Link-protection and FIPP p-cycle designs in translucent elastic optical networks

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Elastic optical networks (EONs) are able to provide high spectrum utilization efficiency due to flexibility in resource assignment. In translucent EONs, by employing regenerators and using advanced modulation formats for transmission, spectrum efficiency can be further improved. Survivability is regarded as an important aspect of EONs, and p-cycle protection is considered to be an attractive scheme due to its fast restoration and high protection efficiency. In this paper, we propose methods for evaluating and selecting p-cycles for both link protection (LP) and failure-independent path protection (FIPP) to survive single-link failures. After considering the various factors that affect the performance of a p-cycle, we propose two evaluation metrics for LP and FIPP, namely, individual p-cycle cost and set of cycles cost. Based on these metrics, we propose two algorithms for selecting a set of p-cycles in translucent EONs: Traffic Independent P-cycle Selection (TIPS), which selects a set of cycles without knowledge of the traffic, and Traffic-Oriented P-cycle Selection (TOPS), which takes given traffic information into account. A routing and spectrum assignment algorithm is designed for translucent EONs, and our p-cycle design algorithms are evaluated using both static and dynamic traffic models. Simulation results show that the proposed algorithms have better performance than commonly used baseline algorithms. We also compare the performance of LP p-cycles and FIPP p-cycles.

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1. INTRODUCTION

With the dramatic growth of network traffic, the elastic optical network (EON) has emerged as a promising solution for the backbone network due to its flexibility in resource allocation and spectrum assignment [1]. Compared with fixed-grid wavelength-division multiplexing (WDM) networks, the major advantage of EONs is variable granularity and a flexible grid. In fixed-grid WDMs, the channel frequencies are fixed (typically spaced 25 or 50 GHz apart) and the bandwidth of each channel is often much larger than the requested bandwidth of a service, leading to poor spectrum utilization [2]. EONs employ a flexible grid with center frequencies spaced a much finer 6.25 GHz apart and orthogonal frequency-division multiplexing to reduce the bandwidth allocation level to the frequency slot (FS), which is 12.5 GHz wide [3]. At the same time, the development of transceivers supporting multiple modulation formats has made it possible for multiple contiguous FSs with the most spectrally efficient modulation format to be allocated to a service as needed, and thus the valuable fiber spectrum can be much more efficiently utilized. The resource allocation issue has evolved from the routing and wavelength assignment problem in conventional WDM networks into the routing and spectrum assignment (RSA) problem with spectrum continuity and spectrum contiguity in EONs [4–7].

Survivability is an important issue for optical networks, and the two main approaches are protection and restoration [8]. This paper focuses on protection methods for EONs. There are many methods for protection [2,9–13], with p-cycle protection being a particularly attractive one due to its high restoration speed and protection efficiency [14–17]. P-cycles provide protection against failures using preconnected ring-like structures. The restoration speed of p-cycles is due to the fact that the switches on the protection path are preconnected, and only the nodes where traffic is diverted to backup paths have to be configured when a failure occurs. There are two types of p-cycle protection: link protection (LP) and failure-independent path protection (FIPP). In LP, a link is protected by a backup path on the p-cycle between the two end nodes of the link. An LP p-cycle can protect a link if the link is an on-cycle link or a straddling link of the p-cycle. All network links can be protected by selecting a set of p-cycles. In FIPP, upon failure, traffic is diverted to a backup path on the p-cycle at the source node. In this case, a p-cycle provides protection to all the working paths between any pair of nodes that are on the
p-cycle, and the protection path is the same for a working path no matter which link on the path fails.

This paper integrates the work in [18,19] (which focus on LP p-cycle design) and extends it to include FIPP p-cycle design. In addition, we present more extensive simulation results in this paper. Our goal in this paper is to design spectrum-efficient p-cycles to protect against single-link failures in translucent EONs for both LP and FIPP. In our work, we assume that protection bandwidth of p-cycles can be shared among multiple working paths as long as they are disjoint. Two evaluation metrics are proposed for both LP and FIPP p-cycles: individual p-cycle cost and p-cycle set cost. These methods consider the regenerator placement and a variety of other factors that affect p-cycle performance. Based on our metrics, two selection methods are proposed: Traffic-Independent P-cycle Selection (TIPS) and Traffic-Oriented P-cycle Selection (TOPS). We then present simulation results showing the performance improvement of our methods over common baseline algorithms. Our contributions are summarized as follows:

- We propose evaluation metrics for a single p-cycle and a set of p-cycles.
- We propose p-cycle design methods for both LP p-cycles and FIPP p-cycles, with and without traffic information.
- We show the effectiveness of our metrics and algorithms for both static and dynamic traffic through simulation results.
- We compare and analyze the performance of LP p-cycles and FIPP p-cycles.

The paper is organized as follows. A brief background on protection in EONs is given in Section 2. Related work is presented in Section 3. The p-cycle design problem is formulated in Section 4. Metrics for LP and FIPP p-cycles are presented in Sections 5 and 6. This is followed by our p-cycle design algorithm based on these metrics in Section 7. A simple RSA algorithm for working paths in EONs is presented in Section 8, and extensive simulation results are presented in Section 9. The paper is concluded in Section 10.

2. BACKGROUND

A. Protection in EONs

Protection can be generally classified as dedicated backup protection and shared backup protection [20]. In dedicated backup protection, each path has a dedicated backup path, while shared backup protection means different paths may have a shared protection path. For dedicated backup protection, Klinkowski and Walkowiak [21] propose an RSA with dedicated path protection (DPP) as an integer linear programming (ILP) model and an adaptive frequency assignment DPP heuristic algorithm.

In shared backup protection, the protection capacity can be shared among different working paths [10,22,23]. Compared with dedicated backup protection, in shared backup protection, a protection unit (which can be a path, fiber, or FS) can be assigned to protect more than one working unit. Thus, a shared backup scheme is able to provide full protection with a lower protection capacity [24].

B. LP P-Cycle

In LP p-cycle protection, all links on the p-cycle as well as straddling links can be protected by a backup path on the p-cycle. Examples of LP p-cycles are shown in Fig. 1. Figure 1(a) shows a p-cycle A-B-F-E-C-A (bold line). The on-cycle link A-B is protected by the path A-C-E-F-B, as shown. Figure 1(b) shows that straddling link A-E can be protected by two paths on the p-cycle, namely, A-C-E and A-B-F-E. One of these paths must be preselected for protecting link A-E. To achieve 100% protection against single-link failures, a set of p-cycles must be established such that each link is protected by a cycle in the set. Even though there may be multiple cycles (in a set of cycles) capable of protecting a given link, only one cycle from the set must be preselected for the link in order to preconfigure the switches. Upon a link failure, all the affected working paths will be switched to the preselected protection path on the preselected p-cycle.

C. FIPP P-Cycle

In FIPP p-cycle protection, the protection path is established along the p-cycle between the source and destination nodes of the traffic. The traffic is switched to the protection path at the source node of an affected working path when a failure occurs. A working path can be protected by an FIPP p-cycle if both of its end nodes are on the p-cycle. Thus, each node pair is assigned an FIPP p-cycle to realize protection.

Figure 2 shows examples of FIPP p-cycles. In Fig. 2(a), suppose that the FIPP p-cycle is A-B-D-H-G-C-A (bold line). The working path is G-E-F-B and two protection paths can be provided by the FIPP p-cycle, since the working path and p-cycle are disjoint. Figure 2(b) shows the protection if there is a single common link between the working path and the p-cycle. Suppose the working path is G-H-F-B (marked with a solid green line); the protection path can only be established on one side of the p-cycle (G-C-A-B, marked with a dotted green line). If the number of common links is more than one, two protection paths are necessary under the single-failure assumption. For instance, in Fig. 2(b), if the working path is C-A-E-F-H-D (marked with a solid blue line), the two protection paths are C-A-B-D and C-G-H-D (marked with dotted blue lines), and only one of these may be used depending on the failure. (Note that by FIPP here, we mean that the same p-cycle is used regardless of which working path link fails; the actual backup path on the p-cycle may depend on which link fails. This usage of FIPP is consistent with other papers in the literature).
3. RELATED WORK

P-cycle protection has received much attention recently. In [25], ILP models for both LP p-cycle and ring cover protection techniques are proposed. The candidate p-cycles of ILP are generated by sorting all the individual p-cycles with a metric called a priori efficiency (AE) [26], but AE is not designed for EONs and does not consider the efficiency of a set of p-cycles. In [27], an ILP model and a column generation algorithm are proposed for transport networks (without spectrum assignment). In [2], an ILP model is presented and a p-cycle ranking method is proposed for fixed-grid WDM networks. In [28], an LP p-cycle algorithm is designed for fixed-grid WDM optical data center networks. In [29], a distance-adaptive LP p-cycle algorithm is proposed for fixed-grid WDM networks that considers modulation selection. All of these LP p-cycle methods are not designed for EONs, which means spectrum assignment is not considered. In [30], the proposed LP p-cycle protection strategy is based on a genetic algorithm, but the protection spectrum sharing issue is not considered. In [24], ILP and heuristic LP p-cycle protection algorithms are designed with spectrum sharing and defragmentation. However, in this work, the traffic on one link can be protected by two p-cycles simultaneously. In [14], a service-availability-oriented LP p-cycle is designed to improve request availability in EONs. In our previous work [18], two LP p-cycle selection algorithms are proposed for EONs.

For FIPP p-cycle designs, in [31], a column generation algorithm is designed for an FIPP p-cycle. An FIPP spare capacity placement iterative heuristic method is also presented. This work is for general transport networks. In [32], an ILP algorithm and four heuristic algorithms are proposed for an FIPP p-cycle in EONs, but these are traffic protection designs, wherein two lightpaths with the same source node and destination node may be protected by two different FIPP p-cycles. The traffic information is also necessary for this p-cycle design. In [9,33], heuristic algorithms for FIPP p-cycles are proposed for EONs, but there is no modulation consideration. In [34], an FIPP p-cycle is designed for dual failure without spectrum assignment consideration. In [35], an FIPP p-cycle is designed with traffic grooming. In [36], a dynamic p-cycle design is proposed with spectrum planning, but this work lacks distance and modulation consideration. In [37–39], FIPP p-cycles are designed for space-division multiplexing. In [40,41], service-availability-oriented FIPP p-cycle algorithms are presented. In [15], p-cycles are designed with power efficiency consideration.

In summary, many p-cycle approaches are presented for fixed-grid WDM networks, and some for EONs. All of these p-cycle methods are designed for transparent networks. Regenerators in translucent networks allow higher-level (i.e., more spectrally efficient) modulation formats and longer p-cycles, which improve spectrum efficiency. LP p-cycle design methods in translucent networks are proposed in our earlier paper [19]. This paper adds FIPP p-cycle design methods and is the first one (to our knowledge) to compare LP p-cycle design with FIPP p-cycle design for our proposed algorithms, as well as several baseline algorithms.

4. MOTIVATION AND PROBLEM STATEMENT

A. Motivation

As mentioned earlier, our goal in this paper is to design spectrally efficient p-cycles for LP and FIPP to achieve 100% protection against single-link failures. Many authors formulate the p-cycle design problem as an ILP problem [25,32,42], which is not scalable beyond very small network topologies because of the large number of cycles that exist even in small topologies. Accordingly, we propose the development of efficient heuristic algorithms for p-cycle design and evaluate their performance against common baseline algorithms. The performance of p-cycles depends on many factors such as the length of the cycle, number of links on the cycle, and number of regenerators on the cycle.

A regenerator is able to relax the transmission distance limitation of a lightpath by cutting a long lightpath into short segments, over which higher levels of modulation can be used. The length of the longest segment on a backup path (and hence the modulation format to be used for the lightpath) depends on the relative positions among links, cycles, and regenerators, as shown in Fig. 3. The white nodes are nodes without regenerators, while the yellow nodes have deployed regenerators. The blue dashed lines represent the lightpaths. S1 and S2 are segments formed by regenerators. The performance of a set of p-cycles is thus determined by the regenerator locations. Given the locations of regenerators, a p-cycle set can be generated and customized for that placement.

However, the placement of regenerators is not the only factor that determines the p-cycle set performance. For instance, since the modulation format is determined by the transparent transmission distance of the lightpath, cycles with a longer physical distance have to be assigned a lower-level modulation format for protection, while small cycles can be assigned higher-level modulation to achieve better spectrum efficiency.
A large p-cycle also implies that more FSs are needed to protect against a single-link failure. However, in a large p-cycle, the protection capacity can be shared among many links. A small p-cycle requires fewer FSs for each link failure protection, but small p-cycles imply a lower probability of having straddling links, leading to a lower protection capacity to working capacity efficiency. Besides these conventional trade-offs, distance-dependent modulation in EONs requires that the physical length of p-cycles also be considered in the evaluation and selection of a p-cycle.

**B. Problem Statement**

We formally define the problem as follows. Consider a translucent network $G(N, E)$ with a given placement of regenerators, where $N$ denotes the node set and $E$ denotes the link set. On each link, there is a pair of fibers (with opposite directions) used for working paths, and a pair of fibers is used for the p-cycle protection paths. A set of unidirectional lightpath requests $R$ is given, where each lightpath is denoted as $r(s, d, w)$, with $s$ and $d$ representing the source and destination nodes, respectively, and $w$ the lightpath data rate. Assume there are several modulation formats with different spectrum efficiencies and distance limitations. Given the placement (i.e., node locations) of regenerators, we assume that there are enough regenerators deployed at each location to regenerate all the lightpaths passing through that node. Spectrum continuity and spectrum contiguity need to be satisfied [43]. For all the traffic requests, working paths and protection paths must have the same FS index. Protection capacity for different link-disjoint working paths may be shared, because single-link failures are assumed. While a regenerator can potentially perform spectrum conversion and/or modulation conversion, in this work, we assume that they are used only to extend the lightpath transmission distance and/or increase the modulation level. (This assumption is partly due to the fact that changing modulation or spectrum along the path may require the source and destination to reconfigure their transmission and reception parameters, respectively. Our current assumption does not require them to be reconfigured when switching to the protection path.) The objective is to select a set of LP p-cycles (or a set of FIPP p-cycles) that can provide full protection with the minimum possible protection bandwidth in static traffic and minimum blocking ratio in dynamic traffic. This problem includes two parts. One is the RSA problem for the working path of each request $r$, and the other is the assignment of a protection path with a set of p-cycles for each request $r$.

In the next two sections, we present metrics for evaluating an individual p-cycle and a set of p-cycles collectively, for both LP and FIPP.

**5. LP P-CYCLE EVALUATION**

We present two approaches for evaluating LP p-cycles in a translucent network, called TIPS and TOPS, for cases when the traffic is not known ahead of time, for example, when requests arrive dynamically.

**A. Traffic-Independent LP P-Cycle Selection**

We now propose evaluation metrics for LP p-cycles that are suitable when the traffic is not known ahead of time, for example, when requests arrive dynamically.

1. **Individual Cycle Protection Cost**

In order to evaluate the efficiency and cost of cycles with different modulation formats and regenerator placements, the metric Individual Cost for TIPS (IC$_{TIPS-LP}$) is proposed as follows:

$$IC_{TIPS-LP} = \frac{L}{NP} \times \sum_{e \in E} AM_e \times PD_e,$$

where $L$ is the length of the cycle in hops and $NP$ is the number of links that can be protected by this p-cycle. The ratio $L/|NP|$ 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. The second ratio is used to evaluate the average protection cost of all the links. Assume that all the links that can be protected by this p-cycle are assigned to be protected by this cycle. (Note that a link may be able to be protected by more than one cycle, but only one of these cycles is assigned for protecting the link.) $\epsilon$ is the set of links that can be protected by the cycle, and $PD_e$ is the protection distance (in hops). $PD_e$ is calculated by finding the number of hops on the p-cycle for a potential failed link $\epsilon$. $PD_e$ is designed to account 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 that have a lower working capacity. The risk of unshareability increases with the cycle length; thus, a p-cycle with a larger $PD_e$ value corresponds to a higher unshareable backup resource cost for individual link failure.

$AM_e$ is the average modulation factor of link $e$. The modulation factor of a link that can be protected by a p-cycle is calculated as follows: We find all the potential working paths that cross this link (these are called “potential” because the traffic is not known). Potential working paths are generated using our Cost Routing (CR) algorithm, which will be introduced in Section 8. By failing a link $e$, we can calculate different potential protection paths corresponding to different potential working paths. Due to the presence of regenerators, these potential protection paths are cut into several transparent segments. Then the modulation format of a protection path is determined by the physical distance of the longest segment. The modulation factor of a link is determined by the average modulation factor of all the potential protection paths. [For binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), and 8 quadrature amplitude modulation (8QAM), the corresponding spectrum efficiencies are 1, 2, and 3 bits/s (bps)/Hz; therefore, we choose the corresponding modulation factor as 1, 0.5, and 0.34, respectively. The modulation factor represents the required spectrum resource...
normalized by that for the lowest modulation level, to support the same transmission bandwidth as its corresponding protection cycle.]

Figure 4 shows an example for calculating the average modulation index of link A-D in p-cycle A-B-C-D-A. Assume that link A-D has two potential working paths (Path 1 is Src 1 to Des 1 in blue and Path 2 is Src 2 to Des 2 in red). There are four 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 four segments (S1, S2 + A-B, B-C-D, and S6) by regenerators at E, B, and D, while potential protection path 2 (Src 2-F-D-C-B-A-Des 2) is cut into four segments (S5, S4, D-C-B, and B-A + S3) by 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 factor 0.5, and B-A + S3 corresponds to BPSK with modulation factor 1, the average modulation factor of link A-D is calculated as \((1 + 0.5)/2 = 0.75\).

2. Set of Cycles Protection Cost

Note that p-cycles may overlap with each other, but a link is only protected by one predetermined p-cycle. Therefore, the summation of each cycle’s IC is not necessarily an effective cost metric for a set of p-cycles. Here, we present the evaluation of a set of p-cycles based on p-cycle SC. If there are overlapping cycles, 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 with 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:

\[
SC_{\text{TOPSIS-LP}} = \sum_{\epsilon \in P} NP_{\epsilon} \times \frac{\sum_{e \in e} AM_{e} \times PD_{e}}{NP_{\epsilon}},
\]

where \(P\) is the set of candidate cycles that provides full protection for the network, \(\epsilon\) is an individual p-cycle in the set, and \(e\) is a link that is protected by \(\epsilon\) (we use \(\sum_{e \in e}\) to denote all the links that are protected by cycle \(\epsilon\)). \(NP_{\epsilon}\) is the number of links that are protected by \(\epsilon\). We need to emphasize that not all the links on the cycle may be assigned to be protected by the cycle. \(NP_{\epsilon}\) is used to evaluate the risk of unshareable protection and cost load imbalance. The ratio \(\sum_{e \in e} AM_{e} \times PD_{e}\) is used to evaluate the average LP cost. \(AM_{e}\) is the average modulation index for link \(e\) protected by \(\epsilon\), as calculated above. \(PD_{e}\) is the protection distance in hops of \(\epsilon\). As we mentioned above, smaller \(AM_{e}\) and \(PD_{e}\) values indicate that fewer protection FSs are required. \(NP_{\epsilon}\) is a measurement of the possibility of unshareable protection and load imbalance. A p-cycle set with a lower SC is expected to result in a better set of cycles and is encouraged to be used for protection.

B. Traffic-Oriented LP P-Cycle Selection

In TOPS, we assume that the set of lightpath requests and their data rates is known. Given a set of lightpath requests with a data rate in gigabits per second, we first find a route for all the lightpath requests without any spectrum assignment by using the CR algorithm (Section 7), and then record the data rate information on all links. We use the total data rate on each link when evaluating the p-cycles. The IC and SC for TOPS are calculated as follows.

1. Individual Cycle Protection Cost

The IC is calculated as

\[
IC_{\text{TOPSIS-LP}} = \frac{D_{\text{max}}}{D_{\text{AVG}}} \times L \times \sum_{e \in e} AM_{e} \times PD_{e} \times \frac{NP_{\epsilon}}{NP_{\epsilon}}.
\]

where \(D_{\text{max}}\) is the maximum data rate over all the links that can be protected by this cycle, \(D_{\text{AVG}}\) is the average data rate of all the links that can be protected by this cycle, \(L\) is the length of the cycle in hops, and \(NP_{\epsilon}\) is the number of links that can be protected by this p-cycle. \(D_{\text{max}}\) and \(D_{\text{AVG}}\) are used to evaluate the load imbalance condition. As we mentioned above, the “extra” backup capacity cannot be shared by the other cycle links that have a lower working capacity. \(L\) is used to account for the extra cost of this imbalance. \(AM_{e}\) is the modulation factor of the link \(e\). \(PD_{e}\) is the protection distance of the cycle in hops. The ratio is used to evaluate the average protection cost of all the links.

2. Set of Cycles Protection Cost

In TOPS, the cycle set evaluation is based on the data rate as well. The SC is calculated as follows:

\[
SC_{\text{TOPSIS-LP}} = \sum_{\epsilon \in P} NP_{\epsilon} \times L \times D_{\text{max}} \times \sum_{e \in e} AM_{e} \times PD_{e} \times \frac{NP_{\epsilon}}{NP_{\epsilon}}.
\]

where \(P\) is a set of cycles that provides full protection, \(NP_{\epsilon}\) is the number of links that are protected by \(\epsilon\), \(NP_{\epsilon} \times L \times D_{\text{max}}\) is used to evaluate the load imbalance and unshareable protection. \(AM_{e}\) is the average modulation index for the link \(e\) protected by \(\epsilon\), as calculated above. \(PD_{e}\) is the protection distance in hops of \(\epsilon\).

6. FIPP P-CYCLE EVALUATION

In this paper, we assume that all working paths between a given pair of nodes use the same backup path (i.e., are protected by the same FIPP p-cycle), and can therefore be switched together regardless of what spectrum these working paths are assigned to. This is different from [32], in which different working
paths for a given node pair may use different p-cycles and therefore different backup paths. We note that doing so would require a more complex frequency-aware switch, as the backup path depends on the slots assigned to the working path. As in the LP p-cycle evaluation, we propose two approaches, TIPS and TOPS, based on the IC and SC.

### A. Traffic-Independent FIPP P-Cycle Selection

We propose the following two cost metrics for IC and SC.

#### 1. Individual Cycle Protection Cost

In FIPP p-cycle IC evaluation, we first assume that all the node pairs that can be protected by a p-cycle are assigned to be protected by this p-cycle. The IC of an FIPP p-cycle is calculated as follows:

\[
IC_{\text{TIPS-FIPP}} = (S + 1) \times \frac{\sum_{n \in c} AM_n \times PD_n}{NP}.
\]

where \( AM_n \) is the modulation factor of node pair \( n \). It is determined by the shortest of the longest segments on the potential working path and protection path(s) for \( n \). PD\(_n\) is the total data rate for all node pairs that can be protected by cycle \( n \). NP is the number of links that can be protected by the p-cycle. AM\(_n\) times PD\(_n\) divided by NP is used to evaluate the average protection cost for each node pair. The ratio of the best protection cost of the cycle. \( S \) is the Unshareable Factor of the FIPP p-cycle, and is calculated as follows.

Given an FIPP p-cycle, we first generate all the potential working paths for every on-cycle node pair based on \( k \)-shortest paths and the shortest longest segment path algorithm (as in the AM calculation). Thus, if the number of hops in the cycle is \( n \), the number of potential working paths is \( n \times (n - 1)/2 \). \( S \) is the number of working path pairs that have a common link. An example of the Unshareable Factor calculation is shown in Fig. 5. In Fig. 5, suppose the FIPP p-cycle is A-B-D-H-G-C-A (bold line) and there are four potential working paths: \( S_{AB} \) (A-B), \( S_{AC} \) (A-C), \( S_{AH} \) (A-E-F-H), and \( S_{GB} \) (G-E-F-B). Of these working paths, only \( S_{GB} \) and \( S_{AH} \) have a common link, so the value of \( S \) is set to 1. Since the number of working path pairs with common links may be 0, we use \( S + 1 \) in Eq. (5).

#### 2. Set of Cycles Protection Cost

As in LP, FIPP p-cycles may overlap with each other, but a node pair is only protected by one predetermined p-cycle. We again assume that each node pair is protected by the lowest-IC p-cycle that can provide protection to this node pair. The SC is then calculated as follows:

\[
SC_{\text{TIPS-FIPP}} = \sum_{c \in P} (S_c + 1) \times \sum_{n \in c} AM_n \times PD_n.
\]

where \( P \) is the set of candidate cycles that provides full protection for the network, \( c \) is an individual p-cycle in the set, and \( n \) is an individual node pair that is protected by \( c \). \( S_c \) is the Unshareable Factor of cycle \( c \) based on the node pairs that are protected by \( c \). AM\(_n\) represents the modulation factor of node pair \( n \). PD\(_n\) represents the protection distance in hops for node pair \( n \). AM\(_n\) times PD\(_n\) is used to evaluate the total protection cost of all the node pairs.

### B. Traffic-Oriented FIPP P-Cycle Selection

In TOPS, the working paths are first routed without spectrum assignment by using the CR algorithm (Section 8), and the data rate information on links is recorded. Then the IC and SC for TOPS are calculated as follows.

#### 1. Individual Cycle Protection Cost

In IC evaluation, we assume that all the node pairs on the p-cycle are assigned to be protected by the p-cycle. The IC of FIPP in TOPS is calculated as follows:

\[
IC_{\text{TOPS-FIPP}} = (S + 1) \times \frac{\sum_{n \in c} AM_n \times PD_n}{D_{\text{Total}}},
\]

where \( AM_n \) represents the modulation factor and PD\(_n\) represents the protection distance in hops for node pair \( n \). \( S \) is the Unshareable Factor for the cycle, as in TIPS. Here \( D_{\text{Total}} \) is the total data rate for all node pairs that can be protected by this p-cycle.

#### 2. Set of Cycles Protection Cost

The SC of FIPP in TOPS is designed as follows:

\[
SC_{\text{TIPS-FIPP}} = \sum_{c \in P} (S_c + 1) \times \frac{\sum_{n \in c} AM_n \times PD_n}{D_{\text{Total},c}}.
\]

Given a set of cycles, each node pair is only protected by one p-cycle, even though a node pair can be protected by more than one p-cycle. Here, we only calculate AM\(_n\) and PD\(_n\) for the node pairs \( n \) that are protected by p-cycle \( c \). \( D_{\text{Total},c} \) is the total data rate for all node pairs that are protected by cycle \( c \). Also, the calculation of \( S_c \) and \( D_{\text{Total},c} \) are only based on node pairs that are protected by \( c \).

### 7. P-CYCLE DESIGN

Having presented the cost metrics for evaluating a single cycle and a set of cycles, we now describe our algorithm for p-cycle design based on IC and SC. The algorithm, whose pseudocode is shown in Algorithm 1, generates a set of LP/FIPP p-cycles.
Algorithm 1. P-Cycle Design

1: procedure Generate-P-cycle-set  
2: while The network is not fully protected do  
3: Initialize p-cycle $p$  
4: Calculate $IC$ for $p$ as $p_{IC}$ and initialize $IC_{\text{min}}$ as $p_{IC}$  
5: while EXPAND_P-CYCLE($p$) $\neq$ NULL do  
6: $p' = \text{EXPAND_P-CYCLE}(p)$  
7: Calculate the IC of $p'$ as $p'_{IC}$  
8: if $p'_{IC} < IC_{\text{min}}$ then  
9: Update the candidate p-cycle to $p'$  
10: Update $IC_{\text{min}}$ to $p'_{IC}$  
11: end if  
12: $p = p'$  
13: end while  
14: Add the candidate p-cycle to p-cycle set P  
15: Mark links (for LP) or node pairs (for FIPP) that can be protected by candidate cycle as protected  
16: end while  

Algorithm 2. LP P-Cycle Initialization

1: procedure Initialize-LP-P-CYCLE  
2: Randomly select an unprotected link $l$  
3: Remove link $l$  
4: Use Dijkstra’s algorithm to find a shortest path $sp$ between the two ends of the link  
5: Merge $l$ and $sp$ as a p-cycle $p$  

Algorithm 3. FIPP P-Cycle Initialization

1: procedure Initialize-FIPP-P-CYCLE  
2: Randomly select an unprotected node pair $a$ and $b$  
3: Use Dijkstra’s algorithm to find a shortest path $sp_1$ between the two ends.  
4: Remove the links on path $sp_1$ from the topology.  
5: Remove links that connect with nodes on $sp_1$ from the network  
6: Use Dijkstra’s algorithm to find a shortest path $sp_2$ between the two ends.  
7: Merge $sp_1$ and $sp_2$ as a p-cycle $p$  

that can protect the entire network against single-link failures. We emphasize that the same Algorithm 1 is used to generate both the LP p-cycle set and the FIPP p-cycle set, but FIPP and LP have different initialization steps, as given in Algorithms 2 and 3.

We start by initializing a p-cycle $p$. For the LP p-cycle, we first randomly find an uncovered link $l$ in the network. Then we find a shortest path $sp$ (in hops) between the two ends of this link. Let the selected link $l$ and the path $sp$ be combined to form an initial LP p-cycle $p$. The pseudocode is shown in Algorithm 2.

To initialize an FIPP p-cycle, an uncovered node pair $(a, b)$ is randomly selected in the network. Then we find a shortest path $sp_1$ (in hops) between $a$ and $b$. Remove the links on path $sp_1$ and the links that are incident on the intermediate nodes (excluding nodes $a$ and $b$) on $sp_1$ from the network. Use Dijkstra’s algorithm on this topology to find a shortest path $sp_2$ between $a$ and $b$. Initialize an FIPP p-cycle $p$ by combining $sp_1$ and the path $sp_2$. This ensures that the resulting cycle is a simple cycle. The pseudocode is shown in Algorithm 3.

After the basic p-cycle is initialized, calculate the IC for this p-cycle and mark this p-cycle as a candidate p-cycle. Then keep expanding the p-cycle until the p-cycle cannot be expanded further. The pseudocode for expanding the p-cycle is shown in Algorithm 4. For each expansion step, assume that the p-cycle after expansion is $p'$. Calculate the IC of $p'$. If the IC of $p'$ is lower than $IC_{\text{min}}$, replace the candidate p-cycle with $p'$ and update $IC_{\text{min}}$ to $p'_{IC}$. After the expansion phase is over, put the candidate p-cycle into the p-cycle set. Then, for the LP p-cycle, we mark the links that can be protected by this p-cycle as protected. For the FIPP p-cycle, we mark the node pairs that can be protected by this p-cycle as protected. If the network is not fully protected, randomly select a link (for LP) or a node pair (for FIPP) that is not protected, and add another candidate p-cycle into the cycle set. After all the links (for LP) or node pairs (for FIPP) in the network are marked as protected, we have a set of p-cycles that can be used to protect the network.

The above algorithm produces a “good” p-cycle set because we used IC to expand the p-cycles, but the p-cycle set is also somewhat random because the starting link (or node pair) and expansion phase for each p-cycle are based on randomly selected links (or node pairs). We generate a large number of such p-cycle sets (by using different initial p-cycles). Then we choose the p-cycle set among these as the set with the lowest SC. Later, we will compare the performance of such a p-cycle set with some baseline algorithms for selecting p-cycle sets.

8. ROUTING AND SPECTRUM ASSIGNMENT

We now present a simple RSA algorithm for the working paths and p-cycle protection. This RSA algorithm is used for both TIPS and TOPS LP p-cycles and FIPP p-cycles. For the working path, we propose a routing algorithm called the CR algorithm for the route. In CR, we first compute $k$-shortest paths (based on the number of hops; we use $k = 5$ in the
Algorithm 5. Routing and Spectrum Assignment

1: procedure ROUTE-AND-ASSIGN-SPECTRUM
2: for Each request \( r(s, d, w) \in R \) do
3:   Calculate working lightpath \( LP \) by CR algorithm
4:   for Each link or node pair do
5:     Calculate the longest segment of protection path
6:     Calculate the modulation factor \( M \) with distance
7:   end for
8: Select the modulation format with the highest modulation factor
9: Determine the number of FSs \( F \)
10: Set \( S_{start} = 1 \)
11: while \( S_{start} \leq S_{max} - F + 1 \) do
12:   for every link \( l \in LP \) do
13:     if FSs with index \( S_{start} \) to \( S_{start} + F - 1 \) are available then
14:       Assign \( S_{start} \) to \( S_{start} + F - 1 \) as working and protection FSs of \( LP \).
15:       BREAK
16:     else
17:       \( S_{start} = S_{start} + 1 \)
18:     end if
19: end for
20: end while
21: end for

evaluation) for each pair of network nodes. For each path, we calculate the cost of the path as follows:

$$\text{Cost of Path} = M \times L,$$

where \( L \) is the number of hops and \( M \) is the modulation factor of the path, which is determined by the physical distance of the longest segment (cut by regenerators) of the path. Recall that by our definition, the modulation factor is lower for higher-level modulation. For each node pair, the path with the lowest cost will be selected as the working path.

For spectrum assignment, we first use the CR algorithm to find a route for the working path. Then we fail the links on this working path one by one. In the LP p-cycle, for each failed link, we select the LP p-cycle with the 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 protection cycle for the failed link. Note that we use the shorter of the two cycle paths to protect 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 levels (over all failed links) is then chosen as the modulation level for this lightpath, and the corresponding modulation format is selected. The lowest modulation level ensures that the distance constraint is satisfied no matter which link fails. In the FIPP p-cycle, for each node pair, we select the FIPP p-cycle with the minimum IC to protect this node pair. The modulation format is determined by the longest segment on the working path and protection paths.

After the modulation format is selected, the spectrum assignment is completed by using the first fit method if slots are available. Different traffic requests cannot share working capacity, but due to the single-link failure assumption, the protection capacity of link-disjoint working paths may be shared. The pseudocode of the RSA algorithm is shown in Algorithm 5.

For dynamic traffic, since the lightpath requests are not known in advance in this case, we use TIPS here. Therefore, a set of p-cycles is generated based on IC and SC, and when a new lightpath request arrives, only RSA is performed and a modulation format is selected as described above. If FSs are not available for the request, the request is blocked.

9. SIMULATION RESULTS

A. Simulation Setting

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. 6) and the pan-European network (consisting of 28 nodes and 44 links, shown in Fig. 7) are used for simulations.

In a static traffic model, a set of unidirectional traffic requests is to be assigned a working path and protection path in the network. The source and destination nodes for each connection request are uniformly randomly selected from the nodes of the network. We assume the rate of traffic demands is an even distribution in the range of 40–400 Gbps with 10 Gbps increments (i.e., 40, 50, 60, …, 390, 400 Gbps). The number of required FSs for a lightpath is determined by its data rate and modulation format. The number of FSs corresponding to different data rates under different modulation formats is determined by following formula:

$$\text{Numb of FS} = \left\lceil \frac{\text{DataRate}}{\text{ME} \times 12.5} \right\rceil,$$

where DataRate is the lightpath rate in gigabits per second; ME is the modulation spectrum efficiency, which is equal to 1, 2, 3, and 4 bps/Hz for BPSK, QPSK, 8QAM, and 16QAM, respectively; and the number 12.5 refers to the bandwidth of each slot in gigahertz. Table 1 shows the transparent transmission distance limitations of different modulation formats. The
over 10 random placements with 20 traffic request sets for each placement in the static traffic scenario and 10 random placements with $10^5$ lightpath requests in the dynamic traffic scenario. We also present results for transparent networks with no regenerators.

### B. Baseline Algorithms

In order to show the effectiveness of our algorithms, we compare the TIPS and TOPS LP p-cycle sets and FIPP p-cycle sets with the following baseline algorithms:

- Hamiltonian cycle: The Hamiltonian cycle is the undirected cycle that visits each node exactly once [44]. The Hamiltonian cycle can be used as both the LP p-cycle and FIPP p-cycle (both the topologies in this paper have a Hamiltonian cycle).
- Random cycle set: We first 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.
- Top AE p-cycle set (TopAE) [25]: TopAE is an LP algorithm. All the cycles are sorted by $AE = \sum_{i \in E} \frac{\chi_{ij}}{(\sum_{k \in E} \delta_{kj} \times C_k)}$, where $\chi_{ij}$ refers to the number of paths that can be protected by cycle $j$ if link $i$ fails (the possible values are 0 and 1 for an on-cycle link, and 2 for a straddling link); $\delta_{kj}$ is a binary parameter that equals 1 if link $i$ is on cycle $j$ and 0 otherwise; $C_k$ is the cost of link $k$ and is assumed to be 1 in this work. The cycle set is formed by selecting p-cycles one by one in non-decreasing order of AE from the pool of all cycles until the network is fully protected.
- Top IC p-cycle set (TopIC): In TopIC, all the p-cycles are sorted by individual cycle cost. The cycle set is formed by selecting p-cycles one by one in non-decreasing order of individual cycle cost from the pool of all cycles until the network is fully protected.
- FIPP-Flex [9,35,42]: FIPP-Flex is a traffic-aware protection algorithm in which RSA is done for each traffic demand and a new p-cycle is established if the existing p-cycles cannot protect a new working path. In order to compare this work with our algorithm, we assume that if a new p-cycle is established, all the s-d pairs on the p-cycle are protected by this p-cycle.

In TopIC and TopAE, for an LP p-cycle, when a p-cycle is selected, all the unprotected links that can be protected by the p-cycles selected first as well. Only cycles that protect at least one as-yet-unprotected link will be added to the p-cycle set. All the baseline algorithms are tested as both an LP p-cycle and an FIPP p-cycle except TopAE, which is designed for LP p-cycles, and FIPP-Flex, which is designed for FIPP p-cycles.

### C. Static Traffic

In the static traffic scenario, the algorithms are evaluated in terms of spectrum usage (i.e., number of FSs used per link) and

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**Table 1. Physical Distance Limitation for Different Modulation Formats [10]**

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Transparent Reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>16QAM</td>
<td>500 km</td>
</tr>
<tr>
<td>8QAM</td>
<td>1000 km</td>
</tr>
<tr>
<td>QPSK</td>
<td>2000 km</td>
</tr>
<tr>
<td>BPSK</td>
<td>&gt;2000 km</td>
</tr>
</tbody>
</table>

performance is evaluated in terms of spectrum usage per link (the total number of FSs used for both working and protection on all links divided by the number of links in the network) and protection-to-working ratio (the total number of FSs used on protection paths divided by the number of FSs used on working paths). Moreover, in order to evaluate the spectrum usage without blocking, we assume that there are an unlimited number of FSs on each fiber. In this way, the spectrum usage of different algorithms can be clearly observed.

In the dynamic traffic model, $10^5$ lightpath requests arrive at the network according to a Poisson process with different arrival rates. Each request has a mean duration time of 1 (arbitrary time unit) with an exponential distribution. Unlike with the static traffic model, the highest FS available on each fiber is assumed to be 352. If there are 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.

For both TIPS and TOPS, our p-cycle design algorithm forms p-cycle sets in advance by generating a large number ($\approx 500$) of 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 in TOPS are also based on the traffic and data rate, as explained earlier. We assume that there are three regenerators in the COST239 network and six regenerators in the pan-European network for the translucent case. The regenerators are placed randomly, and all results presented are averages...
Fig. 8. Performance results for the translucent COST239 network. (a) Spectrum usage of LP p-cycle sets, (b) spectrum usage of FIPP p-cycle sets, (c) comparison of spectrum usage between LP and FIPP p-cycle sets, (d) protection-to-working ratio of LP p-cycle sets, (e) protection-to-working ratio of FIPP p-cycle sets, (f) comparison of protection-to-working ratio between LP and FIPP p-cycle sets.

Fig. 9. Performance results for the transparent COST239 network. (a) Spectrum usage of LP p-cycle sets, (b) spectrum usage of FIPP p-cycle sets, (c) comparison of spectrum usage between LP and FIPP p-cycle sets, (d) protection-to-working ratio of LP p-cycle sets, (e) protection-to-working ratio of FIPP p-cycle sets, (f) comparison of protection-to-working ratio between LP and FIPP p-cycle sets.
Fig. 10. Performance results for the translucent pan-European network. (a) Spectrum usage of LP p-cycle sets, (b) spectrum usage of FIPP p-cycle sets, (c) comparison of spectrum usage between LP and FIPP p-cycle sets, (d) protection-to-working ratio of LP p-cycle sets, (e) protection-to-working ratio of FIPP p-cycle sets, (f) comparison of protection-to-working ratio between LP and FIPP p-cycle sets.

protection-to-working ratio (the number of FSs used for protection to the number of FSs used on working paths). Figures 8 and 9 show the performance results in translucent and transparent COST239 networks, respectively. In general, the spectrum usages of all the algorithms in a translucent network are lower than in a transparent network due to the deployment of regenerators. As we can see, the cycle sets generated by our algorithms have lower spectrum usage. TIPS and TOPS are slightly better than TopIC p-cycle sets, suggesting that p-cycle set selection using our SC cost metric is better than simply selecting a set of cycles with the highest IC values. Moreover, the traffic information helps TOPS-LP and TOPS-FIPP do better than the corresponding TIPS p-cycle sets.

In TIPS, we do consider the load imbalance cost and unshareable risk, and thus the improvement between TIPS and TOPS is not large. For LP p-cycle sets, the Hamiltonian cycle has a low protection-to-working ratio. The reason is that a larger cycle has a higher probability of sharing protection capacity. Also, FIPP p-cycle sets have lower ratios than LP p-cycle sets. In FIPP the protection path is established between the source node and destination node, which leads to a higher sharing probability among different protection paths. In LP, the traffic is only routed around the failure link, and thus the protection capacity of different links is hard to share. However, due to a shorter protection distance, LP p-cycle sets perform well in spectrum usage by using higher-level modulation formats. In FIPP, large p-cycles are necessary to protect a pair of nodes that are on each edge of the network. For instance, in the COST239 network, in order to protect node pair 1 and 11, a large FIPP p-cycle is required. A higher spectrum usage with a lower protection-to-working ratio shows that FIPP p-cycles have to be assigned with lower-level modulation.

We can also observe that with regenerators, the performance gap between the proposed algorithms and Hamiltonian cycle is lower. This is because even though the Hamiltonian cycle may be long, regenerators help reduce the maximum transparent distance of lightpaths, which enables higher-level modulation.

Figures 10 and 11 show the performance results in translucent and transparent pan-European networks, respectively. The performance results in the pan-European network are different from those in the COST239 network. In the pan-European network, the gap between the proposed LP algorithms and the LP Hamiltonian cycle is larger than that in the COST239 network. Here is our explanation. There are two drawbacks to a larger cycle: the load imbalance cost is higher, due to a higher number of hops, and lower-level modulation has to be used for a longer lightpath. Due to the larger size of this network, the LP Hamiltonian cycle is too long in the pan-European network. Here is our explanation. There are two drawbacks to a larger cycle: the load imbalance cost is higher, due to a higher number of hops, and lower-level modulation has to be used for a longer lightpath. Due to the larger size of this network, the LP Hamiltonian cycle is too long in the pan-European network, which means these two drawbacks dominate the final performance of spectrum usage.

If we compare the LP p-cycle set and FIPP p-cycle set, we can see that the LP p-cycle has better performance in terms of spectrum usage but worse performance in terms of protection-to-working ratio. This is because the lightpaths are shorter but the sharing of protection capacity is harder in LP. FIPP p-cycles have better performance in terms of the protection-to-working ratio but have a higher spectrum usage because the lightpaths are longer (thus requiring more working bandwidth); they also enable higher sharing of protection bandwidth.
Fig. 11. Performance results for the transparent pan-European network. (a) Spectrum usage of LP p-cycle sets, (b) spectrum usage of FIPP p-cycle sets, (c) comparison of spectrum usage between LP and FIPP p-cycle sets, (d) protection-to-working ratio of LP p-cycle sets, (e) protection-to-working ratio of FIPP p-cycle sets, (f) comparison of protection-to-working ratio between LP and FIPP p-cycle sets.

Fig. 12. Maximum FS index in the translucent COST239 network. (a) Maximum FS index of LP p-cycle sets, (b) maximum FS index of FIPP p-cycle sets, (c) comparison of maximum FS index between LP and FIPP p-cycle sets.

Fig. 13. Maximum FS index in the transparent COST239 network. (a) Maximum FS index of LP p-cycle sets, (b) maximum FS index of FIPP p-cycle sets, (c) comparison of maximum FS index between LP and FIPP p-cycle sets.
Figures 12 and 13 show the maximum FS index in translucent and transparent COST239 networks, respectively. As we mentioned before, protection capacity can be shared. Due to the spectrum continuity and spectrum contiguity, for each instance of traffic, the working path and protection path must have the same FS indices. We observe once again that our algorithms perform better than baseline algorithms.

**D. Dynamic Traffic**

In dynamic traffic, we present a comparison between the two TIPS algorithms (LP and FIPP) and two baseline algorithms: the Hamiltonian cycle and random p-cycle set. (Recall that TOPS is not applicable for dynamic traffic, as the traffic is not known ahead of time.) Since the Hamiltonian cycle goes through all the nodes in the network, it can be used as both an LP p-cycle and FIPP p-cycle. Figures 14 and 15 show the demand blocking ratio performance in the COST239 network and the pan-European network, respectively. In this work, the protection capacity can be shared by different requests if their working paths are disjoint. Thus, blocking is only caused by insufficient working capacity. Given a traffic instance, a higher level of modulation leads to a lower working capacity requirement, so the p-cycle set that can take advantage of higher-level modulation has a lower blocking ratio. The modulation format of the traffic is determined by the longest segment of the working path and the reserved protection path. As mentioned earlier, large p-cycles are necessary in FIPP, whereas LP p-cycles tend to be smaller. Thus, as we can see from the results, the demand blocking ratio of TIPS-LP is much better than that of TIPS-FIPP. We would like to mention that the size of a cycle may not necessarily mean a lower-level modulation if there are straddling links or paths. The protection lightpath of a straddling link or path may be much shorter than the length of the cycle. For instance, even though the Hamiltonian cycle is the largest cycle in the network, there are many straddling links and paths in such a cycle. This is the reason why the blocking ratio of the Hamiltonian is lower than that of the random cycle set, as can be seen in the figures.

**10. CONCLUSIONS**

P-cycles are attractive for protection in EONs because of their high efficiency and fast restoration speed. P-cycles can be used for LP as well as FIPP. In this paper, we considered single-link failures and analyzed the factors that determine the performance of LP p-cycle protection and FIPP p-cycle protection in translucent EONs, and proposed suitable cost metrics to evaluate an individual cycle as well as a set of cycles. These metrics consider the placement of regenerators, physical distance of lightpaths, and multiple modulation formats. Then we proposed algorithms to select p-cycles both without traffic information (TIPS) and with traffic information (TOPS). A simple RSA algorithm called CR that considers the placement of regenerators is proposed for use with the p-cycle design algorithms. We compared the performance of LP p-cycles and FIPP p-cycles with that of common baseline algorithms and algorithms from the literature and showed that the proposed design algorithms perform better in terms of required spectrum and blocking ratio. In the future, we will focus on p-cycle design with multi-failure p-cycle protection.

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