On Spectrum Efficient Failure-Independent Path Protection *p*-Cycle Design in Elastic Optical Networks

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***Abstract*—High spectrum efficiency and fast restoration speed are highly desired for survivable elastic optical networks (EONs). In this paper, we take the advantages of failure-independent path-protecting preconfigured cycles (FIPP *p*-cycles) and investigate how to realize spectrum efficient resilience design with them. We first study the problem of offline service provisioning with FIPP *p*-cycles. We formulate an integer linear programming model and prove that the problem is $\mathcal{NP}$ hard. Then, several time-efficient heuristics are designed for FIPP *p*-cycle formulation and related routing, modulation format, and spectrum assignment. Extensive simulations on offline provisioning verify that the heuristics can obtain near-optimal solutions. Next, we consider online service provisioning with FIPP *p*-cycles in dynamic EONs. In order to overcome the decrease of protection efficiency during dynamic network operation, we propose a *p*-cycle reconfiguration scheme to reoptimize protection structures on-the-fly. Simulation results demonstrate that the proposed algorithms can improve spectrum efficiency and reduce bandwidth blocking probability simultaneously.**

***Index Terms*—Elastic optical networks (EONs), failure-independent path-protecting (FIPP) *p*-cycle, re-optimization.**

I. Introduction

Recent researches have suggested that spectrum-sliced elastic optical networks (EONs) possess the benefits of high spectrum efficiency and flexible bandwidth allocation [1]. Specifically, different from the fixed-grid wavelength division multiplexing (WDM) networks that operate on discrete wavelength channels, EONs use narrow-band spectrally-contiguous frequency slots (FS') to achieve on-demand bandwidth provisioning in the optical layer.

Meanwhile, it is known that maintaining network survivability is not only important but also necessary in optical networks, since even a single fiber-cut can cause tremendous data loss. Previously, people have tried to improve the survivability of EONs with path-based protection and restoration schemes [2]–[9]. Among them, the shared backup-path protection (SBPP) can be spectrum efficient. However, as SBPP only reserves but does not pre-configure backup resources, the scheme may incur prolonged signaling procedure and complicated switch reconfigurations during restoration [10]. Note that ensuring fast service restoration helps to minimize revenue losses due to network failures and hence is always preferred by network operators [11]. In order to increase the restoration speed of EONs, previous studies have also considered the link-based pre-configured cycles (*p*-cycles) [12] and designed fast recovery schemes with them [13]–[16]. Nevertheless, due to the fact that the *p*-cycle based protection scheme may need to use long restoration paths, the spectrum efficiency during restoration could be low and the additional transmission impairments could be an issue too. To address these issues, we can rely on the failure-independent path-protecting *p*-cycle (FIPP-*p*-cycle) [17], which is known to be able to achieve both fast restoration speed and high spectrum efficiency.

In this paper, we study the resilience design with FIPP-*p*-cycles for EONs and aim to provide 100% restorability for lightpaths during any single link-failure. We start with formulating an integer linear programming (ILP) model for the problem of offline service provisioning with FIPP-*p*-cycles and prove that it is $\mathcal{NP}$-hard. Then, several time-efficient heuristics that can obtain near-optimal solutions are designed for FIPP-*p*-cycle formulation and related routing, modulation format and spectrum assignment (RMSA). In order to overcome the decrease of protection efficiency (PE) during dynamic network operation, we also propose a *p*-cycle reconfiguration scheme to re-optimize protection structures on-the-fly. The proposed algorithms are evaluated with extensive simulations and the results show that they can improve spectrum efficiency and reduce bandwidth blocking probability (BBP) simultaneously.

The rest of the paper is organized as follows. Section II presents a survey on the related work and Section III describes the problem of FIPP-*p*-cycle design in EONs. In Section IV, we study offline service provisioning with FIPP-*p*-cycles, formulate an ILP model and design several time-efficient heuristics. The proposed algorithms are evaluated with simulations on offline provisioning in Section V. Section VI discusses the proposed algorithms' performance for online provisioning. Finally, Section VII summarizes the paper.

II. Related Work

The path-based protection schemes were first investigated for improving the survivability of EONs. In [2], Sone *et al.* studied

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the bandwidth-squeezed restoration for dedicated path protection (DPP) in EONs, under the assumption that the bandwidths allocated to protection paths can be less than those on working paths. To improve the PE in EONs, Xu *et al.*[3] developed an SBPP scheme. In [4], a single-path routing and multi-path recovery scheme was designed to utilize the spectrum fragments in EONs effectively. The problem of offline service provisioning with DPP in EONs was studied in [5] and [9], where Walkowiak *et al.* formulated ILP models and designed several heuristics for adaptive spectrum assignment. In [6], Liu *et al.* proposed to use the first-fit and last-fit schemes for spectrum assignments of working and backup paths, respectively, to enhance the shareability of backup resources in EONs. Wen *et al.* [7] considered the spectrum fragmentation in EONs, and proposed two impairment-aware restoration algorithms to increase the success-rate of restoration. In [8], Ruan and Zheng leveraged multi-path routing to design an over-provisioning scheme for improving the resilience of EONs and demonstrated that it could achieve higher PE than DPP. One drawback of these path-based protection schemes is that they may incur prolonged signaling procedure and complicated switch reconfigurations during restoration.

To accelerate the restoration speed in optical networks, *p*-cycle protection was proposed in [12]. Protection designs with *p*-cycles have been intensively studied for WDM networks [18]–[22], where people have proposed both ILP models and heuristics for realizing efficient *p*-cycle configuration. Previously, we have considered the unique spectrum allocation scenario in EONs, designed dynamic *p*-cycle protection algorithms, and proposed a spectrum planning technique to overcome the spectrum fragmentation [13]. In [14], Wei *et al.* combined *p*-cycle protection with bandwidth-squeezed restoration and developed an ILP model for achieving capacity-efficient resilient design in EONs. The routing and spectrum assignment (RSA) problem for static *p*-cycles was studied in [15], in which a heuristic that could obtain highly-efficient *p*-cycles was proposed. More recently, we considered the service availability oriented *p*-cycle protection in EONs and developed a theoretical model to analyze the service availability of lightpaths protected by *p*-cycles [16]. Note that the aforementioned *p*-cycle schemes may use long restoration paths, and thus both the low spectrum efficiency and the additional transmission impairments during restoration could be issues in EONs [13].

FIPP-*p*-cycle realizes end-to-end path protection with *p*-cycles while still enabling backup resource sharing, and hence can achieve both fast recovery speed and high spectrum efficiency during restoration [17]. In [23], Jaumard and Metnani studied the stability of FIPP-*p*-cycles in dynamic WDM networks and they then extended the work to design FIPP-*p*-cycles to protect against dual link failures [24]. However, these pioneering studies on FIPP-*p*-cycles were based on fixed-grid WDM networks, we need to revisit the problem for EONs because of the unique spectrum allocation mechanism and spectrum fragmentation in them. The implementation of FIPP-*p*-cycles in EONs was first considered in [25], where Oliveira and Fonseca designed a heuristic to solve the RSA problem. However,

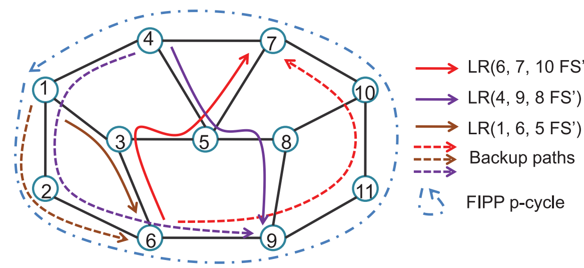

Fig. 1. An example on FIPP-*p*-cycle based protection in EONs.

they did not address the spectrum-efficient FIPP-*p*-cycle design together with RSA or the adaptive modulation selection.

III. FIPP-*p*-Cycle Protection in EONs

In this section, we explain the working principle of FIPP-*p*-cycle based protection in EONs.

The EON topology is modeled as $G(V, E)$, where V and E represent the sets of nodes and directed fiber links in G, respectively. For a lightpath request $LR(s, d, B)$ that is from s to $d\,(s, d \in V)$ for B Gb/s bandwidth capacity, we perform RMSA [26] for its working path and build corresponding FIPP-*p*-cycles such that the data transmission of LR will not be disrupted in case of any single-link failure. Note that in this work, we assume that the EON performs impairment-aware modulation selection and the bandwidth requirement of LR (i.e., B Gb/s) can be transformed to the number of spectrally-contiguous FS' (i.e., size of an FS-block) according to the spectral efficiency of selected modulation format [26], [27]. Meanwhile, in order to minimize spectrum converters and optical-to-electrical-to-optical (O/E/O) converters in the EON, we also assume that the network does not have the capability of spectrum conversion and thus the spectrum assignments on lightpaths and FIPP-*p*-cycles should follow the spectrum continuity and contiguity constraints [28].

A working path can be protected by an FIPP-*p*-cycle if 1) both of its end nodes are on the *p*-cycle, and 2) it is link-disjoint with the protection path on the *p*-cycle. Fig. 1 shows an illustrative example on FIPP-*p*-cycle based protection in EONs. It can be seen that the working paths of three requests can all be protected by the same FIPP-*p*-cycle. For instance, if a link-failure affects the working path 6→3→5→7 of $LR(6, 7, 10\,\text{FS'})$, the two end-nodes (i.e., *Nodes* 6 and 7) will be informed and then they switch traffic to the backup path 6→9→11→10→7. Here, for simplicity, we do not show the spectrum assignments of the working paths and FIPP-*p*-cycle, but we will discuss the details in the following sections.

We want to emphasize that FIPP-*p*-cycle is a pre-configured structure, and thus the latency from switch reconfiguration can be reduced in each restoration. Specifically, FIPP-*p*-cycle based protection can achieve the restoration speed that is comparable to that of 1:1 DPP. Moreover, since an FIPP-*p*-cycle allows multiple working paths to share the backup resources reserved on it, the PE can be improved. Basically, two working paths can share an FIPP-*p*-cycle if they are link-disjoint or their backup paths on the *p*-cycle are link-disjoint. For example, since the three requests in Fig. 1 require 10, 8 and 5 FS', we only need to reserve 10 FS' on the FIPP-*p*-cycle to protect all of their working paths.

IV. Offline Provisioning With FIPP-*p*-Cycles

This section studies offline service provisioning with FIPP-*p*-cycles in EONs. We first formulate an ILP model for the problem and prove that it is $\mathcal{NP}$-hard. Three time-efficient heuristics are then proposed to get the near-optimal solutions.

A. ILP Model

Given a traffic matrix Λ in $G(V, E)$, the ILP below tries to serve all the lightpath requests in Λ while minimizing the total spectrum usage in the EON.

Parameters:

- F: maximum number of FS' on a link.
- P_i: set of pre-calculated path candidates for request LR_i.
- C: set of pre-calculated *p*-cycles in G.
- C_i: set of *p*-cycles that contain the source and destination nodes of request LR_i, and $C_i \subset C$.
- τ_c^e: boolean parameter that equals 1 if *p*-cycle $c \in C$ traverses link $e \in E$, and 0 otherwise.
- $\mu_{i,k}^e$: boolean parameter that equals 1 if the kth path candidate $p_{i,k}$ of LR_i traverses link e, and 0 otherwise.
- b_i^k: number of required FS' if LR_i uses $p_{i,k}$ as working path.
- $b_i'^c$: number of required FS' on the *p*-cycle if c is selected as the *p*-cycle to protect LR_i.
- $T_{i,k}^f$: set of FS' whose indices are within $[\max(f - b_i^k + 1, 0), \min(f, F - b_i^k + 1)]$, where f is a specific FS' index.
- $T_{i,c}'^f$: set of FS' whose indices are within $[\max(f - b_i'^c + 1, 0), \min(f, F - b_i'^c + 1)]$, where f is a specific FS' index.
- d_{i,k_1}^{j,k_2}: boolean parameter that equals 1 if path p_{i,k_1} is not link-disjoint with path p_{j,k_2}, and 0 otherwise.
- $\delta_{i,j}^c$: boolean parameter that equals 1 if the backup paths for LR_i and LR_j on *p*-cycle c are not link-disjoint, where $c \in (C_i \bigcap C_j)$, and 0 otherwise.
- $\varphi_{c_1}^{c_2}$: boolean parameter that equals 1 if *p*-cycles c_1 and c_2 are not link-disjoint, and 0 otherwise.
- $g_{i,k}^c$: boolean parameter that equals 1 if path $p_{i,k}$ is not link-disjoint with *p*-cycle c, and 0 otherwise.
- $m_i^{k,c}$: boolean parameter that equals 1 if *p*-cycle c can protect path $p_{i,k}$, and 0 otherwise.

Variables:

- x_i^k: boolean variable that equals 1 if request LR_i uses path $p_{i,k} \in P_i$ as its working path, and 0 otherwise.
- y_i^m: boolean variable that equals 1 if request LR_i uses the FS-block whose starting index is m on its working path, and 0 otherwise.
- z_i^c: boolean variable that equals 1 if *p*-cycle c is selected to protect request LR_i, and 0 otherwise.
- ω_i^n: boolean variable that equals 1 if LR_i uses the FS-block with starting index n on its *p*-cycle as the backup resources, and 0 otherwise.
- π_e^f: boolean variable that equals 1 if FS f on link e is used or reserved, and 0 otherwise.

Objective:

$$\text{Minimize} \quad \sum_{e \in E} \sum_{f \in [1,F]} \pi_e^f. \tag{1}$$

The optimization objective is to minimize the total number of FS' used/reserved in the EON.

Constraints:

$$\pi_e^f \geq \mu_{i,k}^e \cdot \left(\sum_{m \in T_{i,k}^f} y_i^m + x_i^k \right) - 1 \quad \forall e, f, i, k, \tag{2}$$

$$\pi_e^f \geq \tau_c^e \cdot \left(\sum_{n \in T_{i,c}'^f} \omega_i^n + z_i^c \right) - 1 \quad \forall e, f, i, c. \tag{3}$$

Eqs. (2), (3) obtain the values of π_e^f in the EON

$$\sum_k x_i^k \geq 1 \quad \forall i, \tag{4}$$

$$\sum_{c \in C_i} m_i^{k,c} \cdot z_i^c \geq x_i^k \quad \forall i, k, \tag{5}$$

$$\sum_{m \in [1,F]} y_i^m \geq 1 \quad \forall i, \tag{6}$$

$$\sum_{n \in [1,F]} \omega_i^n \geq 1 \quad \forall i. \tag{7}$$

Eqs. (4)–(7) ensure that each request is served with a working path that can be protected by one *p*-cycle

$$\left(\sum_{m \in T_{i,k_1}^f} y_i^m + \sum_{m \in T_{j,k_2}^f} y_j^m \right) \leq 1 + (2 - x_i^{k_1} - x_j^{k_2}) + (1 - d_{i,k_1}^{j,k_2}) \quad \forall i \neq j, k_1 \in P_i, k_2 \in P_j, f, \tag{8}$$

$$\left(\sum_{m \in T_{i,k}^f} y_i^m + \sum_{n \in T_{j,c}'^f} \omega_j^n \right) \leq 1 + (1 - g_{i,k}^c) + (2 - x_i^k - z_j^c) \quad \forall i, j, k, c \in C_j, f, \tag{9}$$

$$\left(\sum_{n \in T_{i,c_1}'^f} \omega_i^n + \sum_{n \in T_{j,c_2}'^f} \omega_j^n \right) \leq 1 + (2 - z_i^{c_1} - z_j^{c_2}) + (1 - \varphi_{c_1}^{c_2}) \quad \forall i \neq j, c_1 \in C_i, c_2 \in C_j, c_1 \neq c_2, f. \tag{10}$$

Eqs. (8)–(10) ensure that the spectrum assignments on working paths and FIPP-*p*-cycles are not overlapping with each other if they share the same link(s)

$$\left(\sum_{n\in T'^{f}_{i,c}}\omega_i^n+\sum_{n\in T'^{f}_{j,c}}\omega_j^n\right)\le 1+(2-x_i^{k_1}-x_j^{k_2})$$
$$+(1-d_{i,k_1}^{j,k_2})+(2-z_i^c-z_j^c)+(1-\delta_{i,j}^c),$$
$$\forall i\neq j,k_1\in P_i,k_2\in P_j,c\in(C_i\bigcap C_j),f. \quad (11)$$

Eq. (11) ensures that two requests do not share the same FS' on a p-cycle, if their working paths share the same link(s) and their backup paths on the p-cycle are not link-disjoint.

Theorem 1. The problem of offline service provisioning with FIPP-p-cycles in EONs is $\mathcal{NP}$-hard.

Proof. To prove the hardness of the original problem, we first reduce it to a simplified version, namely, S-FIPP. In S-FIPP, the bandwidth requirement of each request is the same as 1 FS and the working paths are pre-determined, while the optimization objective is unchanged. It is known that the weighted set cover (WSC) problem is $\mathcal{NP}$-hard [29]. Given an instance of WSC, i.e., $S=\{s_1,s_2,\ldots,s_n\}$ and $W=\{w_1,w_2,\ldots,w_n\}$, where each set $s_i\in S$ includes certain elements and has a weight w_i, WSC tries to find a subset $S^*\subseteq S$ that includes all the elements in $\bigcup_{i=1}^n s_i$ and provides the minimum total weight. We assume that each s_i represents an FIPP-p-cycle, the elements in s_i are the working paths that it can protect, and w_i indicates the total number of FS' that it uses. Obviously, the instance of WSC is now an S-FIPP instance, and the transformation can be done within a polynomial time. Since WSC is $\mathcal{NP}$-hard, we prove that S-FIPP is $\mathcal{NP}$-hard and hence, the hardness of the original problem is also proved.

B. Heuristic Algorithms

1) Protection Efficiency-Failure-Independent Path-Protecting (PE-FIPP): Inspired by the p-cycle design algorithms developed for WDM networks [18], we first propose a PE based FIPP-p-cycle configuration algorithm and *Algorithm* IV-B1 shows the detailed procedure. For each lightpath request $LR(s,d,B)$, PE-FIPP first performs RMSA to set up the working path as shown in *Line* 2, where we use the K-shortest path routing and first-fit spectrum assignment scheme developed in [26]. Then, in *Lines* 3–18, we calculate the PE of each feasible p-cycle and select the one whose PE is the highest to protect LR. Here, for LR, we define the PE of an FIPP-p-cycle c as

$$\eta(LR,c)=\frac{B}{(N+\epsilon)\cdot|c|}, \quad (12)$$

where N is the number of FS' to be reserved on c, ϵ is a small positive constant to avoid zero-denominator, and $|c|$ returns the number of links on c. Since we allow multiple working paths to share the same FIPP-p-cycle, *Line* 7 checks the shareability of each FS reserved on c. When we recalculate PE of c in *Line* 10, N represents the number of FS' that need to be newly reserved on c for LR. As it is possible that LR shares the existing backup FS' on c totally, N can be 0. The complexity of

Algorithm 1: Protection efficiency based FIPP-p-cycle design (PE-FIPP)

1 **for** *each* $LR(s,d,B)$ *in* Λ **do**
2 perform RMSA to obtain the working path $\mathcal{R}_{s,d}$;
3 **for** *each p-cycle* $c\in C$ **do**
4 **if** *c can protect* $\mathcal{R}_{s,d}$ **then**
5 determine the number of backup FS' N to be reserved on c;
6 obtain the spectrum usage on c;
7 check the shareability of each backup FS on c and mark it as available if $\mathcal{R}_{s,d}$ can share it;
8 **if** *an FS-block with size N exists on c* **then**
9 select the first available FS-block and recalculate N;
10 calculate the PE of c with Eq. (12);
11 **else**
12 mark the PE of c as 0;
13 **end**
14 **else**
15 mark the PE of c as 0;
16 **end**
17 **end**
18 select p-cycle with the highest PE to protect $\mathcal{R}_{s,d}$;
19 **end**

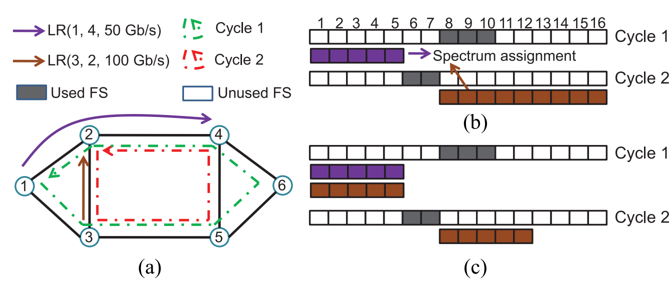

Fig. 2. Examples on spectrum assignments in PE-FIPP and PE-FIPP-MPP. (a) EON topology. (b) Backup spectrum assignment with PE-FIPP. (c) Backup spectrum assignment with PE-FIPP-MPP.

PE-FIPP is $O(|C|\cdot M^2\cdot|E|^2\cdot F)$, where M is the total number of requests.

PE-FIPP tries to minimize the number of backup FS' reserved for each request. However, the shareability of each backup FS is very limited since PE-FIPP only allows single p-cycle protection. For example, with the EON topology in Fig. 2(a), PE-FIPP protects the two lightpath requests, i.e., $LR(1,4,50$ Gb/s$)$ and $LR(3,2,100$ Gb/s$)$ with *Cycles* 1 and 2, respectively. We show the corresponding backup spectrum assignments in Fig. 2(b). Here, if we assume that the bandwidth of an FS is 12.5 GHz and BPSK is selected as the modulation format, 5 and 9 FS' (including one guard-band FS) would be required to be reserved on the p-cycles for protecting $LR(1,4,50$ Gb/s$)$ and $LR(3,2,100$ Gb/s$)$, respectively [27]. We can see that $LR(3,2,100$ Gb/s$)$ does not share any backup

FS' with $LR(1, 4, 50$ Gb/s$)$ on *Cycle* 1. This is due to the insufficient bandwidth on *Cycle* 1.

In order to overcome the drawback mentioned above, we allow PE-FIPP to split the backup FS' of an LR over multiple FIPP-p-cycles by leveraging a multi-path protection strategy (PE-FIPP-MPP). Basically, PE-FIPP-MPP has the similar procedure as PE-FIPP, but we define a metric T_m as the maximum number of blocks that an LR's bandwidth can be divided into. Then, PE-FIPP-MPP tries to protect each LR iteratively with the p-cycles that provide the largest shareable protection capacity until the LR is fully protected or T_m is reached. By doing so, we restrict the times that C needs to be traversed below T_m, and hence the complexity of PE-FIPP-MPP is $O(T_m \cdot |C| \cdot M^2 \cdot |E|^2 \cdot F)$. For the example in Fig. 2(a), Fig. 2(c) shows the backup spectrum assignments with PE-FIPP-MPP. It can be seen that PE-FIPP-MPP protects $LR(3, 2, 100$ Gb/s$)$ with *Cycles* 1 and 2, and if we count in the one additional guard-band FS caused by MPP, we only need to reserve five more FS' on *Cycle* 2 for it.

2) Integrated-FIPP (Inte-FIPP): PE-FIPP-MPP configures the working path and FIPP-p-cycle(s) of each LR separately, and this may cause inefficient spectrum utilization. Hence, we design an Inte FIPP-p-cycle algorithm that optimizes the working and backup spectrum assignments of each LR jointly. The idea of Inte-FIPP is to serve each LR based on the network status and encourage as much backup sharing as possible.

The detailed procedure of Inte-FIPP is described in Algorithm 2. *Line* 2 is for initialization, and the for-loop covering *Lines* 3–32 tries to perform the integrated working and backup configuration with a p-cycle. Specifically, for each feasible p-cycle, Inte-FIPP checks each available FS-block on it and constructs an auxiliary graph (AG) $G'(V, E)$. As shown in *Lines* 9–22, $G'(V, E)$ is initially copied from $G(V, E)$, and then we remove the links that belong to the p-cycle and the working paths that conflict with LR. Here, we say the working path of a served request LR' "conflicts" with LR, when the working paths of LR and LR' are not link-disjoint and they also share certain backup FS' on the p-cycle. By removing these links, we ensure that as long as a working path can be found in $G'(V, E)$ for LR, it can be protected by the p-cycle using the corresponding FS-block. In *Lines* 28 and 29, we record the service provisioning scheme that includes both the working path and the p-cycle configuration. Here, $\mathbf{W}$ is a $|C| \times F$ matrix, and each of its elements $\mathbf{W}(c, f)$ stores the total number of working and backup FS' required for LR, if LR is protected with an FS-block on p-cycle c, of which the starting FS index is f. Finally, *Line* 33 selects the service provisioning scheme that corresponds to the smallest element in $\mathbf{W}$, for saving as many FS' as possible. The complexity of Inte-FIPP is $O(|C| \cdot M^2 \cdot |E|^2 \cdot F^2)$.

Fig. 3 shows an examples of Inte-FIPP. For the topology in Fig. 3(a), we assume that $LR(1, 4, 50$ Gb/s$)$ is protected by *Cycle* 1 with the backup spectra in Fig. 3(b). If we use the shortest path 5→6 as the working path of $LR(5, 6, 50$ Gb/s$)$, it cannot be protected by *Cycle* 1 and hence cannot share any backup FS' with $LR(1, 4, 50$ Gb/s$)$. Therefore, Inte-FIPP constructs an AG for FS-block $[3, 7]$ reserved on *Cycle* 1 as shown in Fig. 3(c), in which the links on *Cycle* 1 and the working path

Algorithm 2: Integrated FIPP-p-cycle design (Inte-FIPP)

```
1  for each LR(s, d, B) in Λ do
2      W = [+∞]_{|C|×F};
3      for each p-cycle c ∈ C do
4          if s ∉ c OR d ∉ c then
5              continue;
6          end
7          determine the number of backup FS' N to be
           reserved on c;
8          for each FS f ∈ [1, F − N + 1] do
9              flag = 1, G'(V, E) = G(V, E);
10             remove links on c from G'(V, E);
11             for i ∈ [0, N − 1] do
12                 if FS (f + i) on c is unused then
13                     continue;
14                 else if FS (f + i) on c is for backup then
15                     for each LR' that uses FS (f + i) do
16                         remove the working links of LR'
                           from G'(V, E) if LR' conflicts
                           with LR;
17                     end
18                 else
19                     flag = 0;
20                     break;
21                 end
22             end
23             if flag = 0 then
24                 break;
25             end
26             obtain the working path of LR in G'(V, E);
27             if working path is obtained successfully then
28                 record the working path;
29                 set W(c, f + i) as the total number of
                   working and backup FS' needed for LR;
30             end
31         end
32     end
33     select the smallest element in W and serve LR with
       the corresponding scheme;
34 end
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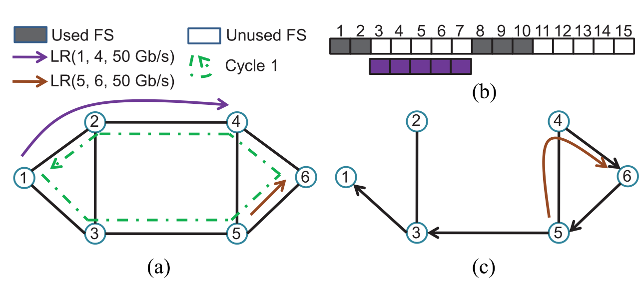

Fig. 3. An example of Inte-FIPP. (a) EON topology. (b) Backup spectrum assignment for LR (1, 4, 50 Gb/s). (c) AG.

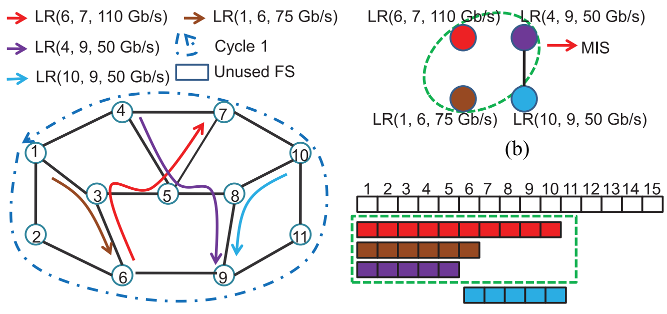

Fig. 4. An example of MIS-FIPP. (a) EON topology. (b) CG and MIS. (c) Backup spectrum assignment with MIS-FIPP.

of $LR(1, 4, 50$ Gb/s$)$, i.e., 1→2→4, are removed. Then, Inte-FIPP performs RMSA in the AG and obtains 5→4→6 as the working path of $LR(5, 6, 50$ Gb/s$)$, which can be protected by using FS-block $[3, 7]$ on *Cycle* 1.

3) Maximum-Independent-Set (MIS-FIPP): PE-FIPP and Inte-FIPP serve each LR sequentially, which may provide sub-optimal solutions. Therefore, we design a MIS based FIPP *p*-cycle configuration algorithm (MIS-FIPP), and optimize the backup spectrum assignments for all the requests jointly. We first use the example in Fig. 4 to illustrate the working principle of MIS-FIPP. Basically, we have 4 requests in Fig. 4(a), whose working paths are plotted with solid lines. For each *p*-cycle candidate, MIS-FIPP finds the requests that can be protected by it and constructs a conflict graph (CG). Fig. 4(b) shows the CG constructed for *Cycle* 1, where each node represents the working path of a request and two nodes are connected if they cannot share the same backup FS' on *Cycle* 1. Then, MIS-FIPP finds the MIS in the CG, and as shown in Fig. 4(b), it includes three requests. According to the principle of MIS, all the requests in it can share the same backup FS' on *Cycle* 1. Therefore, we leverage the MIS to maximize the PE of each *p*-cycle. Then, the spectrum assignments for the requests in the MIS are illustrated in Fig. 4(c). Note that even though $LR(10, 9, 50$ Gb/s$)$ is not in the MIS, it can still share certain backup FS' assigned for the rest three. This is because it only conflicts with $LR(4, 9, 50$ Gb/s$)$ and the summation of their bandwidth requirements is less than the bandwidth allocated to the MIS, as indicated in Fig. 4(c). Finally, MIS-FIPP uses *Cycle* 1 to protect all the requests in a batch.

Algorithm 3 shows the details of the proposed MIS-FIPP. *Lines* 1–6 set up the working paths of all the pending requests. Note that here, we incorporate the MPP scheme discussed in PE-FIPP-MPP to improve the spectrum sharing. In *Lines* 7–42, MIS-FIPP tries to configure *p*-cycles with the highest PE iteratively until all the requests are protected. Specifically, for each *p*-cycle, MIS-FIPP checks its spectrum utilization, finds the requests that it can protect, and constructs a CG to represent the conflicts among them (as shown in *Lines* 9–20). Since we allow MPP here, *Lines* 15–17 still include a request LR_i in set Γ even if it cannot be fully protected by *p*-cycle c, as long as its quote for protection path splitting has not been used up (i.e., $T_i \geq 2$). Since finding the MIS in a general graph is $\mathcal{NP}$-hard, *Line* 21

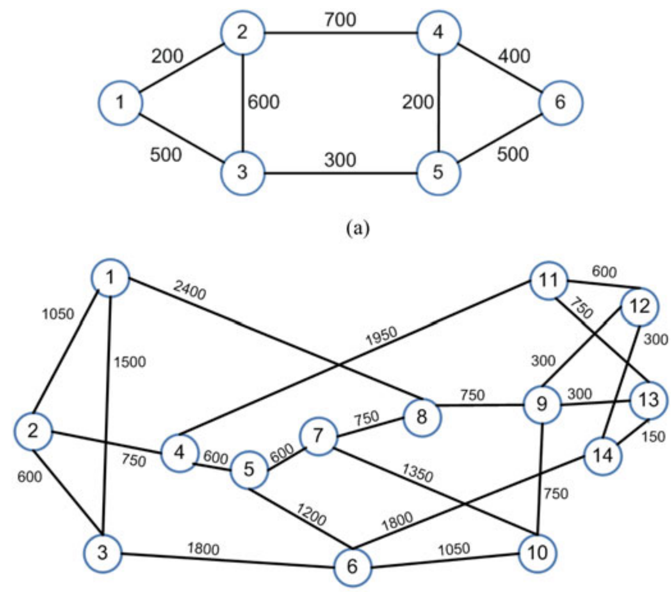

Fig. 5. Simulation topologies (fiber lengths in kilometers). (a) Six-node topology. (b) NSFNET topology.

implements the maximal independent set search algorithm in [30] to reduce computation time. Note that we also incorporate a graph partition strategy to accelerate the computation in *Line* 21, which divides CG into several unconnected subgraphs and searches for the maximal independent set in each of them.

Then, to further improve the spectrum sharing, *Lines* 24–36 try to select requests that are not included in the MIS to share the backup FS' on *p*-cycle c. Finally, *Lines* 39–41 select the *p*-cycle with the highest PE to configure and update the information of pending requests. Since the complexities of constructing the CG and finding the maximal independent set in it are $O(M^2 \cdot |E|^2)$ and $O(M^2)$, respectively, the complexity of MIS-FIPP is $O(T_m \cdot M \cdot |C| \cdot (|E| \cdot F + M^2 \cdot |E|^2 + |LR|^3)$. Hence, we can see that the complexity of MIS-FIPP increases with the number of pre-calculated *p*-cycles $|C|$ linearly.

V. Simulations on Offline Service Provisioning

In this section, we evaluate the proposed algorithms with numerical simulations. Note that all the simulations assume that the bandwidth of an FS is 12.5 GHz, and when the modulation format is BPSK the FS can carry 12.5 Gb/s capacity. The EON supports four modulation formats, i.e., BPSK, QPSK, 8-QAM and 16-QAM, and their spectrum efficiencies and maximum transmission reaches are the same as those in [31]. Note that since we assume that in the EON, all the lightpaths (both working and backup ones) are set up all-optically without O/E/O conversions, we ensure that the path lengths are at least within the transmission reach of BPSK signals and longer paths will not be selected.

We first perform simulations for offline service provisioning with the six-node topology in Fig. 5(a) and obtain a set C with 12 cycles using the method discussed in [20]. We assume that each fiber link can accommodate 358 FS'. The lightpath requests

Algorithm 3: Maximum-independent-set based FIPP-p-cycle design (MIS-FIPP)

$S = \emptyset$;
for *each* $LR_i(s,d,B)$ *in* Λ **do**
  perform RMSA to obtain working path for LR_i;
  store $LR_i(s,d,B)$ in S;
  $T_i = T_m$;
end
while $S \neq \emptyset$ **do**
  for *each p-cycle* $c \in C$ **do**
    get the spectrum utilization on c;
    store size of the largest unused FS-block in N_m;
    $\Gamma = \emptyset$;
    for *each* $LR_i \in S$ **do**
      if p-*cycle* c *can protect* LR **then**
        determine the number of backup FS' N to be reserved on c;
        if $N \leq N_m$ *OR* $T_i \geq 2$ **then**
          store LR_i in Γ;
        end
      end
    end
    construct a CG with Γ;
    calculate the MIS in the CG as I;
    $\Gamma = \Gamma - I$;
    calculate backup spectrum assignments for the requests in I as $\mathcal{SA}$;
    while *TRUE* **do**
      if *no request can share backup FS' of* I **then**
        break;
      end
      select $LR_i \in \Gamma$ that can share the most backup FS' of I;
      insert LR_i into I and update $\mathcal{SA}$;
      if LR_i *is fully protected* **then**
        remove LR from Γ;
      else
        update LR_i to carry the unprotected bandwidth;
        $T_i = T_i - 1$;
      end
    end
    calculate the PE of c with Eq. (12);
  end
  select the p-cycle with the highest PE and obtain the corresponding I, Γ and $\mathcal{SA}$;
  perform spectrum assignments according to $\mathcal{SA}$;
  $S = S \setminus I \cup \Gamma$;
end

are generated according to a uniform traffic model, and their bandwidth requirements are evenly distributed within $[25, 250]$ Gb/s. We monitor the results on spectrum utilization, working-to-backup ratio and running time. Here, the spectrum utilization is defined as the total number of FS' used/reserved in the EON, i.e., calculated with Eq. (1), and the working-to-backup ratio is the ratio of FS' used for working paths to those reserved on FIPP-p-cycles.

Table I summarizes the results, each of which is obtained by averaging the outputs of five independent experiments. We can see that all the heuristics can be solved within reasonably short time and provide similar spectrum utilizations as those from the ILP. Note that we set the longest running time of the ILP as 120 h, within which the ILP can only obtain the best feasible solutions for the situations with 15 requests. Since Inte-FIPP uses the working paths that are relatively long and consumes many working resources, it provides the highest working-to-backup ratio. MIS-FIPP obtains the best solutions among all the heuristics and its maximum optimization gap on spectrum utilization from the ILP is only 5.3%.

We then use the NSFNET topology in Fig. 5(b) to investigate the performance of the proposed heuristics further. Here, we use DPP and the survivable multi-path routing and spectrum assignment (SM-RSA) algorithm proposed in [8] as benchmarks, since they are known as the most spectrum efficient EON protection schemes in the literature, which pre-configure backup resources. For fair comparison, we implement the adaptive modulation selection in SM-RSA and make it SM-RMSA. The simulation parameters are unchanged and we calculate 108 p-cycles for C.

Fig. 6(a) shows the results on spectrum utilization. MIS-FIPP always achieves the smallest spectrum utilization, while the results from SM-RMSA are the largest. This is because our proposed algorithms allow the sharing of backup FS' among requests, and MIS-FIPP optimizes the p-cycle configurations for all the requests jointly. As expected, PE-FIPP-MPP performs better than PE-FIPP on spectrum utilization. The spectrum utilization from DPP is comparable to that of PE-FIPP-MPP when the number of requests is less than 100, and when the request number keeps increasing, the spectrum utilization of DPP increases quickly. The results from Inte-FIPP also increase quickly with the number of requests, which is because when there are more requests to serve, it has to use longer working paths and hence assigns more FS'. Fig. 6(b) illustrates the results on average working-to-backup ratio. SM-RMSA provides the highest working-to-backup ratio as it uses one backup path to protect multiple link-disjoint working sub-paths for each request. However, since it uses the multi-path scheme to set up working paths, the FS' that are used on working paths are also many, which is the reason why in Fig. 6(a), its spectrum utilization is the highest among all the algorithms. The results on working-to-backup ratio from MIS-FIPP are slightly larger than those from PE-FIPP and PE-FIPP-MPP, while DPP possesses the smallest results.

One issue with MPP is that it introduces path difference during restoration. Therefore, we record the results on the maximum path difference (MPD) during restoration and plot them in Fig. 6(c). We observe that the MPDs from SM-RMSA are much

TABLE I
RESULTS FROM SIMULATIONS WITH SIX-NODE TOPOLOGY

	5 LRs			10 LRs			15 LRs		
	Spectrum Utilization (FS')	Running Time (s)	Working to Backup Capacity Ratio	Spectrum Utilization (FS')	Running Time (s)	Working to Backup Capacity Ratio	Spectrum Utilization (FS')	Running Time (s)	Working to Backup Capacity Ratio
ILP	98	6598	29.33%	220	285254	45.76%	302	432000	63.42%
MIS-FIPP	98	0.4358	29.51%	231	0.4566	42.63%	318	0.6881	58.42%
Inte-FIPP	100	0.3780	28.86%	234	0.5427	54.13%	321	0.6583	66.00%
PE-FIPP-MPP	100	0.3206	28.68%	238	0.4738	40.79%	328	0.7323	55.69%
PE-FIPP	105	0.2289	27.43%	235	0.3691	41.56%	340	0.5078	52.79%

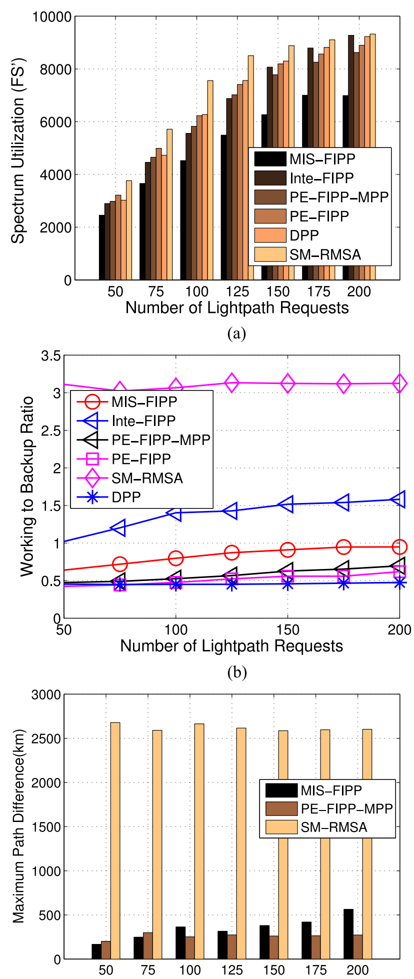

Fig. 6. Results from offline provisioning simulations with NSFNET topology. (a) Spectrum utilization. (b) Working-to-backup ratio. (c) MPD.

larger than those from MIS-FIPP and PE-FIPP-MPP. This is because SM-RMSA can only employ link-disjoint paths, which lead to relatively large MPDs. MIS-FIPP provides larger MPDs than PE-FIPP-MPP since it can divide a request's backup FS' on multiple p-cycles for enhanced backup sharing. Since DPP, PE-FIPP and Inte-FIPP do not apply MPP, their MPD results are all 0. Also, we do not consider the MPD before restoration since the FIPP-p-cycle based algorithms all use the single-path scheme to provision working paths and hence do not incur any path difference.

VI. ONLINE PROVISIONING WITH FIPP-p-CYCLES

This section investigates FIPP-p-cycle based protection for online service provisioning where the lightpath requests can arrive and leave on-the-fly.

A. *Dynamic FIPP-p-Cycle Configuration Algorithms*

All the heuristics designed for offline provisioning can be applied to the online scenario. For instance, MIS-FIPP tries to handle all the requests that arrive during the same provision period in a batch. However, it is known that setting up and tearing down working paths and p-cycles frequently can lead to severe spectrum fragmentation and downgrade PE dramatically [13]. Meanwhile, we notice that when an EON is in the normal working state, reconfiguring the p-cycles in it will not cause any service disruption. Therefore, we propose a p-cycle reconfiguration scheme to re-optimize protection structures dynamically. Specifically, we trigger the reconfigurations periodically and in each operation, we tear down all the existing p-cycles, collect the information of in-service working paths, and reconstruct the p-cycles with MIS-FIPP. We use MIS-FIPP here because it provides relatively high spectrum efficiency in backup resource allocation. When the reconfiguration scheme is included, we refer to the corresponding algorithms as PE-FIPP-MPP-RO, Inte-FIPP-RO and MIS-FIPP-RO.

B. *Simulation Results*

We first evaluate the performance of online service provisioning with the NSFNET topology in Fig. 5(b) and the simulation parameters are also the same. The dynamic requests are generated with the Poisson traffic model and their source and destination nodes are randomly selected. For the algorithms that include p-cycle reconfiguration, each reconfiguration is triggered when 100 requests have expired in the EON. The benchmark algorithms are still SM-RMSA and DPP, and we also include the FIPP-Flex in [25], as it was designed for the service provisioning with FIPP-p-cycle protection in EONs. Note that since FIPP-Flex does not consider adaptive modulation selection or the construction of FIPP-p-cycles, we extend the algorithm to include both of them for fair comparison. Specifically, in the

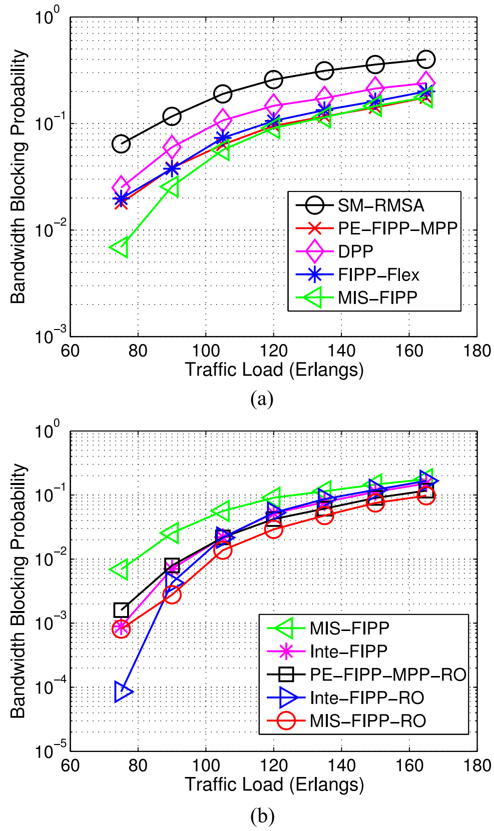

Fig. 7. Results on BBP from online provisioning simulations with NSFNET topology.

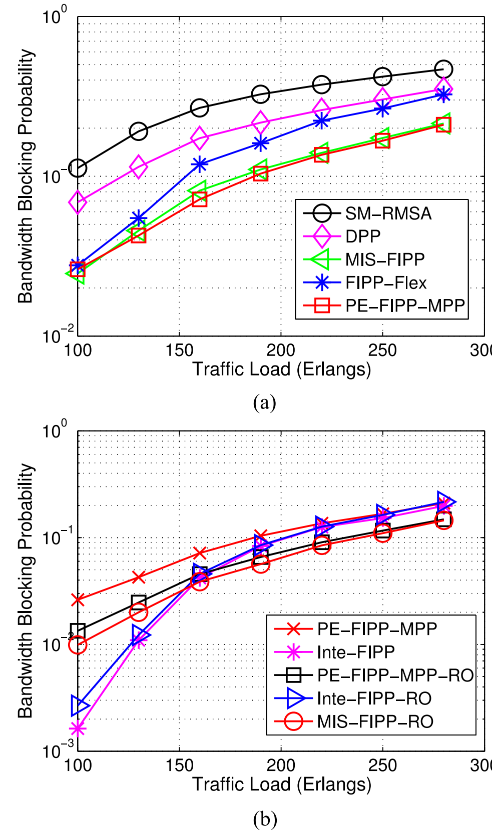

Fig. 9. Results on BBP from online provisioning simulations with COST239 topology.

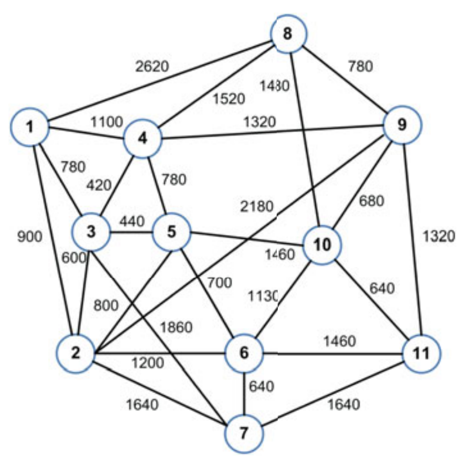

Fig. 8. COST239 topology (fiber lengths in km).

simulations, FIPP-Flex utilizes the PE-based FIPP-*p*-cycle configuration scheme. Fig. 7 shows the results on BBP, which indicate that all the proposed algorithms outperform SM-RMSA, DPP and FIPP-Flex, and Inte-FIPP achieves the lowest BBP among those without the reconfiguration scheme. Note that for clear presentation, we plot the results in Fig. 7(a) and (b), and the results from MIS-FIPP are used as the baseline for the two figures. The BBP results from MIS-FIPP are slightly lower than those from PE-FIPP-MPP but higher than those from Inte-FIPP. This is because in dynamic network operation, MIS-FIPP only serves a relatively small number of requests in each batch, which restricts its advantage on joint optimization. With the reconfiguration scheme, the BBP performance gets improved significantly for all the proposed algorithms except for Inte-FIPP. The BBP results from Inte-FIPP-RO increase rapidly with the traffic load. This is because it prefers to use relatively long working paths, which makes it hard for MIS-FIPP to protect a larger set of working paths when the traffic load is higher.

Table II presents the results on average spectrum utilization ratio in the EON, which help to explain the BPP results. When the traffic load is lower than 105 Erlangs, SM-RMSA utilizes the most spectrum resources among all the algorithms, because the link-disjoint constraint forces it to use long paths. When the traffic load continues to increase, Inte-FIPP provides the highest spectrum utilization ratios as it can accommodate the most requests (i.e., with the lowest BBP). The spectrum utilization ratios from MIS-FIPP are slightly higher than those from PE-FIPP-MPP, which is also because MIS-FIPP serves more requests. We can still see that the *p*-cycle reconfiguration scheme reduces the spectrum utilization ratio effectively.

We also perform more simulations with the COST239 topology in Fig. 8. Most of the simulation parameters are the same, except that we pre-calculate 249 *p*-cycles in C and the bandwidth requirement for each request is evenly distributed within $[25, 500]$ Gb/s. Fig. 9 and Table II summarize the results on BBP and average spectrum utilization ratio, respectively, which exhibit the similar trends as those from the NSFNET topology.

TABLE II
RESULTS ON SPECTRUM UTILIZATION RATIO FROM ONLINE PROVISIONING

	NSFNET							COST239						
Spectrum Utilization Ratio (%) \ Traffic Load (Erlangs) / Algorithms	75	90	105	120	135	150	165	75	90	105	120	135	150	165
SM-RMSA	35.60	38.78	41.69	43.14	44.63	45.59	46.56	34.45	38.59	41.42	43.62	45.08	46.42	48.27
DPP	29.57	32.47	35.30	37.27	38.59	40.02	40.94	28.71	32.51	35.66	38.32	40.54	42.14	43.34
FIPP-Flex	31.33	34.33	37.82	40.08	41.85	43.59	44.71	32.74	38.32	42.69	44.79	46.70	48.50	50.06
PE-FIPP-MPP	31.47	34.52	38.06	40.32	42.30	44.31	45.66	32.77	38.40	43.28	47.15	49.60	52.12	54.93
MIS-FIPP	32.08	35.59	39.39	42.02	43.67	45.39	46.98	35.77	41.40	45.41	48.59	51.16	53.93	56.44
Inte-FIPP	32.37	36.63	40.87	44.02	46.23	48.15	49.67	34.40	40.97	46.99	50.83	53.02	55.24	57.81
PE-FIPP-MPP-RO	27.92	31.08	34.72	37.09	38.94	40.89	42.03	29.44	34.24	38.81	42.20	44.32	46.85	49.02
MIS-FIPP-RO	28.67	31.91	35.75	38.69	40.48	42.64	44.04	31.44	36.35	40.88	44.27	46.54	48.82	50.82
Inte-FIPP-RO	29.76	33.73	37.79	40.89	42.88	44.34	45.56	31.28	37.03	42.13	45.01	47.16	48.77	50.46

Note that, the results from PE-FIPP-MPP are used as the baseline for Fig. 9(a) and (b).

VII. CONCLUSION

This paper studied the resilience design with FIPP-p-cycles for EONs. We first formulated an ILP model for the problem of offline service provisioning with FIPP-p-cycles and proved that it is $\mathcal{NP}$-hard. Then, several time-efficient heuristics, namely, PE-FIPP, PE-FIPP-MPP, Inte-FIPP and MIS-FIPP, were designed for FIPP-p-cycle formulation and related RMSA. Extensive simulations on offline service provisioning verified that the heuristics can obtain near-optimal solutions. In order to overcome the decrease of PE during dynamic network operation, we also proposed a p-cycle reconfiguration scheme, which can re-optimize protection structures on-the-fly for online service provisioning. Simulation results indicated that the proposed algorithms can improve spectrum efficiency and reduce BBP simultaneously.

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