Flexible Availability-Aware Differentiated Protection in Software-Defined Elastic Optical Networks

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***Abstract*—Availability-aware service provisioning tries to satisfy the availability requirements of clients on demand and can improve the resource efficiency in optical networks. This paper studies the problem of flexible availability-aware differentiated protection (ADP) in elastic optical networks (EONs). We first consider the unique features in EONs, e.g., flexible spectrum allocation and bandwidth-squeezed protection, describe the problem of ADP, and present a theoretical analysis on service availability. Then, we develop an ADP algorithm that can change the path protection scheme to adapt to different service availability requirements. An availability-aware backup reprovisioning strategy is also proposed as a supplement of the ADP algorithm to further improve the protection efficiency. We also discuss the system design for OpenFlow-based software-defined EON (SD-EON) framework to facilitate the ADP scheme. Finally, to demonstrate the overall design, we construct an SD-EON control plane testbed that consists of 14 standalone nodes, implement the proposed algorithms in the OpenFlow controller, and perform experiments to evaluate their performance. The results indicate that the system performs well, and the proposed algorithms can reduce blocking probability effectively without sacrificing the service availability of requests.**

***Index Terms*—Availability-aware differentiated protection, backup reprovisioning, software-defined elastic optical networks (SD-EONs).**

I. Introduction

RECENTLY, flexible-grid elastic optical networks (EONs) have attracted intensive attentions due to the high spectrum efficiency and agile resource allocation [1]. Different from the fixed-grid wavelength division multiplexing (WDM) networks, EONs utilize bandwidth variable transponders (BV-Ts) and switches (BV-WSS') that operate on a series of spectrally-contiguous frequency slots (FS') to set up lightpaths. Since these FS' have much narrower bandwidth than the conventional wavelength channels, EONs can provision bandwidth adaptively according to the actual traffic demands.

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Meanwhile, it is known that how to maintain network survivability is always an important problem in optical networks, as a single link failure can cause huge data loss and long traffic disruption. Previously, a few schemes to protect the lightpaths in EONs against link failures have been proposed [2]–[6]. However, they have not addressed the lightpath protection in EONs from the perspective of service availability. Note that in practical network operations, an operator usually guarantees quality-of-service to its clients by specifying the service availability in their service-level agreements (SLAs) [7]. Here, the service availability of a lightpath is defined as

$$A = \frac{T_{\text{on}}}{T}, \tag{1}$$

where T_{on} represents the time duration over which the lightpath's service is on, and T is its total provision period. Statistically, service availability is the probability that the lightpath is seen in-service at any time in its provision period.

Since SLA violations can cause revenue loss to network operators, developing availability-aware protection schemes is important and necessary. In order to make the service provisioning cost-effective, a network operator should guarantee just-enough service availability to the lightpaths by allocating the minimum amount of backup resources. Meanwhile, the protection design should be differentiated, since different SLAs may impose different requirements on service availability. In [8], Song *et al.* utilized different protection schemes to satisfy different requirements on service availability in WDM networks. Zhang *et al.* [9] developed a mathematical model to analyze the service availability of lightpaths using different protection schemes, and proposed an integer linear programming model and several heuristics for achieving availability-aware service provisioning in WDM networks. Kantarci *et al.* developed availability-aware differentiated provisioning algorithms for WDM networks in [10], in which they determined the feasible sharing degree for each availability class and used it to ensure that the SLA on availability would not be violated when adding new lightpaths into a class. A differentiated protection algorithm that got the shareability of backup resources based on the holding time of lightpaths was proposed in [11]. Nevertheless, the previous studies only considered WDM networks and did not address EONs. Due to the unique spectrum allocation scheme in EONs, the service availability analysis and corresponding availability-aware protection could be different and the approaches designed for WDM networks may not be directly applicable. For instance, it is known that in EONs, the amount of bandwidth used for restoring a lightpath during failure can be less than that for working (i.e., bandwidth-squeezed protection [2]).

On the other hand, to realize availability-aware protection efficiently in EONs, we need an intelligent network control and management (NC&M) mechanism that manages the network with the knowledge of global resource utilization and all the in-service lightpaths. Previously, people have studied how to achieve such NC&M with the distributed generalized multi-protocol label switching (GMPLS) or hybrid GMPLS and path computation element architectures [12]–[15], and demonstrated interesting results. Meanwhile, by decoupling the control and data planes of a network, software-defined networking (SDN) makes the network programmable, adaptive and application-friendly [16]–[18]. As a promising implementation of SDN, OpenFlow (OF) [19] has become a standard protocol. The combination of SDN and EONs leads to software-defined EONs (SD-EONs) [20]–[26], which also fit in the requirement of intelligent NC&M well. Moreover, previous investigations have indicated that SD-EON might be able to provide relatively short failure recovery time [27], [28].

In this paper, we study the flexible availability-aware differentiated protection (ADP) in EONs. We first consider the unique features in EONs, e.g., flexible spectrum allocation and bandwidth-squeezed protection, describe the problem of ADP, and present the theoretical analysis on service availability. Then, we develop an ADP algorithm that can change the path protection scheme to adapt to different service availability requirements. An availability-aware backup reprovisioning (ABR) strategy is also proposed as a supplement of the ADP algorithm to further improve the protection efficiency. We also discuss the network architecture and system design for OF-based SD-EON framework that can facilitate the ADP scheme. Finally, to demonstrate the overall design, we construct an SD-EON control plane testbed that consists of 14 stand-alone nodes, implement the proposed algorithms in the OF controller (OF-C), and perform experiments to evaluate their performance. The contributions of this work can be summarized as follows.

- By considering flexible spectrum allocation and bandwidth-squeezed protection, we theoretically analyze the service availability of different path protection schemes in EONs.
- We develop an ADP algorithm that leverages ABR to improve the protection efficiency in EONs.
- We design the system framework to facilitate ADP in SD-EONs and perform control plane experiments to evaluate the performance of proposed algorithms.

The rest of the paper is organized as follows. Section II presents the theoretical analysis on service availability in EONs and details the proposed ADP-ABR algorithm. The SD-EON framework for realizing ADP is discussed in Section III. We show the experimental demonstrations in Section IV, and finally, Section V summarizes the paper.

II. ADP in EONs

In this section, we first analyze the service availability of several lightpath provisioning schemes in EONs, and then propose an ADP algorithm together with an ABR strategy based on the analysis.

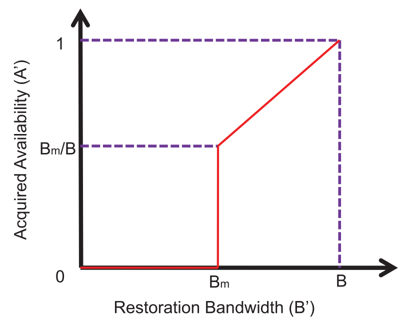


Fig. 1. Relation between acquired availability and restoration bandwidth.

A. Theoretical Analysis on Service Availability in EONs

The EON topology is modeled as $G(V, E)$, where V and E represent the sets of nodes and fiber links in it, respectively. Given a lightpath request $LR(s, d, B, A, T)$, where s and d $(s, d \in V)$ are the source and destination nodes, B is the bandwidth requirement in Gb/s, A is the availability requirement from SLA, and T is the service duration, we need to provision it with sufficient bandwidth as well as satisfying the availability requirement. Hence, if A cannot be satisfied with a single working path, a backup path would be assembled to avoid SLA violations.

Here, in order to realize flexible ADP, we consider the bandwidth-squeezed protection in [2]. Specifically, we allow the situation that the restoration bandwidth used during failure is less than that for working. For the request $LR(s, d, B, A, T)$, we assume that B_m is the minimum bandwidth required during restoration. Note that the key parameter of the request, i.e., the ratio of $\frac{B_m}{B}$, should be specified in the SLA between the client and the network operator, while the rest can be determined dynamically according to the actual service requirement from the client. Fig. 1 shows the relation between the acquired availability A' and the restoration bandwidth B'. Specifically, we assume that with bandwidth-squeezed protection, the request's service availability is related to the bandwidth that it acquires during restoration [29], [30]

$$A' = \begin{cases} 0, & B' < B_m, \\ \dfrac{B'}{B}, & B \geq B' \geq B_m. \end{cases} \quad (2)$$

According to the discussion in [2], if the restoration bandwidth B' is less than B_m, the request is unrecoverable and hence the acquired availability A' is 0. Otherwise, A' increases linearly with B' as the request is only partially recovered.

In order to maximize the revenue-gain of the network operator, we need to minimize the request blocking probability, i.e., trying to successfully serve as many requests as possible. Similar to previous work in [8], [10], we only consider link failures and assume that a request can be provisioned with an unprotected working path, shared path protection (SPP), or dedicated path protection (DPP). Here, we consider the "1 + 1" protection scheme for DPP, i.e., both the working and backup paths carry the request's traffic, and the receiver decides which of the two

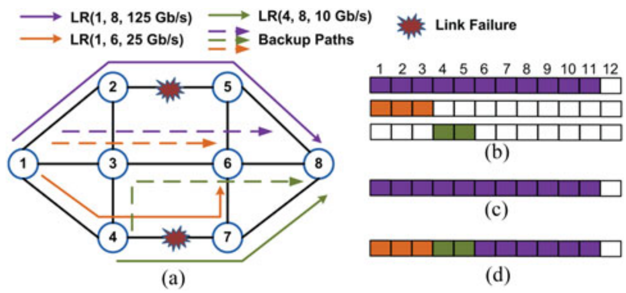


Fig. 2. An example of SPP in EONs.

incoming traffics to pick. The service availabilities of the service provisioning schemes are analyzed as below.

1) Unprotected Working Path: The following notations are defined for calculating the availability of a working path $\mathcal{R}_{s,d}$:

- ρ: Availability of a link, which is assumed to be identical for all the links in E.
- H_w: Hop-count of $\mathcal{R}_{s,d}$.

Note that in practical network operation, the availability of a fiber link has relations with various characteristics, e.g., the link length, the geographical location of the link, etc. Hence, the actual availabilities of two different links cannot be exactly the same [31]. However, consider the fact that link availability usually approaches to 1 closely and thus the actual link availabilities normally have very similar values, it becomes a common and valid simplification to use the average link availability in the network as the availability of each link [31]. Moreover, even when different availabilities have to be used for different links, our theoretical model in this work can still be applicable with just minor modifications. An unprotected working path is available when and only when its links are all available. Hence, the availability is simply as

$$A_L = \rho^{H_w}. \tag{3}$$

2) Dedicated Path Protection: For a request that is protected by a dedicated protection path with bandwidth B' allocated ($B' \geq B_m$), its service is available if its working path is available or its working path is broken but its backup path is intact. Hence, the availability is

$$A_L = \rho^{H_w} + \gamma_0 \cdot (1 - \rho^{H_w})\rho^{H_p}, \tag{4}$$

where H_p is the hop-count of protection path, and $\gamma_0 = \frac{B'}{B}$.

3) Shared Path Protection: In case of SPP, multiple requests may compete for the same backup resources when more than one links fail. Hence, a request provisioned with SPP is only available under two situations, 1) its working path is available, and 2) its working path is broken, but the protection path is available and it successfully secures the backup resources when competing with other requests. In this work, we assume that the competition on backup resources among requests is fair, and thus if multiple requests share the same backup resources, they have the equal probability to win the resource competition during link-failures.

Fig. 2(a) shows an example for SPP in EONs, where LR (Node 1, Node $8, 125$ Gb/s) shares backup FS' on its backup path 1→3→6→8 with LR(Node 1, Node $6, 25$ Gb/s) and LR(Node 4, Node $8, 10$ Gb/s). As an FS can carry 12.5 Gb/s capacity, the backup spectrum assignments are depicted in Fig. 2(b). Note that, one guard-band FS is also assigned for each request. Here, we can see that the backup sharing in EONs is different from that in WDM networks. Specifically, for two requests in a WDM network, their backup wavelength channels are either independent or totally overlapping. However, two requests in an EON can just share partial of their backup spectrum assignments. Therefore, the service availability analysis for SPP is more complex. For instance, consider the case that link-failures occur on *Link* 2–5 first and then on *Link* 4–7, LR(Node 1, Node $8, 125$ Gb/s) can be restored with 100% bandwidth guaranteed (as shown in Fig. 2(c)). However, if *Link* 4–7 fails before *Link* 2–5, LR(Node 1, Node $6, 25$ Gb/s) and LR(Node 4, Node $8, 10$ Gb/s) are first restored, which uses certain backup FS' on *Link* 3–6. Then, LR(Node 1, Node $8, 125$ Gb/s) can only leverage 6 FS' and has to use bandwidth-squeezed protection (as in Fig. 2(d)). Since the requests that share the same backup FS' have equal probability to win in the resource competition, we can obtain the availability of LR(Node 1, Node $8, 125$ Gb/s) in case of the dual-failure on *Links* 2–5 and 4-7 as $p_{(2,5)(4,7)} \cdot (0.5 + 0.5 \times 0.5)$, where $p_{(2,5)(4,7)}$ represents the probability of dual-failure on *Links* 2–5 and 4–7. Then, by enumerating all the scenarios in which a request is available, we can get its service availability.

In this work, we assume that there are at most two simultaneous link-failures in the network. Basically, because the probability of a single link-failure is already very small (i.e., usually ≤ 0.01), the probability of three or more simultaneous link-failures would be extremely small and can be ignored [7]. Therefore, the availability of a request that is provisioned with SPP can be estimated by considering the following three independent "service available" situations, 1) all the working links are intact, 2) only one working link fails while all the links on the backup path are intact and the request successfully secures the backup resources, and 3) a dual-failure happens on the working links while all the links on the backup path and the working paths of the requests that share backup resources with the request are available. The availability from the first situation can be simply obtained with Eq. (3). The second situation can be further categorized into two cases, i.e., the one in which all the requests that share backup resources with the current one are available, and the one in which a link-failure occurs on the working paths of the requests that share backup resources with the current one but it successfully secures enough backup resources in the resource competition. Hence, the availability from the second situation is

$$\begin{aligned} A'_L = \ & H_w(1-\rho)\rho^{H_w+H_p-1}\Bigg[\rho^{|\mathbb{L}|}\gamma_0 + \\ & \sum_{i=1}^{|\mathbb{L}|}\rho^{|\mathbb{L}|-1}(1-\rho)\left(\frac{1}{2}\gamma_0 + \frac{1}{2}\gamma_i\right)\Bigg], \end{aligned} \tag{5}$$

where $\mathbb{L}$ is the set of links on the working paths of the requests that share backup FS' with LR, $\gamma_0 = \frac{B'}{B}$ is from the assigned restoration bandwidth B' ($B' \geq B_m$) of LR (e.g., the situation illustrated in Fig. 2(c)), and $\gamma_i = \frac{B'_i}{B}$ is from LR's actual restoration bandwidth B'_i when a link $i \in \mathbb{L}$ fails earlier than the working path of LR (e.g., the situation in Fig. 2(d)). The availability from the third situation can be obtained as

$$A''_L = \frac{1}{2} H_w (H_w - 1)(1-\rho)^2 \rho^{H_w + H_p + |\mathbb{L}| - 2} \gamma_0. \quad (6)$$

Finally, by summing the availabilities from the three situations, the service availability of LR that is provisioned with SPP is

$$A_L = \rho^{H_w} + H_w (1-\rho) \rho^{H_w + H_p - 1} \Bigg[\rho^{|\mathbb{L}|} \gamma_0 + \sum_{i=1}^{|\mathbb{L}|} \rho^{|\mathbb{L}|-1} (1-\rho) \left(\frac{1}{2}\gamma_0 + \frac{1}{2}\gamma_i \right) \Bigg] + \frac{1}{2} H_w (H_w - 1)(1-\rho)^2 \rho^{H_w + H_p + |\mathbb{L}| - 2} \gamma_0. \quad (7)$$

B. ADP Design

Previous studies on ADP design in WDM networks usually considered the shareability of discrete wavelength channels. Specifically, they first calculated a reliable backup path based on the sharing degree of each link, and then performed wavelength assignment by checking the shareability of each wavelength channel on the links. However, the spectrum assignment in EONs is more sophisticated since it needs to consider the bandwidth-squeezed protection feature and the spectrum continuity and contiguous constraints. Therefore, the ADP design becomes more complicated and the approaches designed for WDM networks are no longer suitable.

Algorithm 1 shows the detailed procedure of the proposed ADP for EONs. First of all, *Lines* 2–10 try to serve a request $LR(s,d,B,B_m,A,T)$ with an unprotected working path while still satisfying its availability requirement (i.e., $A_L \geq A$). In *Line* 2, we perform the routing, modulation-format and spectrum assignment (RMSA) of working path with the shortest path routing and first-fit spectrum assignment. Here, we consider the impairment-aware adaptive modulation selection and determine the lightpath's modulation-format according to its transmission distance [32], [33]. More specifically, we assume that the EON can use four modulation-formats, i.e., BPSK, QPSK, 8-QAM and 16-QAM, and the transmission reaches of them are the same as those in [33]. After determining the modulation-format for a lightpath, we convert its bandwidth requirement B in Gb/s to the number of spectrally-contiguous FS' that we should assign for it, as

$$n = \left\lceil \frac{B}{m \cdot C_{\text{grid}}^{\text{BPSK}}} \right\rceil + F_g, \quad (8)$$

where $m = 1, 2, 3$ and 4 represents the modulation-levels for BPSK, QPSK, 8-QAM and 16-QAM, respectively, $C_{\text{grid}}^{\text{BPSK}} = 12.5$ Gb/s is the transmission capacity that an 12.5-GHz FS can provide with BPSK, and $F_g = 1$ is for the guard-band. *Line* 7 calculates the service availability A_L with Eq. (3) as LR is provisioned with an unprotected working path.

Algorithm 1: Availability-Aware Differentiated Protection (ADP) Algorithm

```
1  for each request LR(s, d, B, B_m, A, T) do
2      do RMSA for working with the shortest path R_{s,d};
3      if no feasible RMSA solution can be obtained then
4          mark LR as blocked;
5          continue;
6      end
7      calculate the availability A_L of unprotected LR;
8      if A_L ≥ A then
9          continue;
10     end
11     get backup path R'_{s,d} that is link-disjoint with R_{s,d};
12     calculate M and N as the maximum and minimum
       numbers of backup FS' needed on R'_{s,d};
13     save the current network status as G';
14     mark the backup FS' reserved on R'_{s,d} as unused;
15     for m = N to M do
16         for each unused block of m FS' on R'_{s,d} do
17             calculate the availability A_L of LR with SPP;
18             if A_L < A then
19                 continue;
20             end
21             recalculate the availability of each in-service
               request that shares backup FS' with LR;
22             if the availability requirements of all the
               in-service requests are still satisfied then
23                 use the FS-block on R'_{s,d} to protect LR;
24                 go to Line 28;
25             end
26         end
27     end
28     if LR is successfully protected then
29         continue;
30     end
31     revert the network status to G';
32     for m = N to M do
33         if R'_{s,d} carries 0 unused block of m FS' then
34             mark LR as blocked;
35             break;
36         end
37         calculate the availability A_L of LR with DPP;
38         if A_L ≥ A OR m = M then
39             allocate an unused block of m FS' on R'_{s,d}
               as backup;
40             mark LR as "availability not satisfied" if
               A_L < A;
41             break;
42         end
43     end
44 end
```

If A_L cannot satisfy the availability requirement A, we proceed to *Lines* 11–30, and try to leverage the SPP scheme to improve the service availability. Note that the bandwidth-squeezed protection is taken care of in *Line* 12, where we calculate the size range of the FS-block that needs to be reserved on the backup path according to the bandwidth requirement B and the minimum restoration bandwidth B_m. Specifically, the maximum and minimum numbers of backup FS', i.e., M and N, are got based on B and B_m, respectively. Then, *Line* 14 marks all the backup FS' reserved on the backup path as available to enable backup sharing. The for-loop that covers *Lines* 15–27 tries to squeeze the request's backup bandwidth while satisfying its availability requirement. Specifically, by checking the unused FS-blocks with their sizes in ascending order, we try to find one that can be used as the backup FS' of LR to satisfy its availability requirement. Meanwhile, *Line* 21 recalculates the availabilities of other in-service requests that are currently using the FS-block as backup and makes sure that the backup sharing with LR will not degrade any of the availabilities below the requirements.

If the availability requirement cannot be satisfied with SPP, we proceed to the DPP scheme as described in *Lines* 31–43. With DPP, we still try to squeeze the restoration bandwidth under the availability constraint. Finally, as shown in *Line* 40, if we cannot satisfy the availability requirement even with DPP, the request is still provisioned with DPP but marked as "availability not satisfied". By doing so, we provision requests with best effort to avoid service blocking, while the clients are also alerted about the risk of potential SLA violations.

The complexity for calculating the availability with Eq. (7) is $O(|E| \cdot |\mathbb{LR}| \cdot n)$, where $|E|$ is the number of edges in E, $|\mathbb{LR}|$ is the total number in-service lightpaths in the EON and n is the number of FS' required by the request. Therefore, the complexity of the proposed ADP algorithm for provisioning a request is $O(|E| \cdot |\mathbb{LR}|^2 \cdot F^3)$.

C. ABR Strategy

Although the ADP algorithm mentioned above can serve requests according to their availability requirements, the protection schemes it provides can become less efficient when the network operation goes on. Basically, Eq. (1) shows that for a request LR, its in-service duration T_{on} is related with the availability A as

$$T_{\text{on}} = T \cdot A, \tag{9}$$

where T is the total provision period. If LR has already been served with T_{good} time without service disruption, the network operator only needs to ensure $T_{\text{on}} - T_{\text{good}}$ in-service time within the rest provision period ($T - T_{\text{good}}$). Hence, we can obtain the evolving availability requirement of LR as

$$A_{\text{evl}} = \frac{T_{\text{on}} - T_{\text{good}}}{T - T_{\text{good}}}, \tag{10}$$

where A_{evl} is a function of T_{good} and becomes smaller when T_{good} increases. To this end, we can see that the service of LR can be downgraded when the error-free network operation carries on, while its overall service availability requirement will not be violated in the future [34]. Since this type of service downgrading improves the backup sharing among requests and releases more available FS', it can make the spectrum utilization more efficient in the network.

By leveraging the service downgrading, we propose to incorporate an ABR strategy as the supplement of ADP. The procedure is shown in *Algorithm 2*. Basically, we notice that when an EON is in the normal working state, reconfiguring the protection structures in it will not cause any service disruptions. Then, the ABR strategy tries to reconfigure the protection structures for in-service requests periodically when time T_m elapses, as shown in *Lines* 3–6. *Lines* 11–17 try to downgrade a request's provisioning scheme to unprotected. If the unprotected scheme cannot satisfy the evolving availability requirement, *Lines* 18–20 try to reprovision the request with SPP to satisfy its evolving availability requirement A_{evl}, using *Algorithm* 1. If A_{evl} still cannot be satisfied, *Lines* 22–23 calculate a DPP scheme for the request. The complexity of ABR is $O(|E| \cdot |\mathbb{LR}|^3 \cdot F^3)$. We refer to the overall combined algorithm as ADP-ABR.

Algorithm 2: Availability-aware Backup Reprovisioning (ABR) Algorithm

1 $t_s = 0$;
2 **for** *each provision time* t_e **do**
3   **if** $t_e - t_s < T_m$ **then**
4   **continue**;
5   **end**
6   $t_s = t_e$;
7   **for** *each in-service lightpath* LR *in the EON* **do**
8   **if** LR *is provisioned as unprotected* **then**
9   **continue**;
10   **end**
11   obtain the evolving availability requirement A_{evl};
12   calculate the availability A_L with Eq. (3);
13   **if** $A_L \geq A_{evl}$ **then**
14   downgrade LR to the unprotected scheme;
15   release redundant backup resources;
16   **continue**;
17   **end**
18   calculate a new SPP scheme that can satisfy A_{evl};
19   **if** *a feasible solution can be obtained* **then**
20   adjust the backup resources of LR;
21   **else**
22   calculate a DPP scheme;
23   adjust the backup resources of LR;
24   **end**
25   **end**
26 **end**

III. Software-Defined Elastic Optical Networks

This section discusses the SD-EON framework for ADP.

A. Network Architecture

Fig. 3 shows the architecture of an SD-EON, which consists of two separate planes, i.e., the data plane and control plane. The data plane includes the network elements such as BV-Ts and BV-WSS', which realize the actual data transfers by setting up lightpaths. The control plane consists of an OF-C and

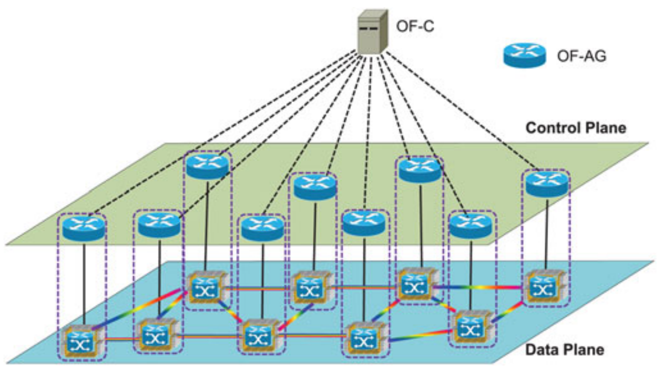


Fig. 3. Architecture of an SD-EON, OF-C: OpenFlow controller, OF-AG: OpenFlow agent.

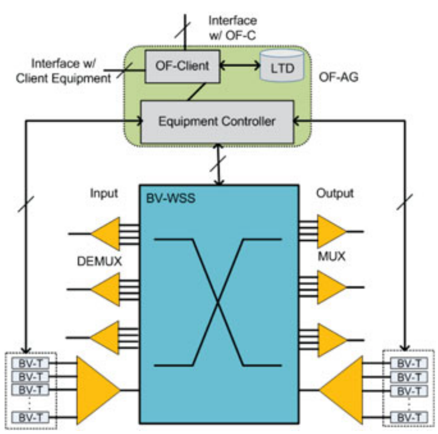


Fig. 4. Detailed structure of an optical node in SD-EONs, LTD: Local traffic database, OF-Client: OpenFlow client, BV-WSS: Bandwidth-variable wavelength-selective switch, BV-T: Bandwidth-variable transponder, MUX/DEMUX: Wavelength multiplexer/de-multiplexer.

several OF agents (OF-AGs). OF-C is in charge of resource management, while each OF-AG attaches to a network element locally and controls the operation for data transfers, i.e., managing lightpaths.

The detailed structure of an optical node in an SD-EON is shown in Fig. 4. Sitting on top of the BV-WSS and BV-Ts, OF-AG takes instructions from OF-C and configures them accordingly with the equipment controller. The dynamic lightpath requests for client traffic (e.g., IP) come to OF-AG from its interface with client equipment. In OF-AG, the OF-client interacts with OF-C using an extended OF protocol, and the local traffic database (LTD) stores the flow-entries for the lightpaths that use the node. By operating on several spectrally-contiguous FS' whose bandwidth and spectral locations are defined in ITU-T recommendation G.694.1 [35] and selecting the modulation-format according to the quality-of-transmission, each BV-T can start/terminate a lightpath. Meanwhile, the BV-WSS makes sure that the optical spectra of each lightpath are switched correctly.

B. OF Extensions

We design the communication between OF-C and OF-AGs in the SD-EONs based on OF v1.0 [19], as it is a stable version that is widely supported by various OF systems. Note that, the

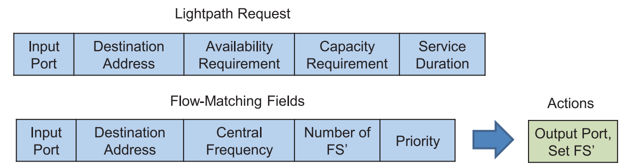


Fig. 5. Principles of OF extensions for enabling ADP.

proposed OF extensions in this work can also easily fit into a newer version of OF, i.e., OF v1.4 [36], which provides more supports on optical ports. Fig. 5 shows the basic principles of our proposed OF extensions for enabling ADP. In order to convey the information for ADP-based lightpath requests, we modify the *PacketIn* message to include the fields in Fig. 5, i.e., *Input_Port*, *Destination_Address*, *Availability_Requirement*, *Capacity_Requirement*, and *Service_Duration*. Here, the *Availability_Requirement* field carries the client's requirement on service availability based on its SLA. Note that the lightpath provisioning can also be triggered by the network operator, and in such a case, OF-C derives the capacity and availability requirements of the lightpath from the client's SLA information and calculates the provisioning scheme with ADP directly. The reason why we allow the client to generate the capacity and availability requirements is that by doing so, we can make the service provisioning more flexible and adaptive.

During lightpath setup, each SD-EON node identifies each lightpath with a flow-entry that consists of flow-matching fields and actions [21]. Note that most of the flow-matching fields in Fig. 5 inherit their definitions from our previous work [23], but we add the *Priority* field to indicate whether the lightpath is for working (i.e., *Priority* $= 2$) or backup (i.e., *Priority* $= 1$). The set of actions associated with the flow-matching fields ensure that when an OF-AG identifies a lightpath with the parameters in them, it will configure its BV-WSS to switch the lightpath's spectra (i.e., a block of FS') from the input port to the desired output port correctly.

C. Implementation of ADP-ABR in OF System

We implement the proposed ADP algorithms in an OF-based SD-EON testbed, which uses the architecture in Fig. 3 and consists of a centralized OF-C and a few stand-alone OF-AGs that are all realized with high-performance Linux servers (ThinkServer RD530). Each OF-AG is programmed based on Open-vSwitch [37] running on Linux, while OF-C is implemented with the POX platform [38]. Since this work focuses on the ADP algorithm design for the control plane of SD-EONs, each OF-AG configures a virtual software-emulated network element but not a real BV-T or BV-WSS.

The working principle of ADP-ABR in the SD-EON testbed is as follows.

- *Step 1:* A lightpath request $LR(s, d, B, B_m, A, T)$ for client traffic (e.g., IP) arrives at an optical core node.
- *Step 2:* The OF-AG on the node encodes the request's information in a *Packet-In* message and sends it to OF-C.
- *Step 3:* OF-C receives the *Packet-In* message, and calculates its provision scheme with ADP-ABR.

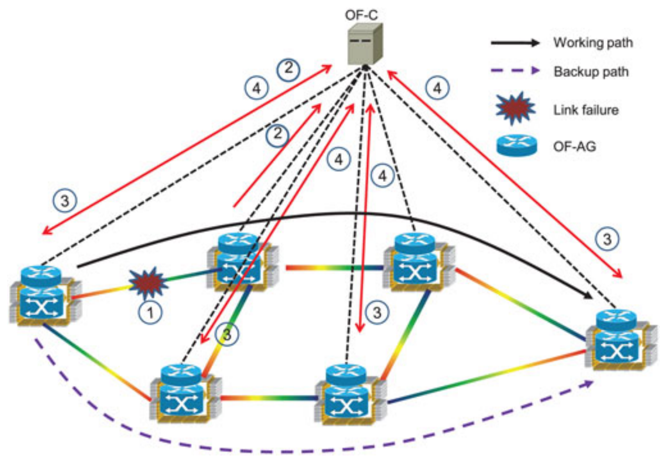


Fig. 6. Procedure of service restoration in SD-EONs.

- *Step 4:* If a feasible scheme can be obtained, OF-C constructs flow-entries for the nodes along the working path. If DPP needs to be used, OF-C also builds the flow-entries for the backup path. If the request cannot be provisioned due to insufficient resources, OF-C instructs the OF-AG on the source node to block it.
- *Step 5:* OF-C distributes the flow-entries to all the related OF-AGs using *Flow-Mod* messages.
- *Step 6:* Each OF-AG parses the received flow-entry, configures its data plane accordingly, and sends a *Barrier-Reply* to OF-C if the lightpath is successfully installed.
- *Step 7:* If all the configurations are completed, the request is successfully provisioned. Otherwise, an error-recovery mechanism is invoked.
- *Step 8:* When a lightpath expires, OF-C instructs the related OF-AGs to release its resources.
- *Step 9:* OF-C performs an ABR operation every T_m.

Note that for the situation where the lightpath provisioning is triggered by the operator, we bypass *Steps 1–2* and utilize the rest of the procedure to realize ADP-ABR. Fig. 6 shows the restoration process in SD-EONs, when a link failure happens.

- *Step 1:* The end nodes of the broken link detect the failure and report it to OF-C using the *Port-Status* message.
- *Step 2:* OF-C identifies the broken link, and finds out the affected lightpaths.
- *Step 3:* For each affected lightpath, if it is provisioned with SPP, OF-C constructs the flow-entries for its backup path and sends them to the related nodes. Otherwise, no action is performed.
- *Step 4:* Each OF-AG parses the received flow-entry, configures its data plane accordingly to apply path switching if necessary, and sends the configuration result to OF-C using a *Barrier-Reply* message.

IV. Experimental Demonstration

A. Experimental Setup

We conduct control plane experiments with the SD-EON testbed discussed in Section III-C. Fig. 7(a) shows the interface of the SD-EON management system that runs on OF-C, which indicates that the SD-EON is configured with 14 stand-alone OF-AGs connected to mimic the NSFNET topology in Fig. 7(b). We assume that each fiber link can accommodate 358 FS' that each has a bandwidth of 12.5 GHz, and its availability is set as $\rho = 0.99$. In the experiments, each OF-AG generates lightpath requests according to the Poisson traffic model, which selects the destination nodes randomly. For each request, the bandwidth requirement B is uniformly distributed within $[25, 500]$ Gb/s, the minimum restoration bandwidth B_m is randomly selected from $[0.5, 0.6, 0.7, 0.8, 0.9] \times B$, and the availability requirement A also follows a uniformly distribution within $[0.9800, 0.9999]$.

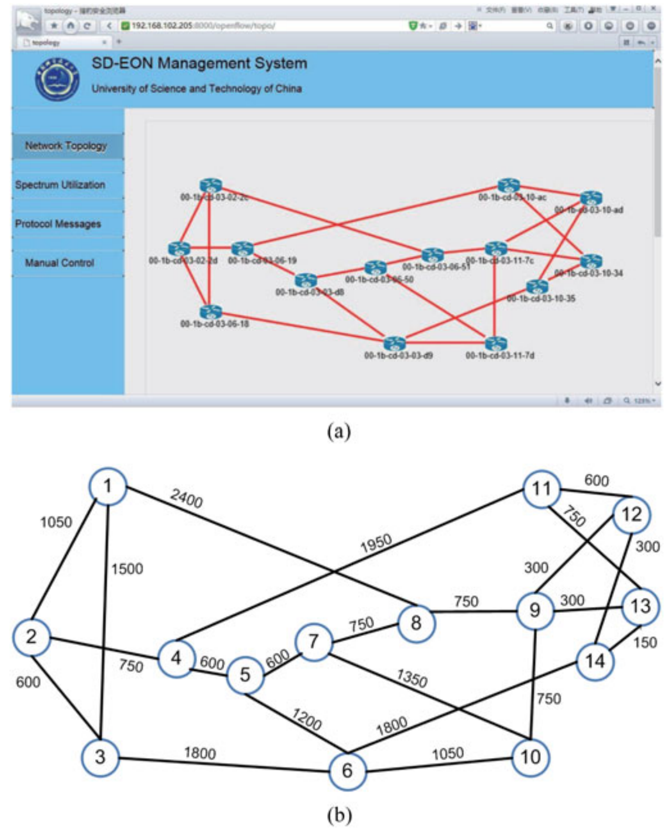


Fig. 7. Network configuration of the SD-EON testbed. (a) Network management system interface on OF-C. (b) Data plane topology based on NSFNET (link lengths in kilometer).

B. Basic ADP Operations

We first perform lightpath provisioning experiments to verify the basic operation of the proposed ADP scheme. Fig. 8 shows the Wireshark capture of a *Packet-In* message from *Node* 9 for the lightpath request that needs to reach *Node* 12. Other parameters are $A = 0.9995$, $B = 248$ Gb/s and $T = 100$ s. The Wireshark captures of the OF messages involved in provisioning such a request with the proposed ADP-ABR are illustrated in Fig. 9. Here, OF-C decides to provision the request with DPP to satisfy its availability requirement and chooses the working and backup paths as 9→12 and 9→13→11→12, respectively. It can be seen that the control plane latency for setting up the

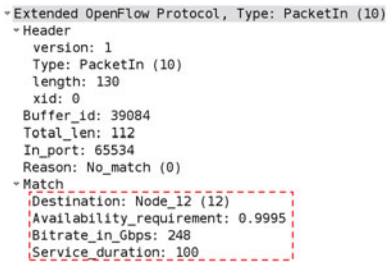


Fig. 8. Wireshark capture of a *Packet-In* message.

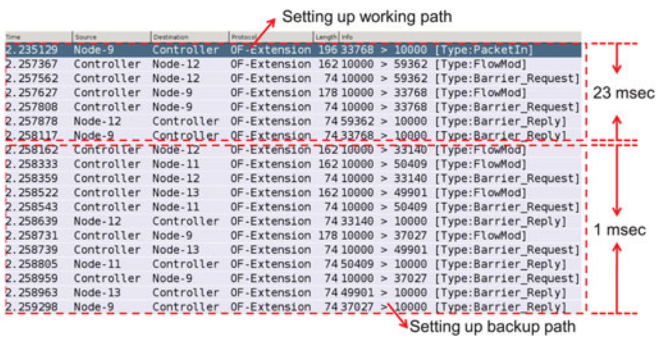
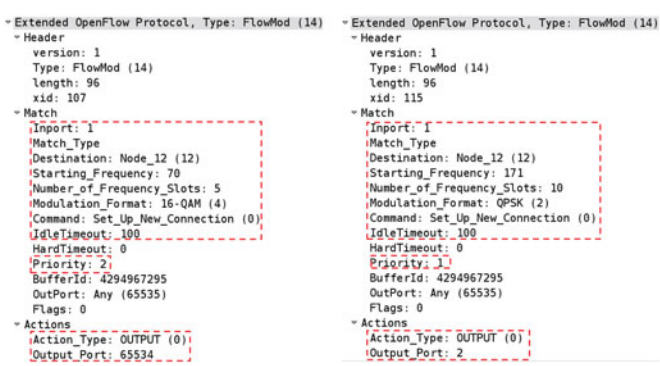


Fig. 9. Wireshark captures of OF messages involved in provisioning a lightpath request with ADP-ABR.



(a) (b)

Fig. 10. Wireshark captures of *Flow-Mod* messages for the DPP scheme. (a) *Flow-Mod* for working path. (b) *Flow-Mod* for backup path.

working path is around 23 ms, and with another 1 ms, the backup path is also assembled. In order to see the details of the working and backup paths, we parse the related *Flow-mod* messages and show them in Fig. 10. We observe that OF-C chooses the modulation-formats for the working and backup paths as 16-QAM and QPSK, respectively. Meanwhile, the numbers of FS' assigned on the two paths are 10 and 5 to satisfy the bandwidth requirement of 248 Gb/s.

C. Long-Term Dynamic Network Operation

We then perform long-term dynamic network operation experiments to compare the performance of the proposed ADP-ABR with existing algorithms. In the experiments, we set a service provisioning period as 1 s, and for ADP-ABR, we try to invoke the ABR operations every $T_m = 40$ s. Note that the service provisioning period in practical optical networks is usually much longer (e.g., in hours or even days). We use such a short provisioning period here to stress-test the proposed SD-EON system and to accomplish the experiments within a reasonable time duration. The benchmark algorithms are ADP without ABR and the traditional SPP and DPP. Fig. 11(a) plots the results on blocking probability. To obtain each data point in Fig. 11(a), the system serves 15000 requests generated by the OF-AGs. We observe that ADP-ABR always achieves better blocking performance than ADP, SPP and DPP. This is because ADP-ABR serves each request with the most efficient protection scheme based on the availability requirement, and can dynamically adjust the protection schemes of in-service lightpaths according to their evolving availability requirements. The blocking performance of ADP is slightly better than that of SPP since we utilize bandwidth-squeezed protection in ADP, which can facilitate more bandwidth-efficient availability-aware provisioning. Due to the high backup resource consumption, DPP provides the highest blocking probability.

To investigate the impact of T_m on the blocking performance of ADP-ABR, we test $T_m \in \{1, 5, 10, 20, 30, 40\}$ s and plot the blocking probabilities in Fig. 11(b). It can be seen that the blocking probability of ADP-ABR increases with T_m. Meanwhile, we also observe that the performance gain on blocking probability becomes smaller when we decrease T_m to below 10 s. Therefore, considering the fact that a smaller T_m means that ADP-ABR needs to trigger the ABR operations more frequently and hence induces more operational complexity, we should carefully decide the value of T_m to balance the tradeoff between algorithm performance and operational complexity.

Fig. 11(c) shows the distribution of protection schemes chosen by ADP-ABR ($T_m = 10$ s) when provisioning the requests initially, which confirms our analysis on the blocking probability results. Basically, ADP-ABR provisions most of the requests with SPP, squeezes restoration bandwidths intelligently and controls the shareability of backup resources well. Table I shows the results on service availability satisfactory ratio when the lightpaths are initially provisioned, which is defined as the proportion of the number of the requests whose availability requirements are satisfied to the total served ones. The results indicate that ADP-ABR and ADP achieve much higher satisfactory ratios than SPP. Here, we still use $T_m = 10$ s for ADP-ABR. The ratio from DPP is comparable to that from ADP-ABR, and if we combine this observation with the results in Fig. 11(a), we can conclude that ADP-ABR can reduce blocking probability effectively without sacrificing the service availability of requests.

D. Link Failure Restorations

We also conduct experiments to evaluate the proposed algorithms' performance on handling link failures. During network operation, we create a link failure on *Link* 6→10, and Fig. 12 shows the OF messages that are involved in restoring a lightpath on 5→6→10, which is protected by SPP. We can see that OF-C gets informed of the failure when receiving a *Port-Status* message from *Node* 6. Then, it instructs the related OF-AGs

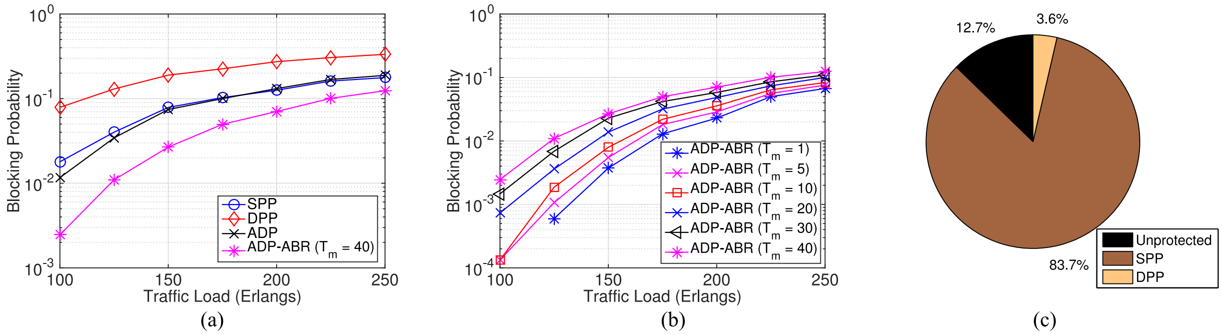


Fig. 11. Experimental results from long-term dynamic network operation. (a) Results on blocking probability. (b) Results on blocking probability (ADP-ABR with different T_m). (c) Distribution of protection schemes in ADP-ABR.

TABLE I
RESULTS ON SERVICE AVAILABILITY SATISFACTORY RATIO

Algorithms	ADP-ABR	ADP	SPP	DPP
Satisfactory Ratio (%)	96.38	96.77	92.36	96.57

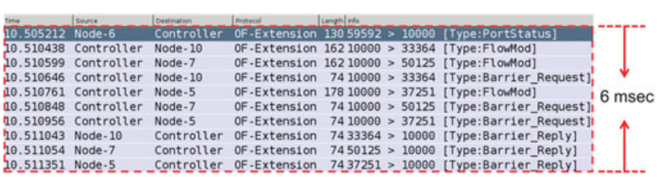


Fig. 12. Wireshark captures of OF messages involved in restoring a lightpath protected by SPP.

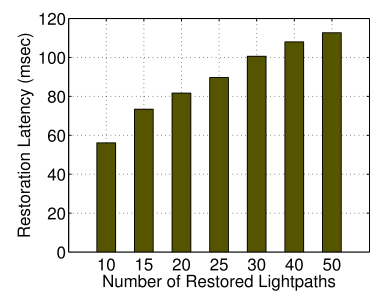


Fig. 13. Results on total latency for restoring lightpaths protected by SPP.

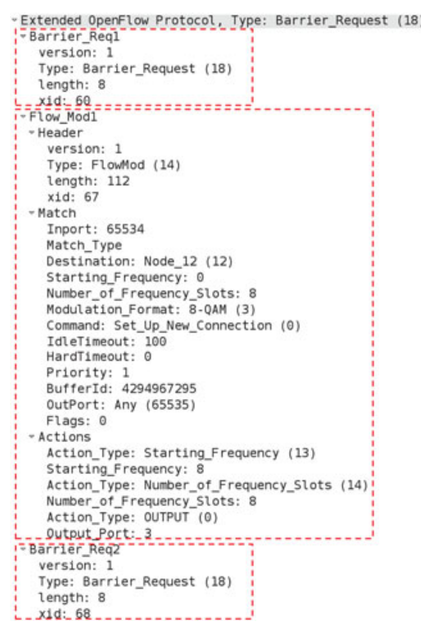


Fig. 14. Wireshark capture of a bundled message.

to switch the lightpath to its pre-calculated backup path, i.e., 5→7→10, to restore the service. The control plane latency for the procedure is only 6 ms, since the path is pre-calculated. Note that here, since the data plane is emulated, we only present the control plane latency but do not consider the latencies from failure detection and switch reconfiguration. Therefore, the real service recovery time in practical networks should be much longer. Meanwhile, since the latencies from failure detection and switch reconfiguration usually only depend on the deployed network elements, the control plane latencies presented here can still be viewed as valid references to show the effectiveness of the proposed system. In our future work, we will include data plane equipment in the testbed and measure the service recovery time for more practical cases.

The experiments also measure the control plane latencies for restoring a few requests simultaneously. The requests are all protected by SPP. We try to restore 10 to 50 requests in a batch and the latency results are plotted in Fig. 13. It can be seen that the total latency increases steadily and slowly, when we increase the number of requests to be restored. It takes 113 ms to restore 50 requests simultaneously. Since there is no dramatic increase on the latency, the results confirm that the scalability of the proposed system is reasonably good. Actually, the system is scalable because we leverage the bundle reconfiguration in OF and develop a message-bundling scheme, which can bundle a set of control messages in one and send it to an OF-AG. Hence, the signaling time for service restoration and lightpath reconfiguration is significantly reduced. Fig. 14 shows an example of the bundled message captured by Wireshark, and we observe that two *Barrier_Request* messages are bundled with one *Flow_Mod* message. These results verify that the SD-EON framework can handle service restoration efficiently. For a request that is protected by DPP, it can be restored automatically by the destination as the backup path is pre-configured with the "1 + 1" scheme, and hence the control plane latency is negligible.

V. Conclusion

This paper investigated flexible ADP in EONs. We first theoretically analyzed the service availability of different protection schemes in EONs, and then proposed an ADP algorithm that can change the path protection scheme to adapt to different service availability requirements. An ABR strategy was also developed as a supplement of ADP to further improve the protection efficiency. Finally, to demonstrate the overall design, we implemented the proposed algorithms in an SD-EON control plane testbed and performed experiments to evaluate their performance. The results showed that the system performed well and the proposed algorithms could reduce blocking probability effectively without sacrificing the service availability of requests.

Note that since the control plane experiments did not incorporate the optical layer implementation of an SD-EON, they might miss certain aspects in practical network operations. However, due to the limited budget, we have difficulties to construct a full-scenario SD-EON experimental testbed now. We will construct a more realistic testbed in our future work.

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