Optimizing FIPP-*p*-Cycle Protection Design to Realize Availability-Aware Elastic Optical Networks

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***Abstract*— This letter tries to optimize the availability-aware service provisioning (AaSP) with failure-independent path-protecting pre-configured cycles (FIPP-*p*-cycles) in elastic optical networks (EONs). We propose a novel AaSP-FIPP scheme by leveraging bandwidth-squeezed restoration, develop a mathematical model to analyze the service availability of the scheme, and design a topology partitioning method to improve its scalability.**

***Index Terms*— Elastic optical networks (EONs), availability-aware service provisioning (AaSP).**

I. Introduction

FLEXIBLE-GRID elastic optical networks (EONs) use narrow-band frequency slots (FS') to achieve high spectral efficiency and adaptive bandwidth allocation in the optical layer [1]–[4]. Previously, people have studied both path- and link-based protection schemes to deal with the link failures in EONs [5]–[9]. However, these schemes suffer from either long recovery latency or low resource efficiency. In this context, the failure-independent path-protecting pre-configured cycle (FIPP-*p*-cycle), which can integrate the advantages of path- and link-based protection schemes (*i.e.*, fast restoration speed and high resource efficiency, respectively), has been put forward in [10] for realizing survivable EONs. Note that, in practical network operations, network survivability is usually quantified with service availability, which is defined as the ratio of service-on time to total provisioning period and is usually specified explicitly in the service-level agreement (SLA) [8]. Hence, a more practical angle to study survivable EONs is to consider availability-aware service provisioning (AaSP), *i.e.*, to satisfy the clients' availability requirements with the minimum spectrum usage.

Perviously, people have studied how to realize AaSP in fixed-grid wavelength-division multiplexing (WDM) networks in [11], and proposed effective algorithms. Nevertheless, because the spectrum allocation schemes in WDM networks and EONs are fundamentally different in a few aspects, we still need to revisit this problem for EONs. For instance, with the flexible spectrum allocation in EONs, one can leverage bandwidth-squeezed restoration to further improve the efficiency of AaSP [9], which is not feasible in WDM networks.

In this letter, we study how to optimize the scheme of AaSP with FIPP-*p*-cycle protection (AaSP-FIPP) in EONs for enhanced resource efficiency. We first propose a novel AaSP-FIPP scheme by incorporating bandwidth-squeezed restoration [12], and develop a mathematical model to analyze the service availability of the scheme. Then, to make the scheme more scalable, we design a topology partitioning method. Our simulations consider both offline planning and online provisioning, and the results confirm the effectiveness of our proposal.

The rest of the paper is organized as follows. Section II describes the principle of AaSP-FIPP in EONs. In Section III, we propose the time-efficient topology partitioning algorithm. The performance evaluations are discussed in Section IV. Finally, Section V summarizes this paper.

II. AaSP-FIPP in EONs

We model the topology of an EON as $G(V, E)$, where V represents the set of nodes and E is the link set. A lightpath request is denoted as $LR(s, d, B, A, T)$, where $s, d \in V$ are the source and destination nodes, its bandwidth requirement is B Gb/s, A is the availability requirement from SLA, and T is its service duration. Then, with B, we can derive the number of FS' to be allocated based on the quality-of-transmission of LR's working path [9]. Next, to satisfy A, AaSP-FIPP configures one or more FIPP-*p*-cycles for LR if necessary.

Fig. 1 shows an intuitive example for AaSP-FIPP in EONs. Basically, a working path can be protected by an FIPP-*p*-cycle, if the *p*-cycle includes both of its end-nodes and can provide a backup path that is link-disjoint with it. Meanwhile, we incorporate the shared protection scheme in the FIPP-*p*-cycle design, allowing two lightpaths to be protected by the same backup FS' allocated on a *p*-cycle when their working or backup paths are link-disjoint. Therefore, the *p*-cycle $1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 5 \rightarrow 4 \rightarrow 1$ in Fig. 1(a) can protect the working paths of the three requests, *i.e.*, LR_1, LR_2 and LR_3 share the backup FS' reserved on the *p*-cycle with the scheme depicted in Fig. 1(b). Furthermore, we can leverage the bandwidth-squeezed restoration technique to make the AaSP-FIPP in EONs more resource efficient. Specifically, for LR, the bandwidth allocated during restoration (*i.e.*, denoted as B') can be smaller than B [12], while the minimum amount of backup bandwidth that is needed to recover the service of LR (also derived from SLA) is assumed as B_m, *i.e.*, $B' \in [B_m, B]$. In such a situation, the acquired availability during restoration (*i.e.*, the availability corresponds to this specific failure restoration scenario) is $A' = \frac{B'}{B}$ [9]. For example, in

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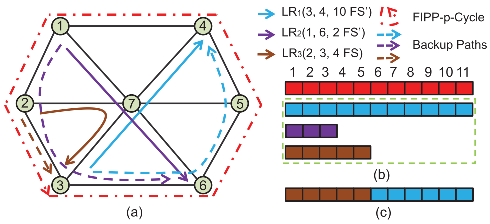

Fig. 1. An example on AaSP-FIPP, (a) lightpaths and an FIPP-p-cycle to protect them, (b) sharing of backup spectra among lightpaths, and (c) spectrum allocations for LR_1 and LR_3 during the restoration for simultaneous failures.

Fig. 1(c), we can allocate 6 and 5 FS' (including 1 guard-band FS) to restore the services of LR_1 and LR_3, respectively, when their working paths fail simultaneously. Consequently, the acquired availabilities of the lightpaths are $A'_1 = \frac{5}{10} = 0.5$ and $A'_3 = \frac{4}{4} = 1$.

Note that, to facilitate the design of AaSP-FIPP, we need to analyze the service availability of each request precisely. Hence, we develop a theoretical model. Firstly, it is easy to obtain the availability of an unprotected LR as ρ^{H_w}, where ρ is the link availability (assumed to be identical for every link in the EON) and H_w is its hop-count. For an LR that is protected by FIPP-p-cycles, we can get its availability by enumerating the situations in which its service is available: 1) its working path is intact, and 2) its working path is broken but its backup path provided by FIPP-p-cycle(s) is available with sufficient bandwidth to ensure a successful recovery (*i.e.*, $B' \in [B_m, B]$). Specifically, its availability is [13]

$$A_L = \rho^{H_w}\Bigg\{1+H_w(1-\rho)\rho^{H_p-1}\Bigg[\rho^{|\mathbb{L}|}A'_0+\sum_{e\in\mathbb{L}}\rho^{|\mathbb{L}|-1}(1-\rho) \times\left(\frac{1}{2}A'_0+\frac{1}{2}A'_e\right)+\frac{1}{2}(H_w-1)(1-\rho)\rho^{|\mathbb{L}|-1}A'_0\Bigg]\Bigg\}, \quad (1)$$

where $\mathbb{L}$ denotes the set of the links on the working paths of other lightpaths, which share backup FS' with LR, H_p is the hop-count of LR's backup path, and A'_0 and A'_e are the acquired availabilities when LR is restored with full or partial working bandwidth, respectively. Note that, the derivation of Eq. (1) ignores the situations in which there are more than two simultaneous link failures, and this is because their probability is so small (*e.g.*, in the magnitude of 10^{-6} if $\rho = 0.99$) that their contributions to the overall availability are negligible.

Then, we design an AaSP-FIPP algorithm that determines the protection scheme of each request based on the spectral efficiency (SE) of FIPP-p-cycles, namely, AaSP-SE-FIPP, whose procedure is shown in *Algorithm* 1. Note that, in *Line* 6, the minimum number of backup FS' N_c refers to the FS' that need to be reserved specifically for LR, while those that can be shared with other in-service requests are not included. In *Line* 9, if no feasible p-cycle can be found, we still provision LR with the working path but mark it as availability unsatisfied.

Algorithm 1: Spectral Efficiency Based AaSP-FIPP (AaSP-SE-FIPP)

```
1  precalculate ℂ as a set of candidate FIPP-p-cycles in the EON;
2  For each LR(s, d, B, A, T) do
3      obtain the working path P_w of LR as the shortest available one;
4      if A cannot be satisfied with P_w then
5          For each candidate p-cycle c ∈ ℂ that can protect P_w do
6              calculate N_c as the minimum number of FS' to be reserved
               on c for LR to satisfy A while the availabilities of all the
               other in-service requests are still satisfactory;
7              set the spectral efficiency of c as SE(c) = B / (N_c · hops(c));
8          End
9          select p-cycle c* = argmin[SE(c)];
10         assign N_{c*} FS' on c* to protect P_w;
11     end
12 End
```

III. AaSP-FIPP With Topology Partitioning

Although AaSP-SE-FIPP can improve the spectral efficiency of FIPP-p-cycle protection, its time complexity is relatively high. This is because *Algorithm* 1 needs to check all the available FS' on all the feasible FIPP-p-cycles to determine LR's protection scheme. In other words, the complexity of the for-loop that covers *Lines* 5–8 is $O(F \cdot |\mathbb{C}|)$, where F represents the total number of FS' that a link can accommodate. However, in a relatively large EON topology, $|\mathbb{C}|$ can easily be thousands or more. Hence, we try to leverage the topology partitioning, which is to divide the topology into a few protection domains and apply AaSP-SE-FIPP to each of them, to improve the time-efficiency of AaSP-FIPP.

Fig. 2 shows an example for AaSP-FIPP with topology partitioning. Here, we calculate the availability of an LR that traverses multiple domains by considering both intra- and inter-domain cases, *i.e.*, link failures happen in single or multiple domains. While the availability associated with the intra-domain case can be obtained with Eq. (1), we analyze the availability of the inter-domain case by considering the two scenarios in Figs. 2(a) and 2(b). Here, we still only consider the situations with two or less simultaneous link failures. Fig. 2(a) shows the scenario in which dual failures happen on LR's working path, which is restored with the p-cycles in two domains independently. The scenario in Fig. 2(b) is more complicated as it involves a failure on the common link of two domains, and thus the domains need to work cooperatively to determine the backup path segments (*i.e.*, $1 \rightarrow 5 \rightarrow 4$ and $4 \rightarrow 8 \rightarrow 7$). Then, the availability of the inter-domain case is

$$A_I = (1-\rho)^2\rho^{\left(\sum_{k=1}^{|\mathbb{D}|}|\mathbb{L}_k^w|\right)} \times\Bigg\{\sum_{e_1\in\mathbb{L}_i^w}\sum_{e_2\in\mathbb{L}_j^w, i\neq j}\rho^{\left(|\mathbb{L}_i^p|+|\mathbb{L}_j^p|-|\mathbb{L}_i^w|-|\mathbb{L}_j^w|\right)} + \sum_{e_1\in\mathbb{L}_i^w}\sum_{e_2\in\left(\mathbb{L}_i^p\cap\mathbb{L}_j^p\right)}\rho^{\left(|\mathbb{L}_i^{p,*}|+|\mathbb{L}_j^{p,*}|-|\mathbb{L}_i^w|-|\mathbb{L}_j^w|\right)}\Bigg\}, \quad (2)$$

where $\mathbb{D}$ is the set of domains in the EON, $\mathbb{L}_i^w$ and $\mathbb{L}_i^p$ are the sets of links in domain $D_i \in \mathbb{D}$, which are on LR's working and backup paths, respectively, and $\mathbb{L}_i^{p,*}$ denotes the set of links on the backup path determined by the scenario shown in

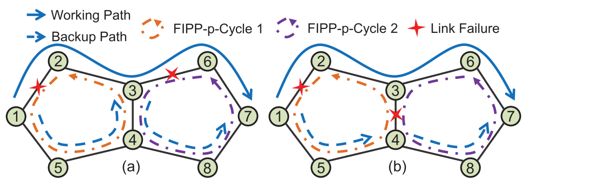

Fig. 2. Examples on AaSP-FIPP with topology partitioning that can restore dual failures on (a) the working path, and (b) the working path and a common link of two domains.

Fig. 2(b). Finally, we obtain the overall availability of LR as

$$A_L = \rho^{\left(\sum_{i=1}^{|\mathbb{D}|} |\mathbb{L}_i^w|\right)} + \sum_{i=1}^{|\mathbb{D}|} (A_{L,i} - \rho^{|\mathbb{L}_i^w|}) \rho^{\left(\sum_{j=1}^{|\mathbb{D}|} |\mathbb{L}_j^w| - |\mathbb{L}_i^w|\right)} + A_I, \quad (3)$$

where $A_{L,i}$ is to the intra-domain availability in domain D_i.

Apparently, how to partition the EON topology can be critical for AaSP-FIPP, which has not been explored in [13]. We first propose a cyclic partition (CP) algorithm, which tries to divide the EON topology into several cyclic-type domains with nodes at center. The rationale behind CP is that with more cyclic elements in a topology, we can configure more FIPP-p-cycles in it and thus AaSP-FIPP has more flexibility to improve the spectral efficiency of protection.

Algorithm 2 shows the procedure of CP. The while-loop that covers *Lines* 2–21 divides the topology into several cyclic-type domains. *Line* 3 selects a node $v \in V$ with the highest node degree as the center of a domain since this can potentially include more nodes in the cyclic-type domain. Then, *Lines* 4–14 find all the adjacent nodes of v and connect them sequentially with shortest paths, to form a path P. Next, we use *Lines* 15-16 to check whether a cyclic-type domain can be formed. Specifically, we try to find a new shorter path P' to connect the end-nodes of P, and if P' exists and the number of nodes in $P' \bigcup P$ plus 1 (node v) does not exceed χ (restriction on the size of each domain as defined in *Line* 1), a new cyclic-type domain D_i can be formed in *Line* 17. When all the feasible cyclic-type domains have been formed, either we have an empty set V or all the remaining nodes in V have been checked. Then, if $V \neq \emptyset$, *Lines* 22-25 form the rest of the non-cyclic domains.

Fig. 3 shows an example of CP. We first select v as *Node* 3 and obtain its adjacent node set $V_1 = \{2, 4, 6\}$. Assume *Node* 2 is selected as the first u, we calculate paths $2 \rightarrow 6$ and $6 \rightarrow 7 \rightarrow 4$ in sequence to form P as $2 \rightarrow 6 \rightarrow 7 \rightarrow 4$ according to *Lines* 8–14 of *Algorithm* 2. Then, as the end-nodes of P (*i.e.*, *Nodes* 2 and 4) can be connected with a new shorter path 2→1→4, we can obtain a cyclic-type domain as *Domain* I in Fig. 3. Next, we repeat the same procedure with *Node* 9 to get *Domain* II. Finally, since no more cyclic-type domains can be formed, we calculate $\mathbb{C}'$ containing cycles 6-7-11-10 and 10-11-13-12 and merge them to form *Domain* III.

IV. Performance Evaluation

The performance of the proposed AaSP-FIPP algorithm (denoted as AaSP-CP-FIPP) are evaluated with simulations using the US Backbone topology in [8]. We assume that each fiber link accommodates $F = 358$ FS', each of

Algorithm 2: Cyclic Partition (CP)

1 set χ as the maximum number of nodes allowed in each domain, $i = 1$;
2 **while** *($V \neq \emptyset$) OR (there are non-selected nodes in V)* **do**
3 select a non-selected node $v \in V$ with the highest node degree;
4 mark v as selected;
5 add all the adjacent nodes of v into V_i;
6 $P = \emptyset$;
7 select a node $u \in V_i$ randomly;
8 **while** $|V_i| > 1$ **do**
9 find the shortest paths from u to all the other nodes in V_i;
10 get u' as the node whose shortest path to u is the shortest;
11 add the shortest path from u to u' into path P;
12 remove node u from V_i;
13 $u = u'$;
14 **end**
15 try to find a new path P' to connect end-nodes of P;
16 **if** *($P' \neq \emptyset$) AND ($|P'| < |P|$) AND ($|P' \bigcup P| + 1 \leq \chi$)* **then**
17 form domain D_i with nodes in $P' \bigcup P$ and v;
18 remove nodes in domain D_i from V;
19 $i = i + 1$;
20 **end**
21 **end**
22 **if** $V \neq \emptyset$ **then**
23 calculate $\mathbb{C}'$ as the set of smallest cycles that each contains at least one unallocated node or link;
24 merge the cycles in $\mathbb{C}'$ as much as possible under the constraint of χ to form the rest of domains;
25 **end**

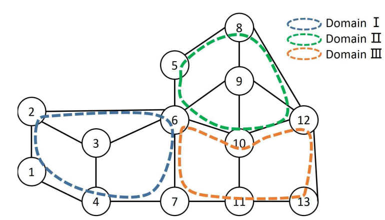

Fig. 3. An example of cyclic partition.

which occupies a bandwidth of 12.5 GHz [14]. The availability of each link is set as $\rho = 0.992$ [8], [11]. The lightpath requests are generated with bandwidth requirements evenly distributed within [25, 250] GHz, availability requirements evenly distributed within [0.970, 0.999], and their minimum restoration ratios (*i.e.*, $\frac{Bm}{B}$) are randomly selected within [0.5, 0.9]. Regarding the baseline algorithms for performance comparisons, we use the PE-FIPP algorithm in [10], the AaSP-TP-FIPP algorithm in [13] and the dedicated path protection based AaSP algorithm (AaSP-DPP, which applies the AaSP principle in Section II but configures protection resources according to DPP).

We first consider the offline planning in which all the requests are known and served simultaneously. For AaSP-CP-FIPP, we investigate the trade off in the number of partitioned domains by restricting the maximum number of nodes in each domain to be 5, 7 and 12, resulting in the partitioning results containing 13, 7 and 5 domains respectively. Fig. 4(a) shows the results on spectrum utilization, which indicate that AaSP-CP-FIPP can improve the spectral efficiency of the service provisioning effectively compared with the baseline algorithms. Meanwhile, we observe that the performance from

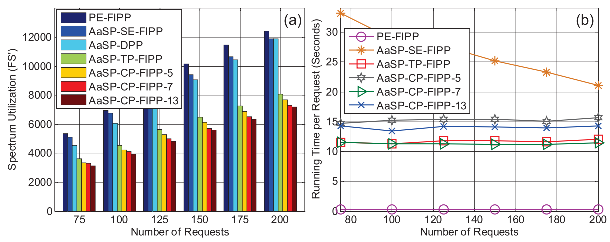

Fig. 4. Results on (a) spectrum utilization and (b) running time from offline network planning.

TABLE I

RESULTS ON AVAILABILITY SATISFACTION RATIO (%)

Algorithms	Offline Simul.	Online Simul.	Algorithms	Offline Simul.	Online Simul.
PE-FIPP	93.1	-	AaSP-CP-FIPP-5	98.3	97.9
AaSP-SE-FIPP	96.1	-	AaSP-CP-FIPP-7	98.8	97.6
AaSP-TP-FIPP	96.3	97.0	AaSP-CP-FIPP-13	99.0	99.1
AaSP-DPP	96.1	80.5			

AaSP-CP-FIPP improves with the number of partitioned domains. This is because by partitioning the topology into more but smaller domains, we can avoid configuring relatively long backup paths and make the FIPP-p-cycle more flexible, *i.e.*, being able to design the protection structures within each small domain independently based on the actual service availability requirements from requests. Table I summarizes the results on average availability satisfaction ratio when the number of requests is 200. Consistently with the observations from the results in Fig. 4(a), AaSP-CP-FIPP can significantly improve the percentage of LRs whose availability requirements get satisfied with FIPP-p-cycle protection, especially when more domains are obtained. On the other hand, we should notice that having more partitioned domains also increases the cost of transponder usage as we need to reserve an additional transponder on each FIPP-p-cycle configured for a lightpath. Specifically, simulation results indicate that the average numbers of FIPP-p-cycles configured for each lightpath are 6.9, 3.7 and 2.1 when we obtain 13, 7 and 5 domains respectively. Therefore, network designers should carefully address these trade-offs according to their performance targets and budgets. Fig. 4(b) shows the results on the running time of the algorithms, confirming that the proposed topology partitioning mechanisms reduce the time-complexity effectively. The running time from AaSP-SE-FIPP decreases with the number of requests due to the fact that fewer FS-blocks need to be inspected for each request when the network gets more saturated.

We then simulate the scenario of online provisioning. Specifically, the dynamic lightpath requests are generated according to the Poisson traffic model, and we assume that they can come and leave on-the-fly. Here, we only compare AaSP-DPP, AaSP-TP-FIPP and AaSP-CP-FIPP, since the results of offline planning have already shown that AaSP-SE-FIPP and PE-FIPP perform significantly worse than AaSP-CP-FIPP. Table I presents the results on availability satisfaction ratio from online simulations when the traffic load is 330 Erlangs. It is interesting to notice that the availability satisfaction ratio from AaSP-DPP drops sharply to only 80.5% while the performance of the other algorithms maintain relatively stable. The rationale behind this can be explained by the results on blocking probability in Table II, where we can see

TABLE II

RESULTS ON REQUEST BLOCKING PROBABILITY (%)

Traffic Load (Erlangs) / Algorithms	130	170	210	250	290	330
AaSP-DPP	2.47	10.50	13.10	18.30	23.83	25.17
AaSP-TP-FIPP	0.38	0.70	1.20	1.98	2.67	2.95
AaSP-CP-FIPP-5	0	0	0.02	0.03	0.20	0.88
AaSP-CP-FIPP-7	0	0	0.03	0.32	0.63	1.87
AaSP-CP-FIPP-13	0	0	0	0.08	0.12	0.33

that AaSP-DPP rejects $\sim 25\%$ requests at the highest traffic load. This implies that AaSP-DPP has exhausted the spectra in the EON, making it difficult to find sufficient spectra for satisfying the availability requirements from future requests. Again, AaSP-CP-FIPP-13 performs the best among all the algorithms.

V. CONCLUSION

This letter studied how to optimize the scheme of AaSP-FIPP in EONs for enhanced resource efficiency. We proposed a novel AaSP-FIPP scheme by leveraging bandwidth-squeezed restoration, and designed and analyzed a topology partitioning method to make the scheme more scalable.

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