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Availability-aware service provisioning in SD-EON-based inter-datacenter networks

Xiaoliang Chen[1,2] · **Fan Ji**[1,2] · **Shilin Zhu**[1,2] · **Qinkun Bao**[1,2] · **Zuqing Zhu**[1,2]

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Abstract The tremendous transmission capacity and flexible spectrum allocation scheme make elastic optical networks (EONs) one of the most promising infrastructures for constructing the interconnection in datacenter (DC) networks. Meanwhile, as DC traffics exhibit highly dynamic and heterogeneous features, differentiated service provisioning schemes are desired. In this paper, we take the advantage of centralized network control and management provided by the software-defined elastic optical networks (SD-EONs) and investigate availability-aware service provisioning in SD-EON-based inter-datacenter (inter-DC) networks. We first describe the problem of availability-aware service provisioning in SD-EON-based inter-DC networks and present the theoretical analysis for service availability. Then, we propose an availability-aware service provisioning algorithm (ASP) that leverages different path protection schemes to satisfy different service availability requirements. A service downgrading (SD) strategy is also designed as a supplement of ASP to further improve its performance. Simulation results show that the proposed ASP-SD algorithm can effectively improve the spectrum efficiency without sacrificing availability.

Keywords Datacenter networks · Software-defined elastic optical networks · Availability-aware service provisioning

1 Introduction

With the emerging of cloud computing [1], datacenter (DC) networks have attracted intensive research interests. It is known that DC applications, e.g., DC backup and virtual DC migration, usually cause high traffic burstiness and high bandwidth consumption. Therefore, the intelligent network infrastructures that can provide dynamic service provisioning with large transmission capacity are highly desired. Recently, spectrum-sliced elastic optical networks (EONs) that leverage advanced transmission techniques, such as optical orthogonal frequency-division multiplexing (O-OFDM), have been proposed [2]. Compared with traditional fixed-grid wavelength-division multiplexing (WDM) networks that operate on discrete wavelength channels, EONs can set up lightpaths according to the actual traffic demands by assigning a series of spectrally contiguous frequency slots (FS') that have much narrower bandwidth (i.e., 12.5 GHz or less) than the common wavelength channels. This is achieved by utilizing bandwidth variable transponders (BV-Ts) and switches (BV-WSS'). Hence, EONs become one of the most promising building blocks for constructing the interconnection in DC networks [3–5].

Meanwhile, network resilience is always an important topic in optical networks, since a single component failure may cause tremendous data loss. Previously, people have tried to improve the survivability of EONs by leveraging both the path-based and link-based protection schemes [6–10]. The resilience of DC interconnection with EONs was studied in [11], where the authors proposed a cross stratum resilience architecture that can jointly optimize the optical network and DC resource allocation for both primary and backup services. More recently, Ahmed et al. [12] proposed a dynamic restoration scheme with service reallocation in optical cloud assuming that the traffic model is anycast.

✉ Zuqing Zhu
zqzhu@ieee.org

[1] University of Science and Technology of China, Hefei 230027, Anhui, China

[2] Key Lab of Optical Fiber Sensing and Communications (UESTC), Ministry of Education, Chengdu, China

On the other hand, as DC traffics exhibit highly dynamic and heterogeneous features, differentiated service provisioning schemes should be developed. It is known that in practical network operations, network operators usually ensure users' quality of service (QoS) by satisfying their availability requirements specified in the service level agreements (SLAs) [13]. Therefore, it is essential to design efficient availability-aware service provisioning schemes to minimize SLA violation risks while maintaining high resource efficiency. In [14], Zhang et al. proposed to use different path protection schemes to satisfy differentiated availability requirements in WDM networks and designed a theoretical model for availability analysis. They also formulated an integer liner programming (ILP) model and designed several heuristics for achieving availability-aware service provisioning. In order to facilitate backup resource sharing, the authors of [15] defined a feasible sharing degree for each availability class, with which they could ensure that the availabilities of in-service lightpaths will not be violated when adding new requests to the class. A holding-time-aware and availability-guaranteed differentiated provisioning algorithm that exploits the knowledge of connection holding time to determine the shareability of backup resources was proposed in [16]. Nevertheless, none of the studies above addressed the availability-aware service provisioning in EONs. Note that, due to the unique features of EONs, i.e., flexible bandwidth allocation and quality of transmission (QoT) adaptive modulation format selection [17], the design of availability-aware service provisioning algorithms in EONs is much more complicated.

Moreover, in order to realize availability-aware service provisioning design efficiently in EONs, we need to have the knowledge of global resource utilization and all the in-service lightpaths in the network. Hence, centralized network control and management (NC&M) is desired. It is known that software-defined networking (SDN) with OpenFlow [18] can improve optical networks' programmability and manageability by decoupling the data and control planes and implementing a centralized controller [19,20]. The centralized NC&M in SDN fits well with the requirement of availability-aware service provisioning. By considering the combination of SDN and EON [i.e., the software-defined EON (SD-EON) [21,22]], we can design efficient availability-aware service provisioning schemes for inter-DC networks.

In this paper, we study availability-aware service provisioning in SD-EON-based inter-DC networks. We first describe the problem of availability-aware service provisioning in SD-EON-based inter-DC networks and then analyze the service availability theoretically. We propose an availability-aware service provisioning algorithm (ASP) that can leverage different path protection schemes to satisfy different availability requirements. A service downgrading (SD) strategy is also designed as a supplement of ASP to further improve its performance. Numerical simulations indicate that the proposed ASP-SD algorithm can efficiently improve the spectrum efficiency without sacrificing service availability.

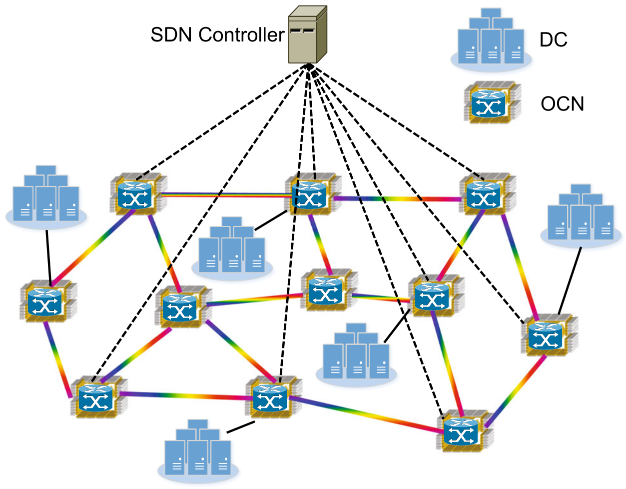

Fig. 1 Architecture of an SD-EON-based inter-DC network

The rest of the paper is organized as follows. We define the problem of availability-aware service provisioning in SD-EON-based inter-DC networks in Sect. 2. Section 3 presents the theoretical analysis for service availability. The details of the proposed ASP-SD algorithm as well as its SD-EON implementation are discussed in Sect. 4. We show the performance evaluations in Sect. 5, and finally, Sect. 6 summarizes the paper.

2 Availability-aware service provisioning in SD-EON-based inter-DC networks

Figure 1 shows the overall architecture of an SD-EON-based inter-DC network. According to the principle of SDN, the network generally consists of two separate planes, i.e., the data plane and control plane. The data plane consists of several geographically distributed DCs, each of which attaches to an optical core node (OCN) in the EON, which realizes the inter-DC data transfers with lightpaths. Meanwhile, by sitting on top of the data plane, the SDN controller facilitates centralized NC&M for efficient resource management.

We model the SD-EON-based inter-DC network as $G(V, E, D)$, where V, E, and D are the sets of nodes, links, and DCs in it, respectively. A lightpath request from DC clients is denoted by $\mathrm{LR}(s, d, B, A, T)$, 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 life-time. For LR, we need to provision it with lightpaths that can satisfy both its bandwidth and availability requirements. Here, when LR is provisioned, its service availability is defined as the proportion of the service-on time T_{on} to the total provision period T, i.e.,

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

Statistically, service availability equals to the probability that LR's service is seen in working at any time in its provision period. Hence, to minimize the SLA violations, a protection scheme will be needed if the availability of a single working path cannot satisfy A. Similar to the previous work in [15], we assume that service availability only relates to link failures, and an LR can be provisioned with an unprotected working path, shared path protection (SPP), or dedicated path protection (DPP).

3 Theoretical analysis on service availability

In this section, we present the theoretical analysis for service availabilities with different protection schemes.

3.1 Unprotected working path

We first define the following notations for calculating the availability of a working path $\mathcal{R}_{s,d}$,

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

The service of an unprotected working path is available when and only when all its links are available. Therefore, the availability is simply obtained as

$$A_L = \rho^{H_w}. \tag{2}$$

3.2 Dedicated path protection (DPP)

If a request is provisioned with both a working path and a dedicated protection path, its service only becomes unavailable when both paths are broken. Hence, the availability is

$$A_L = 1 - (1 - \rho^{H_w})(1 - \rho^{H_p}), \tag{3}$$

where H_p is the hop-count of the protection path.

3.3 Shared path protection (SPP)

The situation of SPP is much more complicated since multiple lightpaths may compete for the same backup resources when multiple link failures happen. Basically, we can denote the lightpaths that share the backup resources with the current one as set $\mathbb{L}$. Then, an LR provisioned with SPP is available when (1) its working path is available or (2) its working path is broken, but its backup path keeps intact and it wins the backup resources when competing with other lightpaths in $\mathbb{L}$. Here, we assume that the lightpaths that share the same backup resources have the equal probability to be restored successfully when failing simultaneously. Therefore, we can obtain the availability of SPP as

$$\begin{aligned} A_L Z = {}& \rho^{H_w} + (1-\rho^{H_w})\rho^{H_p} \Bigg[\rho^{\left(\sum_{i=1}^{|\mathbb{L}|} H_i\right)} \\ & + \frac{1}{2} \sum_{i=1}^{|\mathbb{L}|} (1-\rho^{H_i}) \rho^{\left(\sum_{j=1,j\neq i}^{|\mathbb{L}|} H_j\right)} \\ & + \frac{1}{3} \sum_{i=1}^{|\mathbb{L}|} \sum_{j=1,j\neq i}^{|\mathbb{L}|} (1-\rho^{H_i})(1-\rho^{H_j}) \rho^{\left(\sum_{k=1,k\neq i,j}^{|\mathbb{L}|} H_k\right)} \Bigg], \end{aligned} \tag{4}$$

where $H_i, i \in [1, |\mathbb{L}|]$ is the hop-count of the working path of the ith lightpath in $\mathbb{L}$.

4 Heuristic algorithms

4.1 Availability-aware service provisioning design

Previous studies on ASP were all based on WDM networks, and the algorithms were designed based on the shareability of discrete wavelength channels. This, however, is not suitable for EONs, since they allocate spectrum resources based on spectrally contiguous FS' and the shareability is much more complicated.

In order to address ASP in SD-EON-based inter-DC networks, we design an algorithm based on the aforementioned analysis. Algorithm 1 shows the detailed procedure of the proposed ASP for SD-EON-based inter-DC networks. First of all, *Lines* 1–13 try to serve LR with an unprotected working path while satisfying its availability requirement. Specifically, in *Lines* 1–6, we perform routing, modulation format and spectrum assignment (RMSA) of the working path with shortest path routing and first-fit spectrum assignment. Here, impairment-aware modulation selection is adapted, and we determine the signal's modulation format according to the path's QoT [23,24]. Basically, when the modulation format m is determined, we can convert the request's bandwidth requirement to the number of the required FS' as

$$n = \left\lceil \frac{B}{m \cdot C_{\text{grid}}^{\text{BPSK}}} \right\rceil, \tag{5}$$

where $C_{\text{grid}}^{\text{BPSK}}$ is the transmission capacity that an FS with BPSK modulation format can provide, $m = 1, 2, 3$, and

4 indicate BPSK, QPSK, 8-QAM, and 16-QAM, respectively. *Line* 5 calculates the lightpath's service availability if it is provisioned with an unprotected working path. If the current service availability cannot satisfy the request's requirement, we proceed to *Lines* 14–32, where we switch to the SPP scheme for improving the service availability. Note that *Lines* 18–25 check all the backup FS' reserved for in-service lightpaths and mark one as shareable if it can be used as the request' backup resource under the constraint that the availability requirements of related in-service lightpaths' would not be violated. If the request's availability requirement still cannot be satisfied, we proceed to the DPP scheme as depicted in *Lines* 33–42. Finally, as shown in *Lines* 37–39, if even DPP cannot meet its availability requirement, we still provision the request but mark it as "availability not satisfied" to alert clients on the risk of potential SLA violations.

The complexity for calculating the availability of SPP schemes with Eq. (4) is $O(|\mathbb{LR}|^3)$, where $|\mathbb{LR}|$ is the number of in-service requests and $|E|$ is the number of fiber links in $G(V, E)$. Therefore, the complexity of Algorithm 1 is $O(|E|^2 + |E| \cdot F + |\mathbb{LR}|^4 \cdot F)$, where F is the maximum number of available FS' on a link.

4.2 Service downgrading strategy

Although the aforementioned ASP algorithm can adapt the provisioning schemes intelligently according to requests' availability requirements, the protection solutions it provides can get less efficient when the network status changes. Basically, with Eq. (1), we can obtain the in-service time T_{on} that the network operator should guarantee for LR as

$$T_{\text{on}} = T \cdot A, \tag{6}$$

where A is the availability requirement and T is the total provision period. Hence, if the network operator has already served LR with T_{good} time successfully, i.e., without service disruption, it only needs to ensure $T_{\text{on}} - T_{\text{good}}$ in-service time within the rest $T - T_{\text{good}}$ provision period. Apparently, the availability requirement of LR becomes smaller when T_{good} increases. We define the evolving availability requirement of LR as

$$A_{\text{evl}} = \frac{T_{\text{on}} - T_{\text{good}}}{T - T_{\text{good}}}. \tag{7}$$

Therefore, to further improve the spectrum efficiency, we can downgrade the protection scheme of LR when an error-free service provisioning carries on, while still satisfying its overall availability requirement.

We then design a service downgrading (SD) strategy as the supplement of ASP, and the detailed procedure is shown in Algorithm 2. Basically, we calculate the evolving availability requirement A_{evl} with Eq. (7) and check whether a lower protection scheme (e.g., unprotected to SPP and DPP, and SPP to DPP) can still satisfy A_{evl}. If yes, we downgrade the service to release the redundant backup resources. The

Algorithm 1: Availability-Aware Service Provisioning (ASP) Algorithm

```
Input: Lightpath request $LR(s, d, B, A, T)$, $G(V, E)$, Current
       network status, Set of in-service lightpaths
Output: Provisioning scheme for $LR(s, d, B, A, T)$
1  use the shortest path $\mathcal{R}_{s,d}$ as the working path;
2  determine modulation-format based on QoT on $\mathcal{R}_{s,d}$;
3  calculate $n$ as number of FS' to be assigned on $\mathcal{R}_{s,d}$;
4  if there are enough FS' on $\mathcal{R}_{s,d}$ for $LR$ then
5      calculate current availability $A_L$ with Eq. (2);
6      allocate $n$ contiguous FS' on $\mathcal{R}_{s,d}$ as working;
7      if $A_L \geq A$ then
8          continue;
9      end
10 else
11     mark $LR$ as blocked;
12     continue;
13 end
14 remove links on $\mathcal{R}_{s,d}$ from $G(V, E)$ temporarily;
15 calculate the shortest path $\mathcal{R}'_{s,d}$ in $G(V, E)$ as the backup path;
16 determine modulation-format based on QoT on $\mathcal{R}'_{s,d}$;
17 get $n$ as the number of FS' to be assigned $\mathcal{R}'_{s,d}$;
18 save the current network status as $NS$;
19 mark the backup FS' reserved on $\mathcal{R}'_{s,d}$ as available;
20 for each in-service lightpath $LR'$ that uses FS' on $\mathcal{R}'_{s,d}$ as
   backup do
21     calculate its availability for the case after sharing backup with
       $LR$ using Eq. (4);
22     if the availability of $LR'$ does not satisfy its requirement then
23         mark the backup FS' of $LR'$ as unavailable;
24     end
25 end
26 if there are enough FS' on $\mathcal{R}'_{s,d}$ for $LR$ then
27     calculate current availability $A_L$ with Eq. (4);
28     if $A_L \geq A$ then
29         allocate $n$ contiguous FS' on $\mathcal{R}'_{s,d}$ as backup;
30         continue;
31     end
32 end
33 revert the network status to $NS$;
34 if there are enough FS' on $\mathcal{R}'_{s,d}$ for $LR$ then
35     allocate $n$ contiguous FS' on $\mathcal{R}'_{s,d}$ as backup;
36     calculate current availability $A_L$ with Eq. (3);
37     if $A_L < A$ then
38         mark $LR$ as availability not satisfied;
39     end
40 else
41     mark $LR$ as blocked;
42 end
```

complexity of Algorithm 2 is $O(|\mathbb{LR}|\cdot(|E|^2+|E|\cdot F+|\mathbb{LR}|^4\cdot F))$. Note that Algorithm 2 can either be inserted in between *Lines* 1 and 2 of Algorithm 1, or be invoked independently from Algorithm 1 in a periodic manner. For both cases, we refer to the overall algorithm as ASP-SD.

Algorithm 2: Service Downgrading (SD) for Lightpaths

```
Input: $G(V, E)$, Current network status, Set of in-service lightpaths
Output: Downgraded provisioning schemes for all in-service lightpaths
for each in-service lightpath $LR'$ in the network do
    obtain its instant in-service time $T_{\text{good}}$;
    calculate the evolving availability requirement $A_{\text{evl}}$ with Eq. (7);
    if $A_{\text{evl}} < A$ then
        calculate the availability of a lower protection scheme;
        if the availability still satisfies $A_{\text{evl}}$ then
            downgrade the protection scheme of $LR'$ to the lower one;
            release redundant backup resources;
        end
    end
end
```

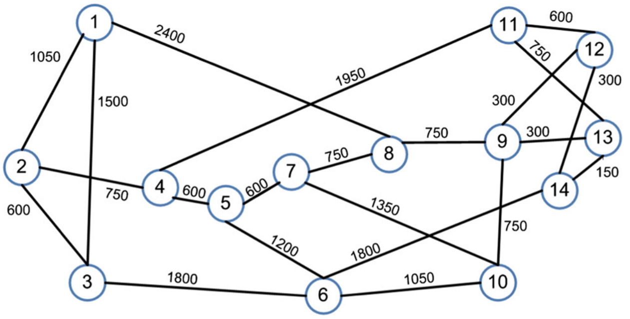

Fig. 2 NSFNET topology used in the simulation

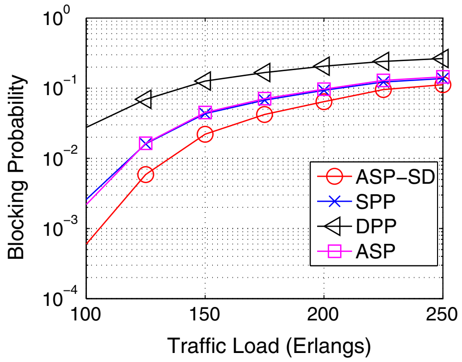

Fig. 3 Results on blocking probability

4.3 SD-EON implementation

With the ASP-SD algorithm described above, we can implement the availability-aware service provisioning in SD-EON-based inter-DC networks as follows.

- **Step 1**: A lightpath request $LR(s, d, B, A, T)$ for DC traffic arrives at an OCN.
- **Step 2**: OCN forwards the request's information to the SDN controller.
- **Step 3**: SDN controller gets the provisioning scheme based on the network status with ASP-SD.
- **Step 4**: If a feasible provisioning scheme can be obtained for the request, SDN controller instructs corresponding OCNs to set up the lightpath.
- **Step 5**: When a lightpath expires, SDN controller instructs the related OCNs to release its resources.
- **Step 6**: SDN controller performs an SD operation by the end of every service provision period.

5 Performance evaluations

We perform simulations on availability-aware service provisioning in SD-EON-based inter-DC networks using the 14-node NSFNET topology shown in Fig. 2. We assume that the SD-EON works in C-band and hence each fiber link can accommodate 358 FS', each of which has a bandwidth of 12.5 GHz. The dynamic lightpath requests are generated by each DC according to the Poisson traffic model with the destination DCs randomly chosen, and their holding times follow the negative exponential distribution. The bandwidth requirement B for each request is uniformly distributed within [25, 500] Gb/s, and the availability requirement A ranges within [0.9800, 0.9999]. Note that in this paper, we set the availability of each link as $\rho = 0.99$.

We compare the performance of the proposed ASP-SD with traditional SPP and DPP that do not consider service availabilities. Figure 3 shows the results on request blocking probability. We can observe that ASP-SD achieves the lowest blocking probability, which is because it can select the most resource-efficient provisioning schemes according to the requests' availability requirements and dynamically adjust them when the network operation goes on. The blocking probability of ASP is similar to that of SPP, while DPP owns the worst blocking performance.

Figure 4 shows the distribution of the provisioning schemes with which ASP-SD serves lightpath requests initially. It can be seen that ASP-SD can choose the provisioning schemes intelligently according to the availability requirements and provision most of the requests with SPP by carefully controlling the shareability of backup spectrum

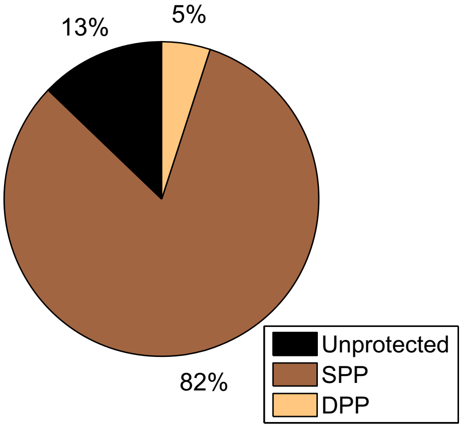

Fig. 4 Distribution of protection schemes in ASP-SD

Table 1 Results on service availability satisfactory ratio

Algorithms	ASP-SD	ASP	SPP	DPP
Satisfactory ratio (%)	96.58	96.70	92.25	96.57

resources. Table 1 presents the results on service availability satisfactory ratios from different algorithms. Here, availability satisfactory ratio is defined as the percentage of the requests whose availability requirements are satisfied initially to the total provisioned ones. We can observe that ASP-SD achieves the similar satisfactory ratio with ASP and DPP, which is much higher that that of SPP. Hence, by combining the observations in Figs. 3 and 4, we can conclude that ASP-SD can improve the spectrum efficiency effectively without sacrificing service availability.

6 Conclusion

This work studied availability-aware service provisioning in SD-EON-based inter-DC networks. We first presented the problem definition for availability-aware service provisioning in SD-EON-based inter-DC networks and developed a theoretical model for analyzing the service availability. Then, the ASP-SD algorithm that could leverage different path protection schemes and exploit the service downgrading strategy was described. Simulation results indicated that the ASP-SD algorithm could effectively improve the spectrum utilization without sacrificing service availability.

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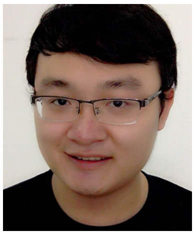
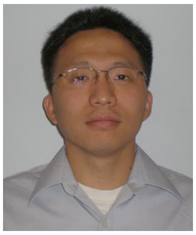
Xiaoliang Chen received the B.S. degree from the North University of china, Taiyuan, China, in 2011. He is currently working toward the Ph.D. degree at the University of Science and Technology of China, Hefei, China. His research focuses on next-generation Internet, multimedia networks, and green networks.

Fan Ji is a master student at the School of Information Science and Technology, University of Science and Technology of China, Hefei, China. Her research interests include optical networks and green networks.



Shilin Zhu is an undergraduate student at the School of Information Science and Technology, University of Science and Technology of China, Hefei, China. His research interests include optical networks and bioinformatics.

Qinkun Bao is an undergraduate student at the School of Information Science and Technology, University of Science and Technology of China, Hefei, China. His research interests include optical networks and software-defined networks.



Zuqing Zhu received the B.S. degree from the Department of Electronic Engineering and Information Science, University of Science and Technology of China, in 2001, and the M.S. and PhD degrees from the Department of Electrical and Computer Engineering, University of California, Davis, in 2003 and 2007, respectively. In July 2007, Dr. Zhu joined the Service Provider Technology Group of Cisco Systems, San Jose, as a senior researcher. In Cisco, he worked on research and development of wideband access routers for hybrid fiber-coaxial (HFC) cable networks and passive optical networks (PON). In January 2011, Dr. Zhu joined the University of Science and Technology of China (USTC), where he is now an Associate Professor. He has published more than 130 papers on the peer-reviewed journals and conferences of IEEE, IEE, and OSA. Dr. Zhu is an editorial board member of IEEE Communications Magazine, Journal of Optical Switching and Networking (Elsevier), Telecommunication Systems Journal (Springer), European Transactions on Telecommunications (Willey), and etc. He has received the Best Paper Awards from the IEEE International Conference on Communications (ICC) 2013, the IEEE Global Communications Conference (GLOBECOM) 2013, and the IEEE International Conference on Computing, Networking and Communications (ICNC) 2014. He is a Senior Member of IEEE and a Senior Member of OSA.