On Efficient Protection Design for Dynamic Multipath Provisioning in Elastic Optical Networks

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***Abstract*—Multipath provisioning (MPP) in elastic optical networks (EONs) can improve the network performance effectively. In this paper, we study the protection schemes for MPP to ensure 100% restoration against single-link failures. We design three algorithms, namely, Instant-ILP, PWCE-MPP and mPWCE-MPP. The first one leverages a simple integer linear programming (ILP) model to design the optimal working-backup structure for each request instantly, while the rest two utilize protected working capacity envelop (PWCE) and spectrum planning to further reduce bandwidth blocking probability (BBP). Moreover, mPWCE-MPP considers the differences among working and backup paths, and ensures that the maximum path-difference (MPD) of a request will not increase dramatically in restoration. Simulation results show that mPWCE-MPP can obtain the best trade-off between BBP and average MPD.**

***Index Terms*—Protection design, Multipath provisioning, Elastic optical networks (EONs).**

I. Introduction

Recently, elastic optical networks (EONs) that operate on flexible wavelength grids [1] have attracted intensive research interests. It is known that by leveraging advanced optical transmission technologies, EONs achieve high spectral efficiency and agile bandwidth management in the optical layer [2]. More promisingly, with the flexible nature of EONs, one can easily split high-throughput data traffic over multiple routing paths to achieve multipath provisioning (MPP). Previously, people have proposed several MPP schemes for utilizing EONs' spectrum resources more efficiently [3, 4]. Meanwhile, improving network survivability with protection is not only important but also necessary in EONs, since a single link failure can cause huge data loss due to the high transmission rate [5]. In order to address this, previous studies have investigated both the path-based and link-based protection schemes for single-path provisioning (SPP) in EONs [5–9]. A bandwidth squeezed restoration scheme for dedicated path-protection in EONs has been proposed in [5]. To efficiently utilize EON's spectral segments for path-protection, the authors of [6] designed a multipath recovery scheme for SPP. The problem of static routing and spectrum assignment (RSA) for EONs with dedicated path-protection was investigated in [7]. An efficient shared path-protection scheme, *i.e.*, "elastic separate protection-at-connection", was presented in [8], and it realizes spectrum sharing by using first-fit and last-fit spectrum assignment for the working and backup paths, respectively. We have taken the advantage of fast protection switching from the link-based pre-configured-cycle (p-cycle) protection and designed a spectrum planning technique for dynamic SPP with p-cycle in EONs [9].

Even though compared with SPP, MPP can effectively reduce the bandwidth blocking probability (BBP) in EONs [3, 4], it also leads to lower service availability for requiring more working links per request. Basically, how to efficiently design the protection structure for a MPP request's multiple working paths is still an open question, as the protection schemes developed for SPP can return complicated protection structures with inefficient backup resource allocation for MPP. In [10, 11], Ruan *et al.* studied how to improve the service availability of MPP with over-provisioning, formulated integer linear programming (ILP) models, and proposed several heuristics. However, the problem of efficient protection design for dynamic MPP against single-link failures was not addressed.

In this paper, we investigate the design of protection structures for MPP in EONs. Specifically, for each request that is provisioned with MPP, we design its protection structure, *i.e.*, the backup links/paths and corresponding spectrum assignments to ensure 100% restoration against any single-link failure in the network. We first formulate an ILP model to obtain the optimal working-backup structure for each dynamic request instantly (Instant-ILP), based on network status. Then, to overcome the spectrum fragmentation caused by building the protection structures instantly, we use protected-working-capacity-envelop (PWCE) [12] to achieve PWCE-based protection for MPP (PWCE-MPP). Finally, we extend PWCE-MPP to consider the path-differences among the working and backup paths, and propose a modified PWCE-MPP (mPWCE-MPP) scheme to ensure that the maximum path-difference of a request will not increase dramatically during restoration.

The rest of the paper is organized as follows. We formulate the ILP model for Instant-ILP in Section II. Section III discusses the designs of PWCE-MPP and mPWCE-MPP. The performance evaluation is in Section IV. Finally, Section V summarizes the paper.

II. ILP Formulation for Instant MPP Protection

The EON topology is modeled as $G(V, E)$, where V and E represent the sets of the nodes and directed fiber links, respectively. Given a request $LR(s, d, n)$, where s and d are the source and destination ($s, d \in V$), and n is the bandwidth demand in number of contiguous frequency slots (FS'), our target is to calculate an MPP scheme with 100% restorability against any single link failure for it. We first formulate a simple ILP model to accomplish instant design of the optimal working-backup structure for a dynamic MPP request based on the network status. Here, "instant design" means that the structure is built instantly at the time when the request arrives. The model is as follows.

Notations:

- F: Maximum number of FS' on each fiber link.
- K: Number of pre-calculated link-disjoint path candidates for each s-d pair in $G(V, E)$.
- $\mathcal{P}_{s,d}$: Set of K path candidates from s to d.
- $p_{s,d,k}$: The k-th link-disjoint path in $\mathcal{P}_{s,d}$, $k \in [1, K]$.
- $h_{s,d,k}$: Hop-count of $p_{s,d,k}$.
- $m_{s,d,k}$: Size of the largest available FS block on $p_{s,d,k}$.

Variable:

- x_k: Number of contiguous FS' allocated on $p_{s,d,k}$.
- g_k: Boolean variable that equals 1 if one FS should be reserved on $p_{s,d,k}$ as guard-band, and 0 otherwise.

Objective:

$$Minimize \quad B = \sum_{k=1}^{K} h_{s,d,k} \cdot (x_k + g_k). \tag{1}$$

Eq. (1) indicates that the optimization objective is to minimize the total FS' used for the request's working-backup structure.

Constraints:

$$x_k + 1 \leq m_{s,d,k}, \quad \forall k. \tag{2}$$

$$0 \leq x_k \leq n, \quad \forall k. \tag{3}$$

Eqs. (2) and (3) ensure that the spectrum assignment on $p_{s,d,k}$ for the working-backup structure is valid.

$$g_k \geq \frac{1}{F} \cdot x_k, \quad \forall k. \tag{4}$$

Eq. (4) ensures that one FS is reserved as guard band if $x_k > 0$.

$$\sum_{k \in \{\{1,\cdots,K\}/i\}} x_k \geq n, \quad \forall i \in \{1, ..., K\}. \tag{5}$$

Eq. (5) ensures that the required bandwidth can be delivered from s to d during any single-link failure in the EON.

This ILP model optimizes the design of a request's working-backup structure with K shortest and link-disjoint path candidates from s to d, and the working and backup paths for the MPP request are determined jointly. In this work, we use first-fit for spectrum assignment and assume that there is no spectrum converters in the EON, and thus each lightpath should be provisioned all-optically end-to-end with the same spectra. Note that, from the perspective of working principle, this ILP is similar to the survivable MPP heuristics in [11], while our approach can provide the optimal solution for each dynamic request. Since the numbers of variables and constraints are very limited (*i.e.*, $2K$ and $5K$, respectively), the ILP can be solved within a reasonably short time, which makes it suitable for dynamic network provisioning. Specifically, the size of its solution space is $(2n)^K$ in the worst case, and n and K are usually small in practical cases. For instance, a request usually require less than 10 FS' ($n \leq 10$) and the number of link-disjoint path candidates K is normally less than 3.

One intrinsic drawback of this type of instant protection design is that setting up and tearing down working and backup paths frequently due to dynamic network operation can cause severe spectrum fragmentation [3, 8], which will degrade the EON's BBP dramatically.

III. PWCE-based Protection Designs for MPP

Compared with instant protection design, EON resilience with PWCE and spectrum planning can reduce spectrum fragmentation [9]. Specifically, for a given EON, we use PWCE to set up a set of *p*-cycles, reserve enough spectrum resources on them with spectrum planning, and build a backup structure that protects all the working links in the network.

A. PWCE-MPP

It is known that in a mesh topology with sufficient connectivity, one can obtain Hamiltonian cycles that traverse all the nodes only once [13]. Moreover, PWCE-based EON protection design using Hamiltonian *p*-cycles has shown promising performance for SPP in [9]. Therefore, we first extend the Ham-*p*-cycle-SP algorithm in [9] to PWCE-based protection design for MPP (PWCE-MPP). Fig. 1 illustrates the procedure of PWCE-MPP. With the six-node topology in Fig. 1(a), we find two Hamiltonian cycles, *Cycles* 1 and 2, which are marked with green-dash-dot and blue-dash lines, respectively. If we configure two *p*-cycles with them, all the links can be protected, since each link is either an on-cycle or a straddling link of the *p*-cycles. Then, spectrum planning partitions the EON's spectrum resources into Working and Backup FS-layers, as shown in Fig. 1(b). Since we aim for 100% restoration against single-link failures, half of the FS' on *Cycles* 1 and 2 are allocated to Backup FS-layer to form *p*-cycles, while all the FS' on their straddling links (*e.g.*, *Link* 2→3) are assigned to Working FS-layer.

During service provisioning, the requests are served with the FS' in Working FS-layer, using the MPP scheme described in *Algorithm* 1. Firstly, in *Lines* 2-9, we try to serve the request with a single path, and if this cannot be done, the MPP mechanism is applied as shown in *Lines* 10-26. Specifically, the algorithm first sorts the path candidates according to the available bandwidth on them, and then tries to satisfy the request's bandwidth requirement iteratively with multiple paths. If the request still cannot be provisioned with MPP, it will be blocked. Note that, in order to limit the number of paths allocated to a request, we apply a constraint that the smallest bandwidth (in number of FS') that can be allocated on a path should not be smaller than a predefined granularity g [3]. Meanwhile, our spectrum planning discussed above ensures that as long as its working path(s) can be set up in Working FS-layer, the request is automatically protected against all the single-link failures in the EON by using Backup FS-layer. By doing so, we avoid the dynamic constructing of protection structures and the impact of spectrum fragmentation is significantly reduced. Moreover, different from the case in Instant-ILP, we do not need to consider the constraint that all the paths (*i.e.*, working or protection) assigned to a request have to be link-disjoint. Hence, more path candidates are available for MPP, which further improves the performance.

Algorithm 1: Service Provisioning with MPP

```
for each lightpath request LR(s, d, n) do
    calculate K-shortest paths from s to d as set P;
    // Single path provisioning:
    for each path p ∈ P do
        if there are n continuous FS' on p then
            allocate n FS' on p to LR with first-fit;
            n = 0;
            break;
        end
    end
    // Multipath provisioning:
    while n > 0 do
        sort the paths in P in descending order of their
        available bandwidth;
        flag = 0;
        for each path p ∈ P do
            if Size of the largest FS-block on p is m ≥ g
            then
                allocate min(m, n) FS' on p to LR;
                n = n − m, flag = 1;
                break;
            end
        end
        if flag = 0 then
            break;
        end
    end
    if n > 0 then
        mark LR as blocked;
    end
end
```

Fig. 1(c) shows an example of PWCE-MPP. For the request $LR(2, 5, 8)$, which is from *Node* 2 to *Node* 5 for 8 FS', we provision it over three paths, *i.e.*, 2→4→5, 2→4→6→5 and 2→1→3→5. In Fig. 1(c), the FS assignments on the three working paths are marked with color blocks. We can see that the protection structure shown in Figs. 1(a)-(b) protects $LR(2, 5, 8)$ against any single-link failure. For example, if the fiber link between *Nodes* 2 and 4 is broken, *Working Path* 3 is unaffected while the traffics on *Working Paths* 1 and 2 need to be restored. Then, according to the principle of *p*-cycle, *Cycle* 1 restores their traffics on *Link* 2→4 with 2→1→3→5→6→4, by using *FS'* 1-4 and *FS'* 5-7 in Backup FS-layer, respectively.

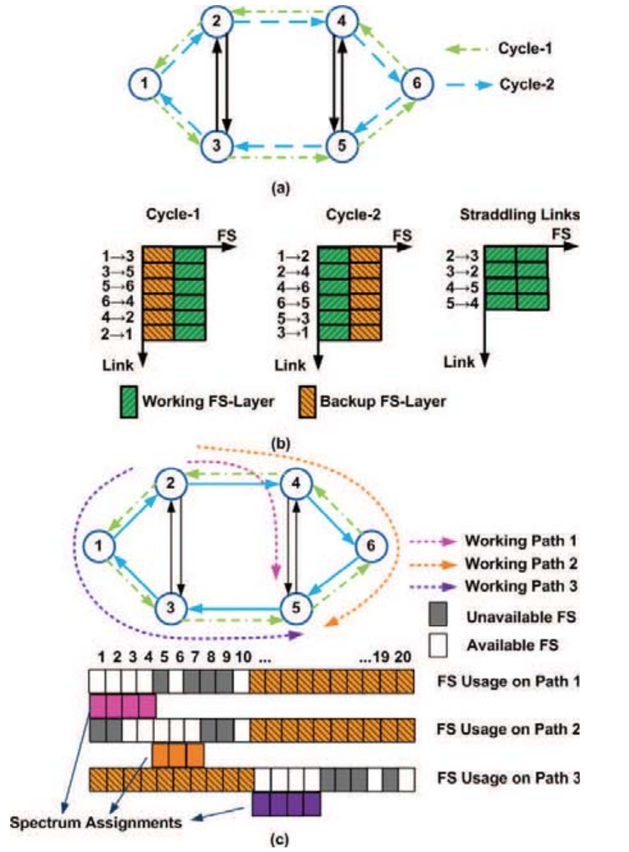


Fig. 1. Procedure of PWCE-MPP, (a) Hamiltonian *p*-cycles, (b) Spectrum planning, and (c) Example of PWCE-MPP.

B. *mPWCE-MPP*

One issue with PWCE-MPP is that the working and restoration paths of a request can have relatively long path-differences. For instance, in Fig. 1(c), if *Link* 6→5 is broken, *Working Path* 2 will be restored with 2→4→6→4→2→1→3→5. Apparently, the restoration path causes excessive path-difference for MPP. This is because the Hamiltonian *p*-cycles have to traverse all the nodes in the topology to ensure 100% recovery coverage. When a link fails, the switches in its end-nodes are reconfigured to activate the *p*-cycle. Hence, in the worst case, all the nodes in the EON can be involved during link restoration.

To overcome this issue, we propose a modified PWCE-MPP (mPWCE-MPP) algorithm that uses path protection and ensures that the maximum path-difference (MPD) of a request will not increase dramatically during restoration. Here, for a MPP request, we define its MPD as the length difference between its longest and shortest paths. For example, if we assume that the length of each link in Fig. 1(c) is identical as 1, then when *Link* 6→5 is working, the MPD of $LR(2, 5, 8)$ is 1. While during the restoration for *Link* 6→5 with PWCE-MPP, the MPD changes to 5.

The basic idea of mPWCE-MPP is to construct several short cycles that facilitate path protection for all the *s*-*d* pairs in the topology. *Algorithm* 2 shows the detailed procedure, which includes four steps. The first two steps design the protection structure and perform spectrum planning, with the aid of a simple ILP that minimizes the FS' reserved for Backup-FS layer under the MPD constraint.

Notations:

- $\mathbb{C}$: Set of pre-calculated cycles in $G(V, E)$, and $\mathbb{C} = \{c_i\}$.
- d_m: MPD to the shortest path $p_{s,d,1}$, *i.e.*, MPD constraint.
- $y_{i,s,d}$: Flag that equals 1 if two link-disjoint paths exist on cycle c_i under the MPD constraint, for a s-d pair.
- $\omega_{i,e}$: Flag that equals 1, if $e \in c_i$, and 0 otherwise.

Variables:

- β_i: Boolean variable that equals 1 if c_i is included in the protection structure, and 0 otherwise.
- m_e: Boolean variable that equals 1 if e is included in the protection structure, and 0 otherwise.

Objective:

$$Minimize \quad F = \sum_{e \in E} m_e. \tag{6}$$

Eq. (6) shows that the optimization objective is to minimize the total number of links in the protection structure.

Constraints:

$$\sum_i \beta_i \cdot y_{i,s,d} \geq 1, \quad \forall s, d \in V. \tag{7}$$

Eq. (7) ensures that for each s-d pair, at least two qualified backup paths can be found in the protection structure.

$$m_e \geq \frac{1}{|E|} \cdot \sum_i \beta_i \cdot \omega_{i,e}, \quad \forall e \in E. \tag{8}$$

Eq. (8) ensures that each link is counted at most once, where $|E|$ represents the total number of links in $G(V, E)$. The ILP contains $|E| + |\mathbb{C}|$ variables and $|V| \cdot (|V| - 1) + |E|$ constraints, where $|V|$ is the number of nodes in V. However, since we only need to solve this ILP once in initialization, it will not cause excessive delay during dynamic network operation.

The third step of *Algorithm* 2 serves each request with *Algorithm* 1 using Working FS-layer. When a link fails, the fourth step restores all the affected working paths with the precalculated protection paths and the FS' in Backup FS-layer.

Theorem 1. *With the protection structure designed by the ILP above, all the affected working paths can be fully restored during any single-link failure in the EON.*

Proof: We prove the theorem by considering two cases.

Case 1: the failed link is on the protection structure. For this case, according to the ILP formulation, we can find at least one restoration path in the protection structure for each affected working path. Hence, the paths are guaranteed for restoration. If we assume that each fiber link accommodates F FS', then the link failure can affect at most $\frac{F}{2}$ working FS', since the link is on the protection structure and the rest $\frac{F}{2}$ FS' on it have already been reserved for Backup-FS layer. As we have already reserved $\frac{F}{2}$ FS' on the protection structure for backup, all the affected working FS' can be restored.

Case 2: the failed link is not on the protection structure. For this case, the ILP ensures that at least two link-disjoint restoration paths can be found in the protection structure, and each one can contribute $\frac{F}{2}$ FS' during restoration. Since the link failure can affect at most F working FS' in this case, all the affected working FS' can also be fully restored.

To this end, we prove that all the affected working paths can be fully restored during any single-link failure in the EON. Meanwhile, the MPD constraint is satisfied. ■

Algorithm 2: mPWCE-MPP

```
// Initialization:
calculate a set of cycles in G(V, E) and store them in ℂ;
solve the ILP with ℂ to get the set of cycles that can
  protect all the s-d pairs under the MPD constraint;
merge the obtained cycles as the protection structure;
// Spectrum Planning:
for each link e in the protection structure do
  | assign the second half FS' on e as Backup FS-layer;
end
assign the rest FS' in the EON as Working FS-layer;
// Provisioning a Request:
provision requests with Algorithm 1 using the FS' in
  Working FS-layer;
// Restoration during a Link Failure:
for each affected working path do
  | establish the restoration path in Backup FS-layer;
end
```

Fig. 2 shows an example of mPWCE-MPP. For the topology in Fig. 2(a), the ILP obtains six cycles as shown in Figs. 2(b)-(g), under the MPD constraint $d_m = 2$. Note that the length of each link is still 1. Each cycle protects certain s-d pairs, for instance, *Cycle* 1 protects s-d *pairs* 1-2, 2-3 and 1-3, while *Cycle* 5 backs up s-d *pair* 1-6. We then merge all the cycles to construct the protection structure as shown in Fig. 2(h) and reserve half of the FS' on it as the Backup FS-layer. Note that, since the backup FS' are shared among the cycles, certain nodes in the protection structure, *i.e.*, *Nodes* 2, 3, 4 and 5 are not pre-configured. When a link fails, each affected working path is restored using the backup paths in purple-dash lines with the spectrum resources in Backup FS-layer.

IV. Performance Evaluation

We first evaluate the performance of the algorithms, *i.e.*, Instant-ILP, PWCE-MPP and mPWCE-MPP, with simulations with the NSFNET topology in Fig. 3(a) and compare them with the dynamic SM-RSA in [11]. The bandwidth of each FS is 12.5 GHz and each fiber link accommodates 358 FS'. The requests are generated using the Poisson traffic model with the s-d pairs randomly selected. The bandwidth requirement of each request is uniformly distributed within $[1, 20]$ FS' and K

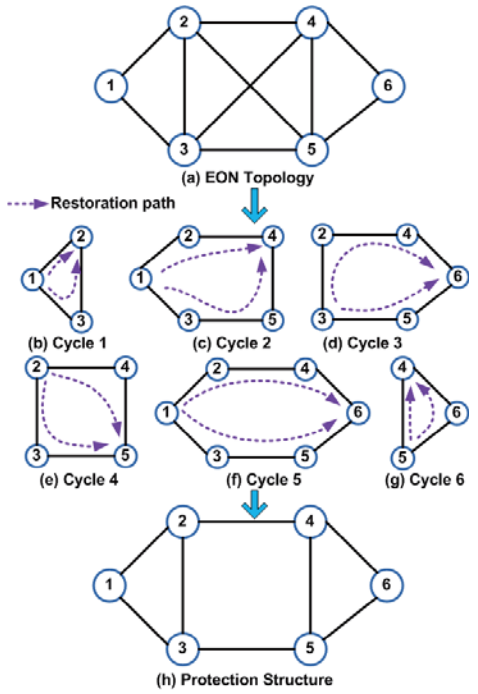
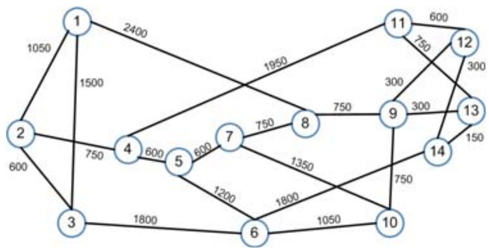
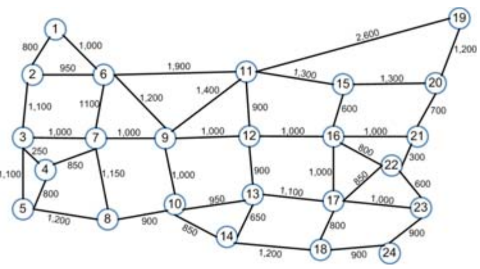


Fig. 2. Example of mPWCE-MPP.



(a) NSFNET.



(b) US Backbone.

Fig. 3. Simulation topologies (fiber lengths in kilometers).

is set as 3. For PWCE-MPP and mPWCE-MPP, the bandwidth granularity $g = 1$ FS. For mPWCE-MPP, we set $d_m = 3750$ km and the ILP obtains protection structure with $\mathbb{C}$ containing 91 short cycles. All the simulations are programmed with MATLAB on a PC that is equipped with a 3.3 GHz CPU and 4 GB RAM, and we solve Instant-ILP using the Branch-and-Bound method which can give the optimal MPP solution for each request within 25.7 msec in average.

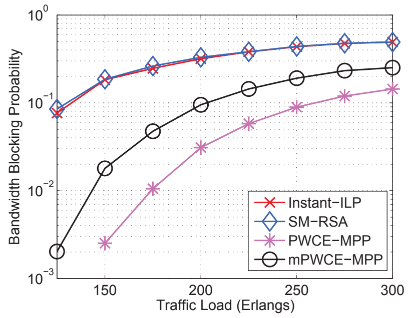
In Fig. 4(a), we observe that PWCE-MPP provides the lowest BBP, while the BBP performances of Instant-ILP and SM-RSA are the worst. This is because the spectrum planning relieves spectrum fragmentation in dynamic network operation, and makes more spectra available for MPP. The BBP results of mPWCE-MPP are higher than those from PWCE-MPP, due to the fact that mPWCE-MPP includes more links in protection structure to satisfy the MPD constraint and hence allocates more FS' to Backup FS-layer. Fig. 4(b) shows the results on total spectrum utilization, which verify our analysis above. SM-RSA provides the lowest spectrum utilization because spectrum fragmentation makes the spectra hard to be utilized for future requests. Instant-ILP has a slightly higher spectrum utilization than SM-RSA as it can accommodate a little bit more requests. The results from mPWCE-MPP are larger than those from PWCE-MPP, as mPWCE-MPP reserves more spectra for the Backup-FS layer, while the difference gets smaller when the traffic load increases due to the fact that PWCE-MPP accommodates more requests in the network.

Fig. 4(c) shows the results on average MPD when the traffic load is 300 Erlangs. At each provision time, we enumerate all the link failures, determine the restoration schemes, and calculate the MPDs during restoration. Then, the average MPD is obtained for the whole dynamic provisioning. Note that, when calculating the average MPD, we do not include the SPP requests since they do not have the issue with path-difference. Before restoration, the MPD from Instant-ILP is the shortest, since the ILP always tries to use the shortest available paths for MPP and selects the paths with the shortest MPD as the working ones. The MPD results from PWCE-MPP and mPWCE-MPP before restoration are similar, since they use the same MPP algorithm for allocating the working resources. After restoration, PWCE-MPP provides the longest MPD as expected, while mPWCE-MPP reduces MPD effectively and provides the result that is even shorter than those from Instant-ILP and SM-RSA. Note that for the traffic loads that are lower than 300 Erlangs, since smaller numbers of requests will be provisioned with MPP according to the operation principle of *Algorithm* 1, mPWCE-MPP's advantage on MPD over Instant-ILP and SM-RSA would become larger.

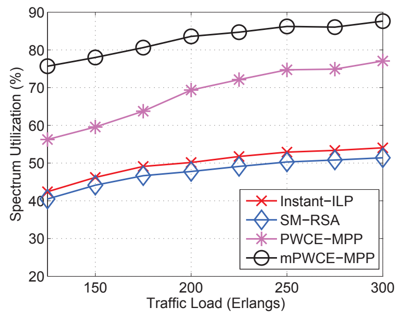
We also perform simulations with the US Backbone topology as in Fig. 3(b). The simulation setup is similar, while we calculate 276 short cycles for $\mathbb{C}$ and set $d_m = 4000$ km. Fig. 5 shows the results on BBP, resource utilization and MPD, and we can see the results follow the similar trends.

V. CONCLUSION

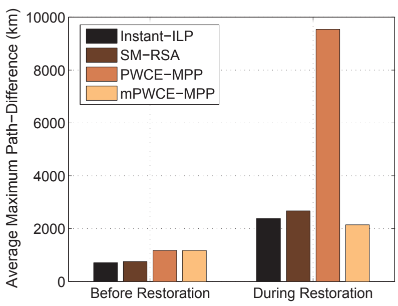
We discussed the design of protection structures for MPP in EONs. In order to ensure 100% restoration against single-link failures, we designed three algorithms, *i.e.*, Instant-ILP, PWCE-MPP and mPWCE-MPP. Instant-ILP could get the optimal working-backup structure for each request based on the network status, while by using spectrum planning, PWCE-MPP and mPWCE-MPP could further improve the provision efficiency in EONs and hence provided better BBP performance. Moreover, mPWCE-MPP considered the differences among the working and backup paths, and guaranteed that



(a) Bandwidth blocking probability.

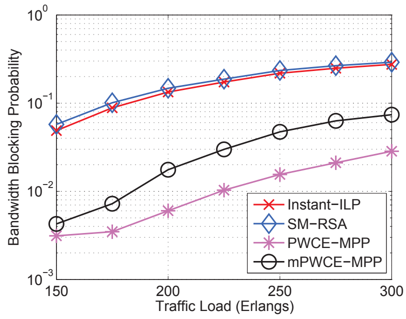


(b) Resource utilization ratio.

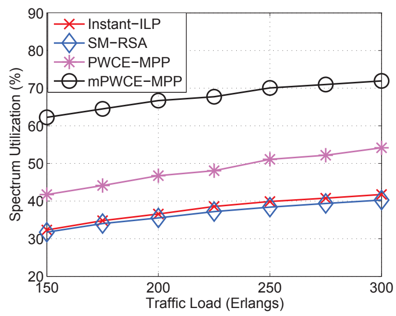


(c) Average MPD after restoration (300 Erlangs).

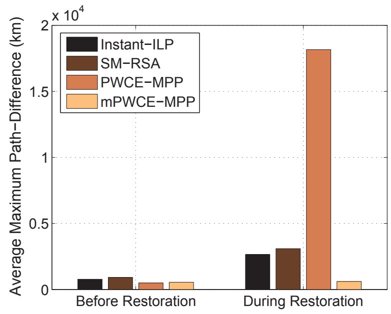
Fig. 4. Simulation results for NSFNET topology.



(a) Bandwidth blocking probability.



(b) Resource utilization ratio.



(c) Average MPD after restoration (300 Erlangs).

Fig. 5. Simulation results for US Backbone topology.

the MPD of a request would not increase dramatically during restoration. Simulation results showed that mPWCE-MPP obtained the best trade-off between BBP and average MPD.

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