P-cycle Designs in Elastic Optical Networks

by Rujia Zou

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Suresh Subramaniam
Professor of Electrical and Computer Engineering

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Abstract

P-cycle Designs in Elastic Optical Networks

Elastic optical networks (EONs) are able to provide high spectrum utilization efficiency due to flexibility in resource assignment. Survivability is regarded as an important aspect of EONs. Due to fast restoration and high protection efficiency, p-cycle protection is very attractive for EONs. P-cycles have been well studied for conventional fixed-grid WDM networks; however, p-cycle design and selection for EONs has received much less attention. The p-cycle protection in translucent EONs is still unexplored. In this thesis, we propose two novel link-based p-cycle evaluation methods: individual p-cycle selection and p-cycle set selection for both transparent EONs and translucent EONs. Based on these methods, we proposed Traffic Independent P-cycle Selection (TIPS) and Traffic-Oriented P-cycle Selection (TOPS) for transparent EONs. For translucent EONs, Traffic Independent P-cycle Selection with 3R Regenerator (TIPS-3R) and Traffic-Oriented P-cycle Selection with 3R Regenerator (TOPS-3R) are proposed. Further, we propose p-cycle generation algorithms and Routing and Spectrum Assignment (RSA) algorithms as well. We evaluate our algorithms using both static and dynamic traffic models. Simulation results indicate that the proposed algorithms have better performance than commonly used baseline algorithms.

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Chapter 1: Background

1.1 Elastic Optical Networks

With the dramatic growth of network traffic, Elastic optical networks (EONs) have arisen as an efficient solution due to the flexibility in resource allocation and spectrum assignment [11]. Compared with Wavelength-division multiplexing (WDM) network, the major advantage of EONs is variable granularity. Since each wavelength channel of a WDM optical network has a higher rate, each wavelength in the WDM optical network can provide a larger bandwidth granularity. However, the available bandwidth above the wavelength is often much larger than the requested bandwidth of the service in the actual application. If we need to provide a high-speed dedicated wavelength for each low-speed service, the resource utilization is obviously low and costly. Considering the number of optical transceivers in the network node and the number of wavelengths in the fiber, for each service connection request it is not practical to establish an end-to-end independent optical path. The elastic optical network can provide variable granularity bandwidth for each service request. Through the Orthogonal Frequency-Division Multiplexing (OFDM) technology, the optical network node can modulate the service information onto a contiguous set of OFDM carriers according to the size of the service request. Thereby a variable granularity bandwidth transmission is achieved.

EONs use OFDM technology to reduce the bandwidth allocation level to the Frequency Slot (FS), which is 12.5 GHz wide. When a mixed granularity service with different bandwidth requirements occurs, it is only required to assign the required number of FSs. This effectively realizes the on-demand configuration of optical layer resources, and greatly improves network bandwidth utilization and flexibility.

Routing and Spectrum Assignment (RSA) is one of the key issues in EONs. It needs to assign all the traffic requests with connection requirements. For each traffic request, an end-to-end optical path is established and a sufficient amount of bandwidth resources are allocated on the route. Compared with routing and wavelength assignment (RWA) problem in Wavelength Division Multiplexing (WDM) optical networks, the design of RSA is more complex due to the spectrum continuity and spectrum contiguity [2]. This double constraint makes traditional RWA designs not suitable for RSA. In EONs, RSA aims at satisfying all the requests. According to the traffic request and connection requirements, an end-to-end optical path is established, and a sufficient amount of bandwidth resources are allocated on the route.

The RSA issue in EONs has been well studied. In [1], a QoT-aware RSA with modulation consideration is proposed. The RSA is done in three steps: path computation with QoT-aware modulation level assignment, path selection, and spectrum assignment. In [41], a novel integer linear programming (ILP) formulation and low complexity heuristics algorithms are proposed for resource allocation in EONs with modulation format consideration. In [31], a routing, fiber, band, and spectrum assignment (RFBSA) for multi-granular elastic optical networks are proposed with a novel auxiliary layered-graph framework. In [8], authors present a dynamic routing and spectrum assignment for multi-fiber EONs. In [30], given a set of traffic requests, the RSA problem is solved jointly with both ILP model and a heuristic algorithm.

1.2 Survivability and Protection

Survivability is regarded as an important aspect for optical networks. Protection, in which resources for recovering from a potential failure are pre-reserved, is an important survivability technique. Protection can be generally classified as dedicated backup protection and shared backup protection [22]. In dedicated backup protection, each path has a dedicated backup path, while shared backup protection means different paths may have a shared protection path. There are two dedicated backup protection schemes, one is 1+1 protection, the other is 1:1 protection. In 1+1 protection, data is simultaneously transmitted on two paths and the destination node chooses the better signal. In 1:1 protection, data is transmitted only on the working path normally. If the working path fails, data is switched to the protection path. Further, 1: N protection is a generalization of 1:1 protection in which N working paths are protected by a single protection path. 1+1 requires less switching time while 1:1 and 1: N protection require a protocol for the receiver to indicate to the transmitter that there is a failure along the traffic path.

For dedicated backup protection, Klinkowski et al. [15] propose a routing and spectrum assignment with dedicated path protection (DPP) as an ILP model and an adaptive frequency assignment DPP with heuristic algorithm. Static traffic demand is considered. For the ILP formulation, several constraints are considered including: path selection, slice capacity, and occupancy. The objective of ILP is minimizing the number of spectrum slices used in the network. The adaptive frequency assignment DPP is established by a heuristic algorithm with collision metric. The collision metric is used to select paths that do not include links that can be potentially selected in a large number of demands. The assignments are done by doing spectrum allocation and checking the collision metric.

In shared backup protection, the protection capacity can be shared among different working paths [26]. Compared with dedicated back protection, in shared back protection, a protection unit (can be a path, a fiber, or a frequency slot) can be assigned to protect more than one working unit. Thus, shared backup scheme is able to provide full protection with a lower protection capacity at the cost of higher restoration time [12].

The protection method can be classified in terms of link protection and path protection as well. In link protection, when the failure occurs, the recovery will be applied around the failure link. A protection path is established between two nodes of failure link. The source node and destination node of the lightpath are not aware that there is a link failure on the lightpath. In path protection, when a link or a node fails, the recovery will be applied between the source node and destination node. A new lightpath will be established to replace the lightpath that failed.

Further, protection can be classified as whether the protection algorithm is failure independent or not. Failure-independent protection has a lower recovery time because it does not need to identify the location of failure. In failure-dependent protection, the establishment of protection path requires the location of failure.

Based on these classifications, the protection of optical network can be a combination. For instance, shared backup path protection (SBPP) is well studied. SBPP is a failure-independent shared path protection strategy in which the protection route is identified in advance. For sharing method, the primary paths do not share any link while the backup paths can use common links. SBPP is able to guarantee full recovery unless multiple paths that share a backup path fail simultaneously. In other words, in SBPP, backup resources can be shared between the demands whose primary paths are not likely to fail at the same time. There are many works related to SBPP. Shen et al. [23] propose an SBPP algorithm with ILP model in order to minimize the required spare capacity and the number of frequency slots used. Also, the transponder tunability and Bandwidth Squeezed Restoration is considered with ILP. Walkowiak et al. [25] propose an RSA-SBPP with ILP which is less complex than that presented in Eira et al. Static traffic demand and single failure condition are considered. The objective of ILP is minimizing the width of spectrum used in the network. Then, authors provide several heuristic SBPP algorithms including the Most Subcarriers and Average Longest Path First (MSALPF) algorithm. Wang et al. [26] proposed a Distance Adaptive Dynamic RSA with SBPP. This paper assumes that EON employs different modulation formats depending on the actual physical distance of a lightpath, the working and protection lightpaths may use different modulation formats and may be assigned with different number of FS. The heuristic algorithm provided by authors aims to minimize the bandwidth blocking probability. Eira et al. [6] develop an ILP and a heuristic algorithm for SBPP so as to maximally share spare capacity. These algorithms aim to reduce the width of spectrum usage and guarantee survivability to single-link failures. But compared with heuristic algorithm, the ILP solution presented by author does not reach a feasible solution.

1.3 P-cycle Protection

P-cycle is a protection scheme in which the spare capacity is pre-connected by a ring-like structure called p-cycle [3, 7]. A failure that occurs on the p-cycle is recovered by the ring-like structure. All the on-cycle links can be protected by p-cycle protection and ring-cover protection. The major difference between the p-Cycle and ring-cover protection is that p-cycle is able to provide protection to the straddling links of the cycle as well, which cannot be protected in ring-cover protection [9].

We use Fig. 1.1 to explain the concept of p-cycle. In this network, assume that there is a p-cycle named A-B-D-E-F-A (marked by the bold lines). When a failure occurs on link A-B, both p-cycle protection and ring-cover protection are able to protect link A-B. The protection path of link A-B is A-F-E-D-B and B-D-E-F-A. However, only p-cycle protection is able to protect straddling link A-E. In p-cycle protection, the protection path of link A-E is A-B-D-E or E-D-B-A. Also, the protection path can be A-F-E or E-F-A.

In p-cycle protection, links and nodes in network are covered by a set of p-cycles. In failure-independent protection, p-cycles are not allowed to overlap with each other. As we mentioned before, failure-independent protection does not need to identify the location of failure [4]. Without failure location, all the switches can only do an ON-OFF reconfiguration. When the failure occurs, only two simple ON-OFF switch reconfigurations are made at the two end nodes of failure link and the traffic is switched from working path to the protection path by switches. Therefore, p-cycles cannot overlap with each other. However, in failure-dependent protection, with the information of failure location, all the switches are able to do an N $\times N$ reconfiguration to recover the failure link. Thus p-cycles are allowed to overlap with each other in failure-dependent protection. Failure-dependent p-cycle protection has a higher efficiency due to the fact that p-cycles can be selected freely without the consideration of overlap, but the recovery time is higher than failure-independent protection because of more complex switch reconfigurations.

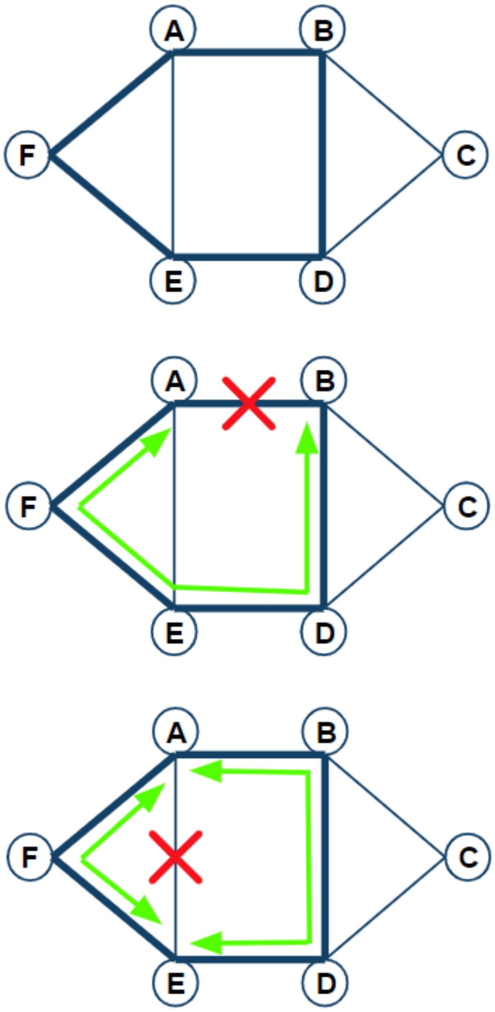

Figure 1.1: Examples of p-cycle

Oliveira et al. [20] propose a heuristic algorithm for FIPP p-cycle path protection. The paper provides an RSA algorithm followed by an FIPP algorithm. Authors use multi-graph to represent the network spectrum. In FFIP algorithm, a lightpath is established if and only if it can be protected by an FIPP p-cycle which can have both on-cycle and straddling link. Wei et al. [28] develop an ILP algorithm for p-cycle with/without the consideration of spectrum conversion. The objective of ILP is minimizing the required protection capacity. Also, BSR is also applied to meet the maximum restoration level. The performance of this ILP is compared with ring cover technique. Wei et al. [29] consider the p-cycle protection with/without spectrum conversion in ILP. Wei et al. also deal with the design of a span-restorable elastic optical network under different spectrum conversion capabilities, including 1) no spectrum conversion, 2) partial spectrum conversion, and 3) full spectrum conversion. This paper develops ILP to minimize the required spare capacity and the maximum number of link frequency slots used in the network.

Chapter 2: P-cycle Evaluation and Generation

In this section, we first present the motivation of p-cycle evulation and generation, including the analysis of factors that is able to influence the p-cycle protection performance. Then we present the p-cycle evulations and p-cycle generation algorithm in both transparent network and translucent network.

2.1 Motivation and Problem Statement

2.1.1 Motivation

In p-cycle protecction, the performance of p-cycle is determined by the set of p-cycles that are used to protect the network. The following factors are able to influence the performance of p-cycle:

The physical length of p-cycle is directly related with optical signal modulation format. The modulation format is determined by the transparent physical transmission distance. Low level modulations have long distance limitation with less spectrum efficiency, while high level modulations have short distance limitation with high spectrum efficiency. So a p-cycle with a longer physical length corresponds to a lower level modulation format since the lower level modulation format has a higher transmission distance limitation. The protection path length of a link is determined by the length of p-cycle. Therefore, small p-cycles have higher probability to be assigned with higher level modulation format while large p-cycles are usually assigned with lower level modulation format. Current p-cycle works lack consideration of multiple modulations.

Length of p-cycle in hops is also able to influence the performance of p-cycle protection. Assume that there is a link that needs to be protected and there are two p-cycles can be used to protect the link, namely cycle 1 and cycle 2. This link is an on-cycle link for both cycles. If the length in hops of cycle 1 is 5 while the length in hops of cycle 2 is 9, the length of protection paths in hops is 4 and 8 respectively. Suppose both paths correspond to the same modulation format. All the links that are used for protection are assigned with FS according to the data rate of lightpath and modulation. The number of FS for cycle 1 protection path is two times that for cycle 2 protection path due to the larger number of hops.

The number of protected links of an individual p-cycle is determined by the number of straddling links and the number of on-cycle links. The number of protected links of a cycle is related to the protection ability that can be provided by this cycle. This factor can be used to measure the protection capacity of an individual cycle.

If a p-cycle is able to protect many links, this p-cycle has a high possibility to suffer the load balance issue. Assume that all the links on the p-cycle can share the protection capacity. If the working capacity on a link is higher than the working capacity on other links, the protection capacity of the extra working capacity cannot be shared with the other protection capacity.

According to all of these factors, two extreme scenarios are needed to be considered in tradeoff. One is using a set of long p-cycles to achieve the protection of all the links in mesh network. The other is using a set of short p-cycles. If the size of cycle is small, the length of cycle is able to satisfy the distance limitation of high level modulation. Thus the spectrum resource can be saved by this high spectrum efficient modulation format. Therefore less spectrum resource is needed for each p-cycle. However, because of the p-cycles' short size, we need more p-cycles to cover the entire network, so the total spectrum resources used for protection may be increased by the large number of cycles. For large cycles, one p-cycle is able to protect more links, thus fewer cycles are needed to cover the network. If spectrum conversion is taken into account, the protection cycle for these links can share the spectrum resource with each other, which means large cycles maybe much more efficient than short cycles. However, large cycles have to be assigned with low level modulation. Therefore each cycle needs more spectrum resource than small cycle to achieve the same protection ability.Therefore, based on this qualitative analysis, we need to improve the number of links that the p-cycle can protect. We also need to try to use high level modulation in order to minimize the network resources used for protection.

There are many works that have studied p-cycle evaluation. In [13], a p-cycle protection algorithm is designed to minimize the total power consumption with a mixed integer linear programming model. In [28, 29], all the p-cycles are generated and sorted with A Priori Efficiency (AE) first and top-rank-AE p-cycles are used for ILP design. In [32], the p-cycle protection algorithm is proposed with load-balance consideration. In [14], the p-cycle set is generated without cycle enumeration. The transponder cost and spare capacity cost are used to evaluate individual p-cycle. However, none of the above papers consider all of these factors in EONs.

2.1.2 Problem Statement

We formally define the problem as follows. For transparent EONs, we are given a network $G(N,E)$, where N represents the node set and E represents the link set. On each link e, a pair of fibers (with opposite directions) is 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 represented as $r(s,d,w)$, s and d denotes the source and destination nodes, and w denotes the lightpath data rate. Assume there are several modulation formats with different spectrum efficiencies and distance limitations. The objective is to select a set of p-cycles that is able to provide full link-protection with the minimum possible protection bandwidth. This problem includes two parts. One is the RSA problem for each request r, the other is the assignment of a protection path with a set of p-cycles for each link along the working path of request r. We assume that spectrum conversion is not allowed.

For translucent EONs, the problem is defined 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.

2.2 P-cycle Evaluation in Transparent EONs

In this section, we present two novel ways to evaluate the p-cycle in transparent network, called Traffic-Independent P-Cycle Selection (TIPS) and Traffic-Oriented P-Cycle Selection (TOPS), respectively. For each evaluation, we propose the individual cycle protection cost evaluation (IC) and set-cycle protection cost evaluation (SC). In TIPS, both IC and SC are purely based on network topology. In TOPS, the traffic information is known in advance so IC and SC are based on the specific traffic condition.

2.2.1 Traffic-Independent P-cycle Selection

In TIPS, we try to design IC and SC without traffic information.

2.2.1.1 Individual Cycle Protection Cost

In order to evaluate the IC of cycles, the Individual Cost for TIPS (IC_{TIPS}) is proposed as follow:

$$IC_{TIPS} = \frac{M \times L}{S} \times A \tag{2.1}$$

where M is the modulation index, L is the number of links on the p-cycle, and S is the number of links that can be protected by the p-cycle. A is the average protection distance (in hops). A 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. The rationale for this cost is as follows. A higher level modulation has lower value of M indicating that fewer slots are needed for a given data rate. Here, since we do not know the working paths, M is determined by the physical length of the p-cycle. For BPSK, QPSK, and 8QAM, the corresponding spectrum efficiencies are 1, 2, and 3 bits/s/Hz; therefore we choose the corresponding M as 1, 0.5, and 0.34, respectively [26]. 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.

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. A is designed to capture the risk of unshareable protection due to load imbalance. If the working capacity on a link is higher than on other links, a p-cycle with larger A implies a larger number of backup FSs for an individual link failure.

We need to emphasize that Individual Cost (IC) is a metric for an individual p-cycle that is based purely on the network topology. A p-cycle with a lower IC is expected to be more efficient than a p-cycle with a higher IC.

2.2.1.2 Set of Cycle Protection Cost

As p-cycles may overlap with each other, and since a link is only protected by one p-cycle, adding the ICs of the p-cycles in a set of p-cycles may not be an effective cost metric for a *set* of p-cycles. The evaluation of a set of p-cycles is based on p-cycle Set protection Cost (SC). Since overlap between p-cycles in a set is possible, we assume that every link is protected by the lowest IC p-cycle from the selected set that can provide protection to this link. If a link can be protected by multiple p-cycles that 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:

$$SC_{TIPS} = \sum_{p \in \mathbf{P}} M_p \times A_p \times N_p \tag{2.2}$$

where $\mathbf{P}$ is the set of candidate p-cycles that provides full protection for the network, p is an individual p-cycle in the set, M_p is the modulation index of p, and A_p is the average protection distance of p in hops, and N_p is the number of links protected by p. As before, smaller M and A indicate that fewer protection FSs are required. N_p is a measure of the possibility of unshareable protection and load imbalance. The more links that are protected by the p-cycle, the higher the risk of load imbalance. We need to emphasize that not all the links that can be protected by a p-cycle are in fact protected by this p-cycle due to the overlapping of p-cycles. A p-cycle set with a lower SC is expected to a better set of cycles and is encouraged to be used for protection.

2.2.2 Traffic-Oriented P-Cycle Selection

2.2.2.1 Individual Cycle Protection Cost

In TOPS, the p-cycle evaluation and selection are based on the given traffic. Given a set of lightpath requests with data rate in Gbps, we first route all the lightpath requests without any spectrum assignment using Dijkstra's shortest path algorithm with physical distance. We use the total data rate on each link when evaluating the p-cycles. The IC and SC for TOPS are calculated as follows:

$$IC_{TOPS} = M \times D_{\max} \times L^2 \tag{2.3}$$

where M is the modulation index (same as in $TIPS$), $D_{\max}$ is the maximum data rate over all the links that can be protected by this cycle, and L is the length of the cycle in hops. M, $D_{\max}$

and L are used to measure the consumption of backup FSs in full protection sharing scenario. We use another factor of L here to capture the risk of unshareable protection FSs. If the backup FSs of a link cannot be shared with other links, the backup capacity is increased, and a larger L indicates more backup extra FSs.

2.2.2.2 Set of Cycle Protection Cost

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

$$SC_{TOPS} = \sum_{p \in \mathbf{P}} M_p \times D_{p,\max} \times L_p \times N_p \tag{2.4}$$

where $\mathbf{P}$ is the set of p-cycles that provides full protection, $D_{p,\max}$ is the maximum data rate over all the links that are protected by p-cycle p, L_p is the length of p in hops, and N_p is the number of links that are assigned to be protected by p. Smaller M, $D_{\max}$, and L indicate fewer backup FSs required, while larger N indicates higher unshareable consumption and lower possibility for a full sharing scenario. The p-cycle set that has a lower SC_{TOPS} is considered to be better.

2.2.3 Examples for TIPS and TOPS

Consider Fig. 2.1 as an illustrative example to calculate IC for TIPS. For instance, consider p-cycle 1 and p-cycle 2, namely A-B-C-D-F-E-A and A-E-H-G-A. P-cycle 1 has a longer physical distance while p-cycle 2 has a shorter physical distance. Assume that p-cycle 1 has a modulation cost factor of 0.5, and p-cycle 2 has a modulation cost factor of 0.34. The numbers of links that can be protected by p-cycle 1 and p-cycle 2 are 8 and 4 respectively, while the numbers of links that are used for protection on p-cycle 1 and p-cycle 2 are 6 and 4 respectively. For p-cycle 1, the protection distance (in hops) of on-cycle links is 5 and the protection distance of straddling links B-E and C-F is 2. The total protection distance is 34, therefore the average protection distance is 34/8. Finally, the IC of p-cycle 1 is $0.5 \times 6 \times 34/(8 \times 8) \approx 1.59$. Using the same approach, the IC of p-cycle 2 is $0.34 \times 4 \times 12/(4 \times 4) \approx 1.02$. Therefore cycle 2 is encouraged to be used due to a lower individual cycle cost.

Fig. 2.1 and Fig. 2.2 show two different p-cycle sets. For p-cycle set in Fig. 2.1, there are four p-cycles with different sizes and modulation cost factors. Suppose that p-cycle 1 has a modulation cost factor 0.5, while the otherf p-cycles have modulation cost factor 0.34. The IC of p-cycle 1 is higher than the IC of p-cycles 2, 3, and 4 which have the same IC. Suppose that A-E is protected by p-cycle 2, E-F is protected by p-cycle 3, F-D is protected by p-cycle 4, and E-H and F-I are protected by p-cycle 3. The SC_{TIPS} of this cycle set is $(0.5 \times 34/8 \times 5) + (0.34 \times 3 \times 3) + (0.34 \times 3 \times 4) + (0.34 \times 3 \times 3) = 20.825$. For p-cycle set in Fig. 2.2, the IC of cycle 2 is 2.48, therefore all the overlapping links A-E, E-F, and F-D are protected by cycle 1 due to its lower IC. The SC_{TIPS} of this cycle set is $(0.5 \times 34/8 \times 8) + (0.5 \times 62/10 \times 7) = 38.7$. Thus, according to our cost metric, cycle set 1 would be deemed better than cycle set 2. We will present extensive simulation results using our proposed cost metrics and p-cycle design algorithms later in the paper.

Now consider Fig. 2.1 as an illustrative example for TOPS individual cost. The data rate of working path on each link is shown on the link in the unit of Gbps. Consider p-cycle 1 and p-cycle 3. For p-cycle 1, $D_{\max}$ is 20 since it goes across link E-F. For p-cycle 3, $D_{\max}$ is 20 as well. Therefore the IC_{TOPS} of p-cycle 1 is $0.5 \times 20 \times 6^2 = 360$ while the IC_{TOPS} of p-cycle 3 is $0.34 \times 20 \times 4^2 = 108.8$. Thus p-cycle 3 is determined to be better that p-cycle 1.

Now consider the two sets of p-cycles in Fig. 2.1 and Fig. 2.2. For the cycle set in Fig. **??**, the $D_{p,\max}$ of p-cycle 1 to 4 are 10, 10, 20, and 10, respectively. The lengths of p-cycle 1 to 4 are 6, 4, 4, and 4, respectively. Since links are assigned to be protected by the lowest-IC p-cycle that can protect the link, N_p of p-cycle 1 to 4 are 5, 4, 2, and 4, respectively. Therefore, the SC_{TOPS} of this cycle set is $(0.5 \times 10 \times 6 \times 5) + (0.34 \times 10 \times 4 \times 4) + (0.34 \times 20 \times 4 \times 2) + (0.34 \times 10 \times 4 \times 4) = 313.2$. For the cycle set in Fig. **??**, the ICs of cycles 1 and cycle 2 are 360 and 640. The overlapping links A-E,

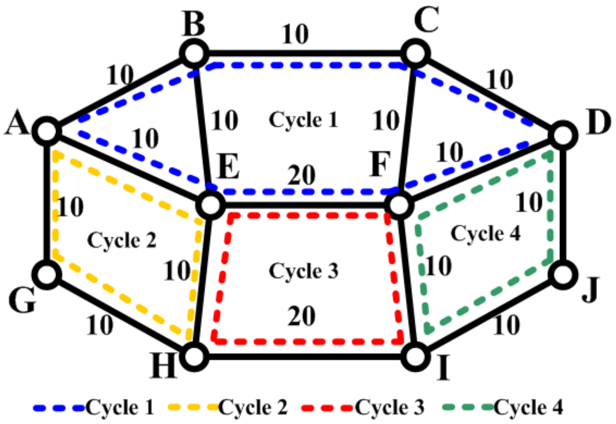

Figure 2.1: P-cycle set 1.

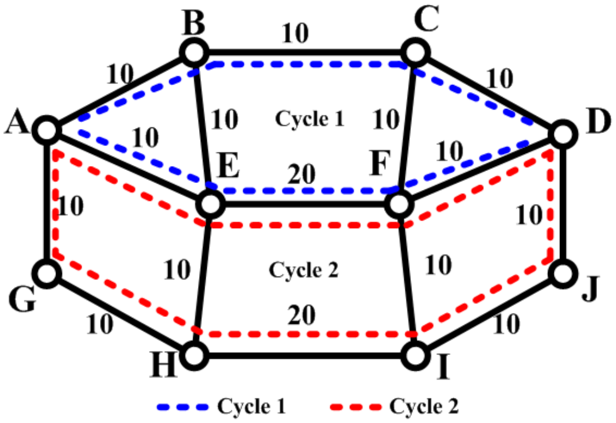

Figure 2.2: P-cycle set 2.

E-F, and F-D are protected by cycle 1 due to its lower IC. So the SC_{TOPS} of this cycle set is $(0.5 \times 20 \times 6 \times 8) + (0.5 \times 20 \times 8 \times 7) = 1040$. Thus, the cycle set in Fig. 2.1 is determined to better than the one in Fig. 2.2.

2.3 P-cycle Evaluation in Translucent EONs

In this section, we present the p-cycle evaluations in translucent network. Now TIPS and TOPS are updated to Traffic-Independent P-Cycle Selection with 3R regenerator (TIPS-3R) and the Traffic-Oriented P-Cycle Selection with 3R regenerator (TOPS-3R)

2.3.1 Traffic-Independent P-cycle Selection with 3R Regenerator

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.

2.3.1.1 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:

$$IC_{TIPS-3R} = \frac{AM \times L}{S} \times AP \tag{2.5}$$

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

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

on physical distance; we use $k = 5$ in the evaluation) are computed for each pair of network nodes. The path which has the smallest longest segment among these paths is selected as the working path for a node-pair.

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 [**?**]. 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. 2.3 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 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 $(1+0.5)/2 = 0.75$.

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[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.

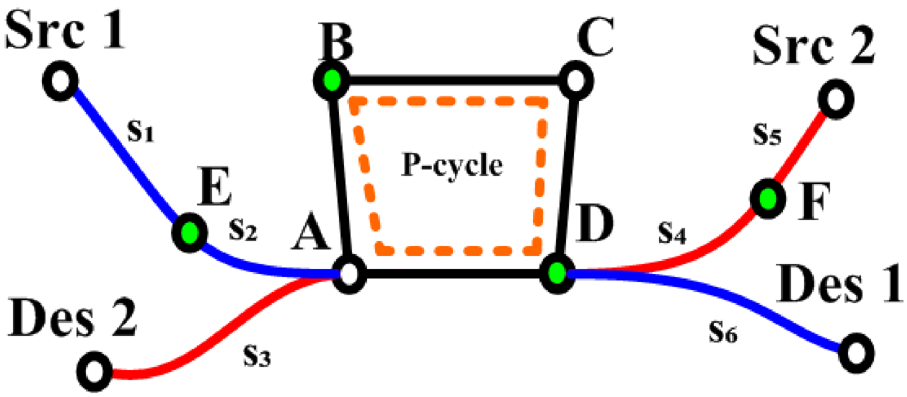

Figure 2.3: Example for average modulation index calculation.

2.3.1.2 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:

$$SC_{TIPS-3R} = \sum_{p \in \mathbf{P}} \sum_{l \in \mathbf{p}} AM_l \times P_l \times N_p \tag{2.6}$$

where **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.

2.3.2 Traffic Oriented P-cycle Selection with 3R Regenerator

Now we present the TOPS-3R. In TOPS-3R, traffic information are known in advance, which is same as TIPS.

2.3.2.1 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:

$$IC_{TOPS-3R} = \frac{AM \times D_{\text{max}}}{D_{\text{total}}} \times AP \tag{2.7}$$

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.

2.3.2.2 Cycle Set Protection Cost

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

$$SC_{TOPS-3R} = \sum_{p \in \mathbf{P}} AM_p \times D_{p,\max} \times AP_p \times N_p \tag{2.8}$$

where **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 $IC_{TOPS-3R}$

2.3.3 Examples for TIPS-3R and TOPS-3R

Fig. 2.4 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 A-B, B-D, A-D, B-E, D-E have average modulation index of 0.34 while link B-C

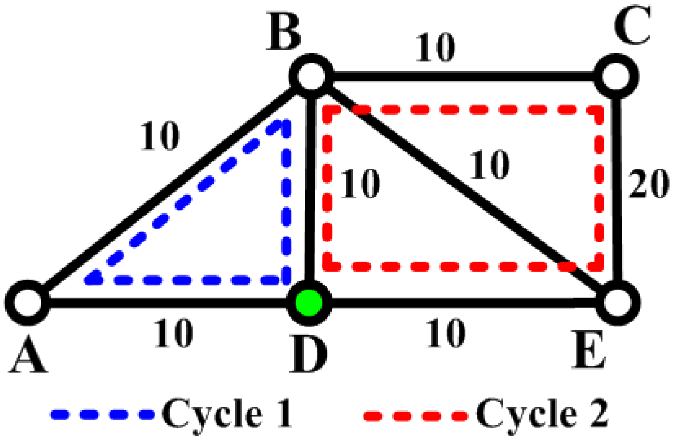

Figure 2.4: Example for IC and SC in TIPS and TOPS.

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. 2.4 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 $(0.34 \times 10 \times 2 \times 3) + (0.4 \times 20 \times 2.75 \times 4) = 108.4$.

2.4 P-cycle Generation

In this subsection, we describe the algorithm for finding a set of p-cycles based on IC and SC. This algorithm is used in all the algorothms we proposed (TIPS, TOPS, TIPS-3R and TOPS-3R). The pseudocode is shown in Algorithm 1.

Algorithm 1 Finding a set of p-cycles

```
Require: Network topology
Ensure: A candidate set of p-cycles
while the network is not fully protected do
    Randomly select an unprotected link $l$
    Use Dijkstra's algorithm with physical distance to find a shortest path $sp$ between the
      two ends of the link
    Merge $l$ and $sp$ as a p-cycle $p$ and initialize the candidate p-cycle as $p$
    Calculate $IC$ for $p$ as $p_{IC}$
    Initialize $IC_{\min}$ as $p_{IC}$
    while $\text{EXPAND\_P-CYCLE}(p) \neq NULL$ do
        $p' = \text{EXPAND\_P-CYCLE}(p)$
        Calculate the $IC$ of $p'$ as $p'_{IC}$
        if $p'_{IC} < IC_{\min}$ then
            Update the candidate p-cycle to $p'$
            Update $IC_{\min}$ to $p'_{IC}$
        end if
        $p = p'$
    end while
    Add the candidate p-cycle to p-Cycle set P
    Mark links that can be protected by candidate cycle as protected.
end while
```

We start by randomly finding a link l in the network. Then we find a shortest path sp between two ends of this link. Let the selected link l and the path sp be combined to form a basic p-cycle p. Calculate the IC for this p-cycle and mark this p-cycle as a candidate p-cycle.

Continue to expand the p-cycle unless the p-cycle cannot be expanded further. The pseudocode of expanding p-cycle is shown in Algorithm 2. For each expanding step, assume that the p-cycle after expanding is p'. Calculate the IC of p'. If the IC of p' is lower than $IC_{\min}$, update the candidate p-cycle to p' and update $IC_{\min}$ to p'_{IC}. After the expansion phase is over, put the candidate p-cycle into the p-cycle set and mark the links that can be protected by this p-cycle as *protected*. If the network is not fully protected, randomly select a link that is not protected and add another candidate p-cycle into the cycle set again and continue. After all the links in the network are marked as protected, we have a set of p-cycles that can be used to protect the network.

The above procedure produces a “good" p-cycle set since we used IC to expand the p-cycles, but the p-cycle set is also somewhat random because since the starting link and expansion phase for each p-cycle are based on randomly selected links. We generate a large number of such p-cycle sets (by using different random links as starting link for each p-cycle and while expanding). Then, we choose the best p-cycle set among these as the set with the lowest SC. Later, we will compare the performance of such a p-cycle set (simply called *Best*) with some baseline algorithms for selecting p-cycle sets.

Algorithm 2 EXPAND_P-CYCLE

```
Require: p-cycle $p$
Ensure: Larger p-cycle $p'$
1: Randomly select an on-cycle link $l$ on cycle $p$
2: Mark two ends of $l$ as $a$, $b$
3: Remove all the links on $p$ from the network
4: Use Dijkstra's algorithm with physical distance to find the shortest route $R$ in physical distance between $a$ and $b$
5: if $R$ does not exist then
6:     goto line 1
7: end if
8: Merge $R$ and $p$ as the new cycle $p'$
```

Chapter 3: Routing and Spectrum Algorithms

In this chapter, we propose Routing and Spectrum Algorithms (RSA) for both transparent network and translucent network.

3.1 RSA in Transparent Network

In TIPS, the Best p-cycle set can be found purely based on topology. In TOPS, the working paths are first routed without spectrum assignment by using Dijsktra's shortest path algorithm and the maximum 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 Dijkstra's shortest path algorithm to find a route for the working path. Then 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 protection path on the protection cycle for the failed link. Note that we use the shorter of the two cycle paths for protecting straddling links. The highest modulation index that is acceptable for this total length is then recorded, and the minimum of these modulation indexes (over all failed links) is then chosen as the modulation index for this lightpath. 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 is completed by using the first fit method if slots are available. Otherwise, the request is blocked.

We adapt the above approaches for dynamic traffic as follows. Since the lightpath requests are not known in advance in this case, we use TIPS here. Therefore, a set of p-cycles based on IC and SC are selected at the beginning, and when a new lightpath request arrives, only RSA is performed and a modulation index is selected as described above. If

Algorithm 3 Routing and Spectrum Assignment

```
Require: Network topology, traffic requests, a set of P-cycles
Ensure: The working and protection spectrum assignment
for Each $LR(s,d,B) \in A$ do
    Use Dijkstra's algorithm with physical distance to find the working lightpath $LP$.
    for Each $l \in LP$ do
        Assume failure occurs in $l$
        Calculate the total distance of $LP$ and p-cycle protection path
        Determine the modulation with distance as $M$
    end for
    Select the lowest modulation index for working and protection
    Decide the number of FSs as $F$
    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
    if $SI_{start} = SI_{max} - FS$ then
        Block the request
    end if
end for
```

FSs are not available for the request, the request is blocked.

3.2 RSA in Translucent Network

This section presents the routing and spectrum assignment for the working paths and p-cycle protection. Both TIPS and TOPS use Algorithm 3 for RSA.

Algorithm 4 Routing and Spectrum Assignment

```
Require: Network topology, traffic requests, a set of P-cycles
Ensure: 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.

Chapter 4: Simulation Results

In this section, simulation results are presented to demonstrate the effectiveness of our proposed p-cycle design methods under both static and dynamic traffic. The network topologies used for simulations are the COST239 network and the Pan-European network. The COST239 network consists of 11 nodes and 26 links (shown in Fig. 4.1), while the pan-European network consists of 28 nodes and 44 links (shown in Fig. 4.2). The physical distance in km is shown adjacent to the links. In translucent network, we double the physical distance in COST239 topology to guarantee all the modulation formats are used. On each link in the network, a pair of working fibers in opposite directions are used for working path, and a pair of protection fibers in opposite directions are used for protection. In 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 three different types of demands with rate 40/100/400 Gbps. The data rate is generated from the following distribution: 40 Gbps, 100 Gbps, and 400 Gbps with probability 0.2, 0.5, and 0.3, respectively. The number of required FSs for a lightpath is determined by its data rate and modulation format. Table I shows the number of FSs corresponding to different data

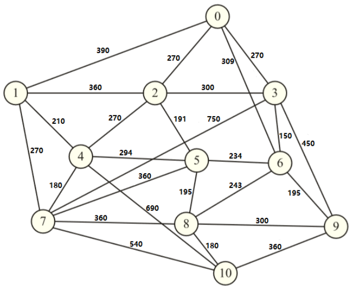

Figure 4.1: 11-node COST239 network.

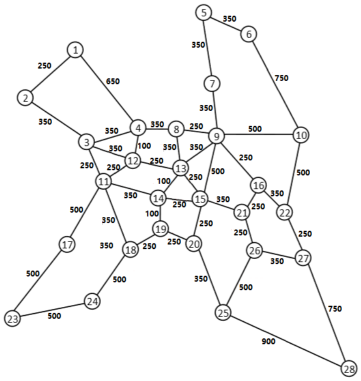

Figure 4.2: 28-node pan-European network.

rates under different modulation formats [26]. The performances are evaluated in terms of spectrum usage per link (the total number of used FSs for both working and protection on all links divided by number of links in the network). Moreover, in order to evaluate the spectrum usage without blocking, we assume that there are an unlimited number of FSs on each fiber.

In dynamic traffic model, the 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. The distribution of data rate of requests is the same as before. The highest FS available on each fiber is assumed to be 352. We use the demand blocking ratio of dynamic traffic requests to indicate the performance of p-cycle selection and protection. For each simulation, the results of 1 million dynamic requests are computed.

For each modulation format, the physical distance limitations are shown in Table II [26]. The modulation index in p-cycle evaluation and selection are also determined by this limitation. In our tests, we assume that there is no physical distance limitation for BPSK in order to guarantee that all the requests can be established in the static case. We also present the bandwidth blocking ratio if the distance limit for BPSK is set to 4000 km.

For p-cycle selection, the Best p-cycle set is found in advance by generating a large number of ($\approx$ 3000) p-cycle sets and selecting the one with the lowest SC, which is SC_{TIPS} for TIPS and SC_{TOPS} for TOPS. 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.

Table 4.1: Number of required FSs for various data rates and modulations [26].

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

We compare the Best p-cycle set selection algorithm with the following three baseline

Table 4.2: Physical distance limitation for different modulations [?].

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

algorithms for p-cycle set selection: namely, random cycle set (Random), top individual p-cycle set (TopIC), Hamiltonian cycle [21],[1] and top A Priori Efficiency p-cycle set (TopAE). A Priori Efficiency (AE, $AE = \sum_{i \in E} \chi_{ij} / \left(\sum_{k \in E} \delta_{kj} \times C_k \right)$, where χ_{ij} refers to the number of paths can be provided by the cycle j if link i fails; the possible values are 0, 1 for on-cycle link and 2 for straddling link; δ_{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 which is assumed 1 in this work) was proposed as a single p-cycle evaluation for WDM networks without modulation and spectrum sharing consideration [28, 29]. For Random, TopIC, and TopAE, the set $\mathscr{C}$ of all candidate cycles is first generated offline in advance using a depth-first-search algorithm. In Random, a random p-cycle set is formed by randomly selecting cycles from $\mathscr{C}$ one by one until the network is fully protected. In TopIC and TopAE, the cycles in $\mathscr{C}$ are sorted based on IC or AE, respectively, in non-decreasing order, and the TopIC p-cycle set and TopAE p-cycle set are formed by selecting cycles in this order until the network is fully protected.In both cases, only cycles that protect at least one as-yet unprotected link will be added to the p-cycle set.

4.1 Simulation Results of P-cycle Designs in Transparent EONs

4.1.1 Static Traffic in Transparent Network

Fig. 4.3 and Fig. 4.4 show the results for spectrum usage (i.e., number of FSs used per link) in COST239 and pan-European network respectively. We make several observations from the results. First, we compare the Best cycle set with Hamiltonian cycle and Random

---

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

cycle set. There is an improvement of more than about 40% in spectrum usage in COST239 network, while the improvement is more than about 20% in pan-European network. The Best cycle set has a better performance because we select cycles with lower individual cost and cycle set cost.

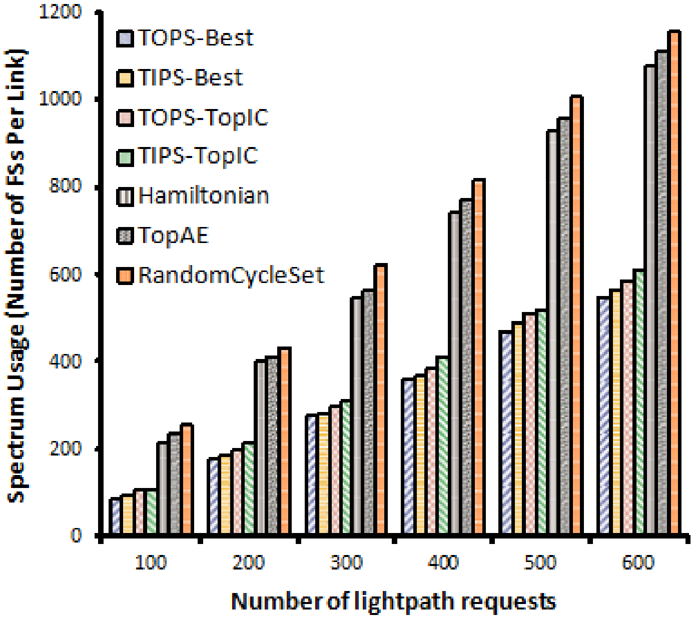

Figure 4.3: Spectrum Usage in COST239 in transparent EONs.

Compared with TopAE, the Best and TopIC p-cycle sets have much better performance, which shows the need for an improved p-cycle evaluation method which takes modulation and cycle size into account in EONs. Moveover, the results show that the cycle set consisting of the top individual cycles is not the best cycle set. This demonstrates the effectiveness of cycle set evaluation. Since we take load balance risk into account when the IC is measured, the TopIC cycle sets have a good performance as well. Moreover, for the Best cycle set, the performance of TOPS is better than TIPS, because TOPS also takes into account traffic and data rate.

Suppose we assume that there is a 4000 km physical distance limitation for BPSK. In COST239, the bandwidth blocking ratio for all the proposed algorithms and baseline

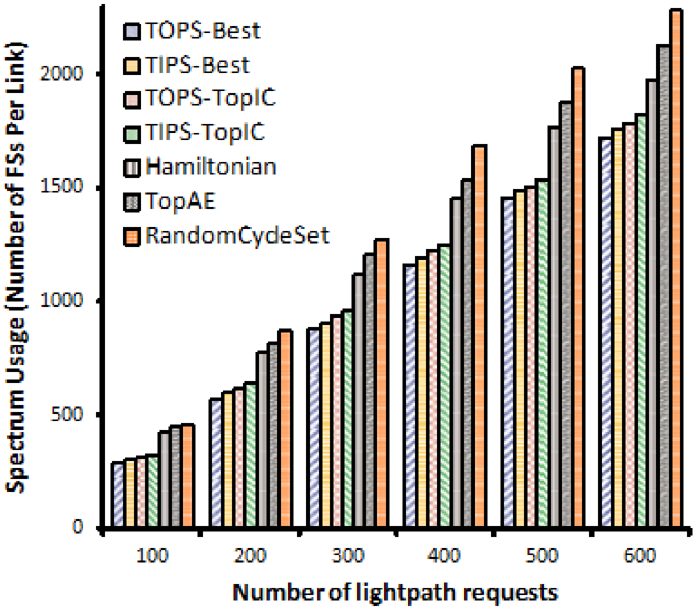

Figure 4.4: Spectrum Usage in Pan-European in transparent EONs.

algorithms are lower than 0.5%. In pan-European network, the bandwidth blocking ratio for TOPS-Best, TOPS-TopIC, TIPS-Best, and TIPS-TopIC are lower than 1%, whereas it is 94% and 91% for the Hamiltonian cycle and random cycle sets, respectively, due to the large network size. Therefore with physical distance limitation, large cycles are even more vulnerable to failure and blocking.

4.1.2 Dynamic Traffic in Transparent EONs

Fig. 4.5 and Fig. 4.6 show the result of blocking ratio under dynamic traffic for the COST239 and Pan-European networks. We can see that the Best cycle set has the best performance. In pan-European network, the p-cycles in TopIC tend to be small-sized cycles and are likely to be assigned high modulation index, therefore the blocking ratio is similar to the Best cycle set.

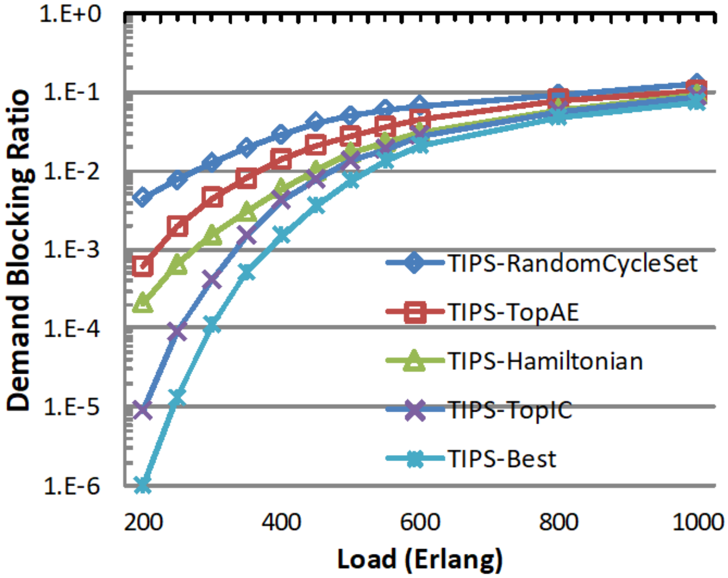

Figure 4.5: Demand blocking ratio in COST239 in transparent EONs.

4.2 Simulation Results of P-cycle Designs in Translucent EONs

In translucent networks, 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.

4.2.1 Static Traffic in Translucent EONs

Fig. 4.7 shows the results for spectrum utilization for COST239, while Fig. 4.8 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 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.

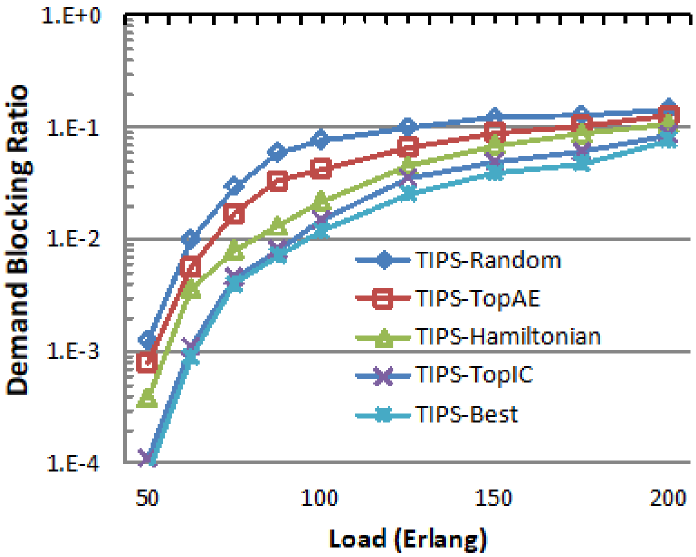

Figure 4.6: Demand blocking ratio in Pan-European in transparent EONs.

4.2.2 Dynamic Traffic in Translucent EONs

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. 4.9 and Fig. 4.10 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.

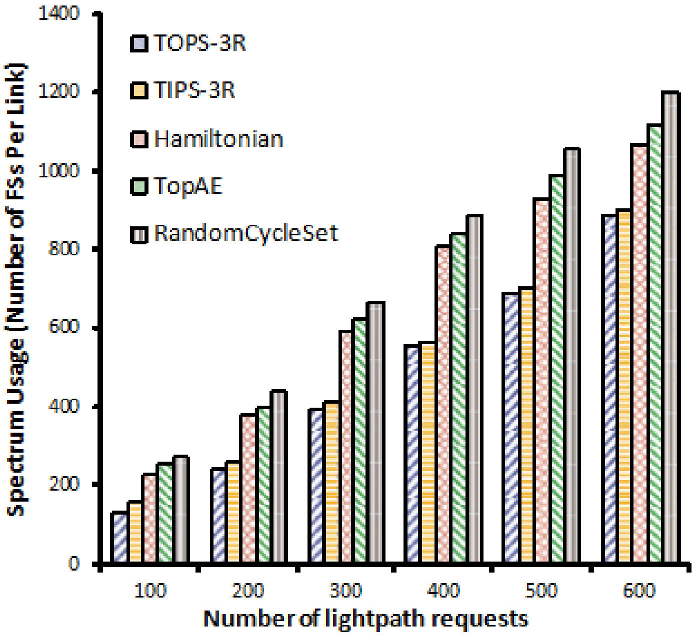

Figure 4.7: Spectrum utilization in COST239 in translucent EONs.

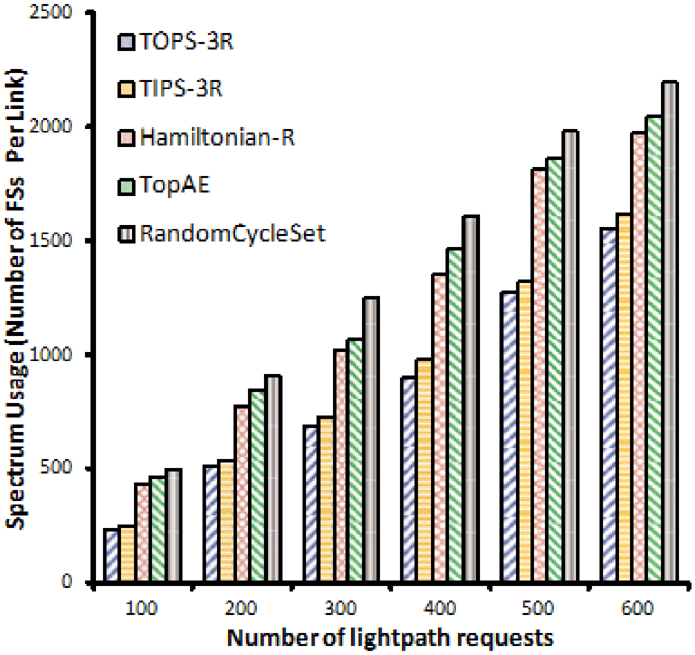

Figure 4.8: Spectrum utilization in Pan-European translucent EONs.

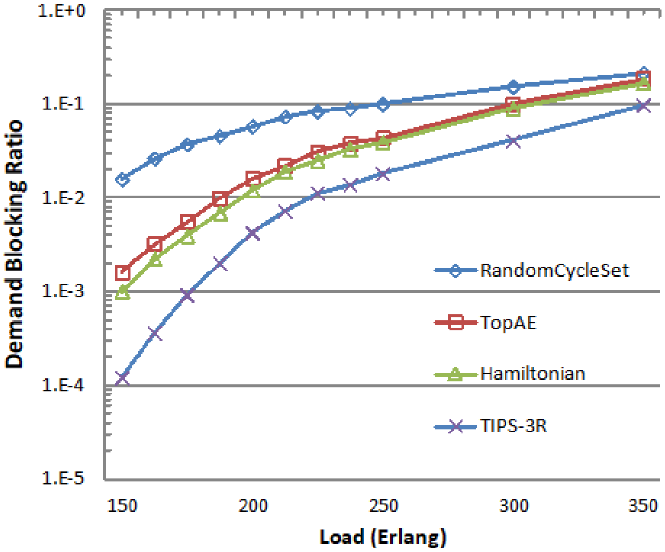

Figure 4.9: Demand blocking ratio in COST239 translucent EONs.

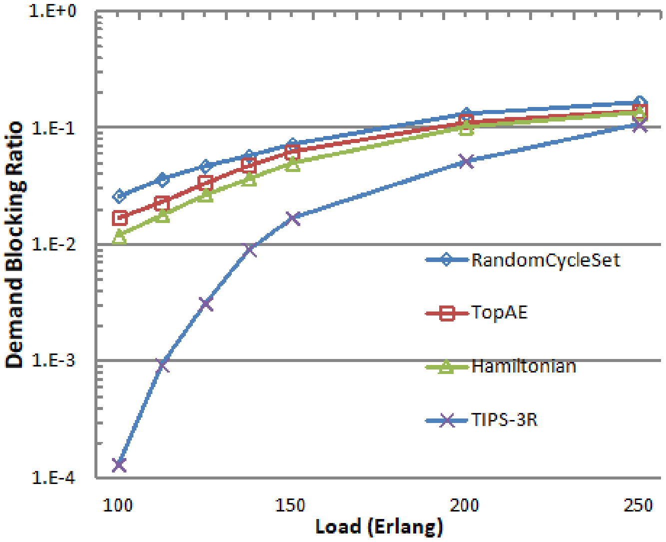

Figure 4.10: Demand blocking ratio in Pan-European translucent EONs.

Chapter 5: Discussions

P-cycle selections and protection algorithms can be designed with following technologies:

5.1 Spectrum Conversion

Most existing studies on the EON assume that there is no spectrum conversion at each optical switch node and therefore, the constraint of spectrum continuity should be met. This constraint can greatly limit the spectrum resource sharing and utilization of the EON. If we can abandon the spectrum continuity, it is possible to make a further improvement. In terms of spectrum conversion, the spectrum allocation scheme can be classified as Same Channel (SC) and Different Channel (DC). SC means a traffic demand is allocated the same segment of the optical frequency spectrum on its primary path and backup path while DC means traffic demand is allocated the different segment of the optical frequency spectrum on its primary path and backup path. It is important to say both dedicated protection and shared protection use SC and DC.

Klinkowski et al. [15] firstly mention the term SC and DC, the ILP algorithm and heuristic algorithm provided in their paper are established with SC or DC. Shen et al. [23] use the term transponder tunability to describe the same issue as SC/DC. The ILP is proposed with/without transponder tunability. The ILP constraint 5, 12 and 13 are used to applied/or not applied the transponder tunability. Walkowiak et al. [25] also consider SC/DC in ILP issue. Spectrum converter lies in the middle of a lightpath.

5.2 Bandwidth Squeezed Restoration

Bandwidth Squeezed Restoration (BSR) is another method to improve the spectrum assignment efficiency. BSR is first proposed by Jinno et al. [10]. The BSR technique makes it is possible to partially recover the bandwidth of the failure working lightpath by using whatever remaining capacity is available on the backup link. A traffic demand can be squeezed from high bandwidth to a lower bandwidth path as best effort recovery. Sone et al. [24] presented the description on the BSR technique in detail and the BSR technique is verified with an experiment to maximally restore the bandwidth of an affected elastic optical channel. Shen et al. [23] present BSR based SBPP protection and 1+1 protection. The core part of deploy the BSR into the protection is author assume all the traffic can be squeezed in a fixed ratio. All the ILP constraints are modified with the ratio and BSR is applied in protection issue. Wei et al. [27] present a span-restoration with BRS and spectrum conversion. BRS is used to obtain the maximal restoration levels for the affected service flows, subject to the limited frequency slot capacity on each fiber link.

5.3 Energy Efficiency

Energy efficiency issue is everywhere in engineering designs. In [40], a novel data center energy optimization framework is proposed with QoS constraints. In [39], using the existing processor and platform sleep states, the proposed algorithm is able to achieve higher energy savings. In [38], authors explore techniques that make smart use of the processor and system low-power state and propose a workload adaptive energy-latency optimization. Many protection schemes have been proposed so far, but in most of the cases the energy efficiency has not been taken into account in EONs protection design [13]. Lopze et al. [19] show the benefits in energy efficiency of an EON network compared to the WDM networks. This paper evaluates the energy efficiency of dedicated protection and shared path protection. The power of optical devices including optical transponder and OXC is considered.

5.4 Other Related Works

The protection algorithm can be designed with machine learning [33].

Li et al. [16] present a joint spectrum and storage resource backup (JSSRB) to improve the survivability of elastic optical datacenter networks (EODNs) for cloud services. This paper proposes an ILP model and heuristic algorithms in order to improve the survivability and spectrum efficiency of EODNs. However, according to the simulation result, JSSRB has a same performance with dedicated backup path protection. In addition, authors consider the impact of distance adaptive modulation.

Davis and Vokkarane [5] propose an ILP based approach to solve the problem of multicast resource node failure, and focus on protecting connections against the failure of any one multicast resource out of the set of resource nodes. The paper presents the protection against this type of failure can be provided with the trade-off of increased frequency slot consumption, compared to less-protected solutions. The formal problem definition and NP-hardness proof is given. The ILP solution and multicast resource protection heuristic algorithm is presented.

Liu et al. [18] present a shared protection algorithm with traffic grooming. This paper proposes the elastic-separate-protection-at-connection (ESPAC). This algorithm provides traditional backup sharing, and offers a new opportunity of spectrum sharing enabled by the elasticity of the transponders. Two conditions are considered. First is if the working paths of two connections are link disjoint physically, and second one is if their backup paths traverse two lightpaths which are adjacent on a fiber link, then the two backup light paths can share spectrum.

The protection issue also exists in optical data center. The protection algorithm can be designed with features of data centers [17, 34–37].

Chapter 6: Conclusions and future direction

P-cycles are attractive for protection in EONs because of high efficiency and fast restoration speed. In this thesis, we analyzed the factors that are able to determine the performance of p-cycle protection. Then we proposed metrics to evaluate the cost of an individual p-cycle and cost of p-cycle set in transparent EONs and translucent EONs. We proposed algorithms to select p-cycles both in the absence of traffic knowledge (Traffic-Independent P-cycle Selection, TIPS) and with traffic knowledge (Traffic-Oriented P-cycle Selection, TOPS) in tranparents EONs. We also proposed algorithms to select p-cycles with 3R regenerator placement, named Traffic-Independent P-cycle Selection with 3R Regenerator (TIPS-3R) and Traffic-Oriented P-cycle Selection with 3R Regenerator (TOPS-3R). Further, p-cycle set generation algorithms based on these metrics are designed. From extensive simulation results, we observed that the performances of the proposed selection algorithms are significantly better than baseline algorithms in terms of required spectrum and blocking ratio. In the future, we will focus on spectrum conversion algorithm design with 3R regenerator and ILP design for p-cycle protection.

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