectively. We can see that the *Best* cycle set has the lowest blocking ratio. Since the *Best* p-cycle sets tend to have a short protection path, the lightpaths protected by these p-cycle sets have a higher probability of being assigned a higher level modulation, and is a reason for the superior performance of TIPS-3R.

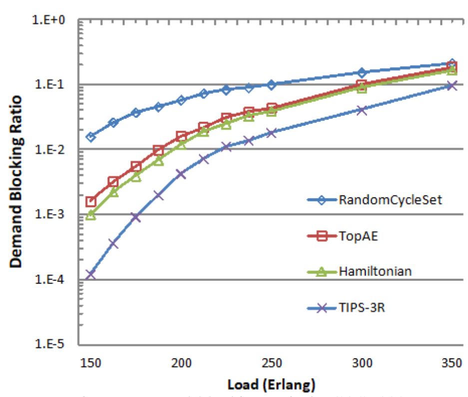

Fig. 7: Demand blocking ratio in COST239.

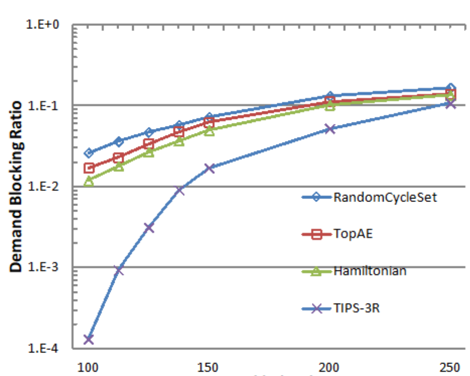

Fig. 8: Demand blocking ratio in pan-European.

VI. Conclusion

P-cycle protection in EONs requires the generation of a set of p-cycles that can provide 100% protection. In this work, we proposed methods to evaluate an individual p-cycle and a set of p-cycles in translucent EONs. These metrics consider the physical distance of lighpaths, multiple modulation formats, and the placements of the regenerators. Based on these evaluations methods, Traffic Independent P-cycle Selection with 3R regenerator (TIPS-3R) and Traffic-Oriented P-cycle Selection with 3R regenerator (TOPS-3R) are designed to generate a good set of p-cycles with a given 3R regenerator placement. Extensive simulations with both static traffic and dynamic traffic verified that the proposed metrics and algorithms can obtain a better p-cycle set compared with baseline algorithms in terms of spectrum utilization and blocking ratio. In this paper, we considered 3R regenerators to be available only to extend the reach of lightpaths. Our planned future work includes p-cycle design with both spectrum and modulation conversion using 3R-regenerators.

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References

[1] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, “Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies,” *IEEE communications magazine*, vol. 47, no. 11, pp. 66–73, 2009.

[2] M. Klinkowski, “On the effect of regenerator placement on spectrum usage in translucent elastic optical networks,” in *2012 14th International Conference on Transparent Optical Networks (ICTON)*. IEEE, 2012, pp. 1–6.

[3] A. E. Eshoul and H. T. Mouftah, “Survivability approaches using p-cycles in wdm mesh networks under static traffic,” *IEEE/ACM Transactions on Networking (TON)*, vol. 17, no. 2, pp. 671–683, 2009.

[4] H. M. Oliveira and N. L. da Fonseca, “Algorithm for fipp p-cycle path protection in flexgrid networks,” in *2014 IEEE Global Communications Conference*. IEEE, 2014, pp. 1278–1283.

[5] C. Wang, G. Shen, and S. K. Bose, “Distance adaptive dynamic routing and spectrum allocation in elastic optical networks with shared backup path protection,” *Journal of Lightwave Technology*, vol. 33, no. 14, pp. 2955–2964, 2015.

[6] P. Layec, A. Dupas, A. Bisson, and b. Bigo, “Qos-aware protection in flexgrid optical networks,” *IEEE/OSA Journal of Optical Communications and Networking*, vol. 10, no. 1, pp. A43–A50, 2018.

[7] Y. Wei, K. Xu, H. Zhao, and G. Shen, “Applying p-cycle technique to elastic optical networks,” in *2014 International Conference on Optical Network Design and Modeling*. IEEE, 2014, pp. 1–6.

[8] M. Ju, F. Zhou, S. Xiao, and H. Wu, “Leveraging spectrum sharing and defragmentation to p-cycle design in elastic optical networks,” *IEEE Communications Letters*, vol. 21, no. 3, pp. 508–511, 2017.

[9] X. Chen, M. Zhou, S. Zhu, S. Kang, L. Sun, and Z. Zhu, “Optimizing fipp-p-cycle protection design to realize availability-aware elastic optical networks,” *IEEE Communications Letters*, vol. 22, no. 1, pp. 65–68, 2018.

[10] R. Zou and S. Subramaniam, “Novel P-Cycle selection algorithms for elastic optical networks,” in *ONDM 2019 - 23rd International Conference on Optical Network Design and Modeling (ONDM 2019)*, Athens, Greece, May 2019.

[11] D. A. Schupke, “On hamiltonian cycles as optimal p-cycles,” *IEEE communications letters*, vol. 9, no. 4, pp. 360–362, 2005.