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Gradual Migration of Co-Existing Fixed/Flexible Optical Networks for Cloud-Fog Computing

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ABSTRACT Fog computing emerges as a great candidate to mitigate the unsolved problems of cloud computing. Data migration between fog nodes and datacenters is placing huge bandwidth requirements on substrate optical networks. To increase network capacity and to improve network flexibility, broad attention has been given to flexible-grid technology. This paper addresses the issue of how to migrate substrate optical networks from the fixed-grid network era to the flexible-grid network era gradually, due to the unbearable capital expenditure and service stability. First, we model the network migration and elucidate the upgrade probability by calculating the node demands for upgrading. Then, based on the upgrade probability, three schemes are proposed to construct Potential Upgrade Nodes Group (PUNG). Besides, to maintain the traffic stability, a Migration-aware Service Provisioning (MSP) scheme is proposed based on PUNG. Numerical results illustrate that the proposed MSP scheme can effectively enhance the traffic stability compared to Non-migration-aware Service Provisioning (NSP) scheme, and the connection interrupted ratio is excessively reduced.

INDEX TERMS Measurable migration, flexible optical networks, potential upgrade nodes group (PUNG), migration-aware service provisioning (MSP) scheme.

I. INTRODUCTION

Dr iven by the rapid development of the Industrial Internet and the large-scale commercialization of 5G, edge computing has developed fiercely [1]. By deploying computing, storage, and applications at the edge of the network, edge computing can meet users' requirements in terms of agile connectivity, real-time business, and data optimization [2]. Cloud computing has the advantages in processing and analyzing full-scale, non-realistic, and long-term data [3]. However, it is also with shortages, such as with unreliable latency and mobility support [4]. The low-latency and distributed features of fog computing are complements to cloud computing. The cooperation of cloud computing and fog computing can provide users with higher quality services [5]. Especially enabled by network function virtualization [6] and block chain technique [7], cloud computing and fog computing can achieve lower cost and be more intelligent. The communication between fog nodes and cloud nodes are carried by substrate optical networks. As these services are more flexible and require higher bandwidth. Traditional fixed-grid optical networks cannot satisfy their requirements. The substrate network nodes have to be upgraded.

The services between fog nodes and cloud nodes are carried by substrate optical networks. As these services are pretty dynamic and require high bandwidth, traditional substrate carrier fixed-grid optical networks cannot satisfy these requirements [8]. It can deteriorate the network service quality. Thus these substrate nodes have to be upgraded to solve this issue. Advanced optical transmission solutions have been continuously explored to increase the network capacity [9]. Specifically, flexible-grid technique has been extensively studied due to its high capacity and extraordinary flexibility [10], [11]. Unlike conventional fixed-grid optical network architectures, the emerging optical network architecture based on

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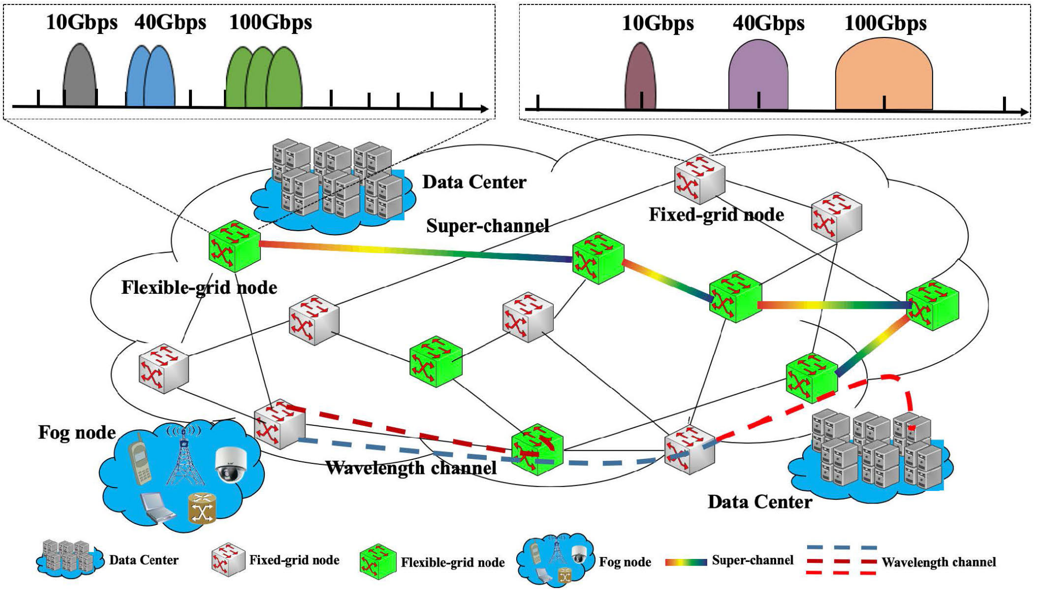

FIGURE 1. Migration scenario: several nodes have been upgraded to flexible-grid nodes.

flexible-grid technique can curve the coarse granularity and rigid spectrum assignment constraints [12], [13], and can provision lightpath with on-demand fine-grained spectrum slots [14]. Due to the upcoming advantages and mature techniques, flexible-grid optical networks are the most promising candidate for the next generation optical networks [15]. Due to the Capital Expenditures (CAPEX), Operation Expenditures (OPEX) and complex network management [16], comprehensive deployment of flexible-grid optical networks one-time is unrealistic. In this situation, choosing several important nodes to upgrade step by step, while keeping other fixed-grid nodes, will be favoured by network operators. This gradual evolution from fixed-grid optical networks to flexible-grid optical networks is called migration, which will be much more economical for upgrading. As illustrated in Fig.1, the green nodes represent the upgraded flexible-grid nodes, and the white nodes are the fixed-grid nodes. If all the equipments along a path are upgraded to be flexible, a super-channel can be set up to satisfy the service requirements. The upgraded path is shown in a colourful line. If the flexible-grid nodes and the fixed-grid nodes are coexisting along a path, the super-channel cannot be set up. Considering the CAPEX and OPEX, it is impossible for upgrading all the nodes to be flexible. Thus we design a node upgrade probability to select the nodes that should be upgraded first.

Most existing migration algorithms focus on the network planning [17]–[19], how to upgrade the substrate optical devices [20]–[23], and routing and spectrum allocation (RSA) algorithms in fixed-grid and flexible-grid co-exist optical networks [23], [24]. Pastorelli *et al.* studied various migration options from fixed-grid optical networks to flexible-grid optical networks and discussed the different impacts on expense [17] and flexibility issues [18]. Christodoulopoulos *et al.* investigated more details on physical layer constraints planning from fixed-grid optical networks to flexible-grid optical networks [19]. In the previous works [20], [21], the problem on when should the optical networks be upgraded to flexible-grid optical networks [20] and how should they be upgraded [21] have been discussed. The RSA algorithm has been studied in fixed-grid and flexible-grid co-existing optical networks [24]. Zhang *et al.* designed a multi-path RSA algorithm in fixed-grid and flexible-grid co-existing optical networks based on the split spectrum technique [23].

Although the migration problem has been studied in several aspects, there are several main problems left for studying. First, few of the studies have modelled a measurable scenario to describe the migration process from fixed-grid optical networks to flexible-grid optical networks. Second, the traffic stability issue that how to maintain the stability of network traffic at an acceptable level when the nodes are gradually upgraded has not been studied.

When the substrate network begins to be migrated(either be upgraded the entire ROADMs [21] or be upgraded the WSSs in ROADMs [22]), existing services in the network might be affected, which will cause the loss of traffic. For mission-critical services, it becomes extremely serious. It seems that based on the extended protection techniques, stable connections can be established for services migration scenario [25]. In addition, they have the ability to resist connection interruption with a pair of working and protection paths [26]. However, the scheme directly derived from the traditional survivable protection scheme is unaware of the migration procedure, and it can hardly handle the situation where the replacement of node facilities in optical networks damages the network connectivity and interrupts the running services.

A. CONTRIBUTION STATEMENTS

In this paper, we focus on the migration issue that when the nodes need to be upgraded from fixed-grid to flexible-grid, and how to maintain the service stability during the migration process. The main contributions of this paper are summarized as follows:

- We formulate the migration process and design a Potential Upgrade Nodes Group (PUNG) to measure the migration process to select the nodes scheduled for upgrade.
- A novel Migration-aware Service Provisioning (MSP) algorithm is proposed based on Potential Upgrade Nodes Group to cope with the traffic stability issue.

B. PAPER ORGANIZATION

This paper is organized as follows. In Section 2, we model the measurable migration and give the definition of upgrade probability, then we design PUNG to realize the management of migration procedures. A Migration-aware Service Provisioning (MSP) scheme with Candidate Migration-aware Routing Pairs (CMRP) algorithm based on PUNG is proposed in Section 3. In Section 4, we evaluate the performance of the measurable migration and compare the proposed MSP scheme with the Non-migration-aware Service Provisioning (NSP) scheme. Finally, we conclude the paper in Section 5.

II. MIGRATION MODEL

To realize a measurable migration, we begin by modelling the substrate network, and explaining the spectrum constraints for co-existing fixed/flexible optical networks. Next, We define the upgrade probability to describe the node requirement for upgrading. In particular, to schedule the sequence of fixed-grid nodes to be upgraded, we design a Potential Upgrade Nodes Group (PUNG).

A. NETWORK NOTATIONS

There are two notations on network model for the migration, physical network $G(N, E, f)$ and requests $R(S, D, B)$.

- $G(N, E, f)$ indicates the substrate optical networks, where fixed-grid nodes and flexible-grid nodes coexist. N is the set of nodes and E is the set of links. $f(i, j)$ is the spectrum bandwidth of each link, and (i, j) stands for any link in set E, which denotes a link from node i to node j, $(i, j) \in N$.
- $R(S, D, B)$ denotes a request, S represents the source node of the request, and D is the destination node of the request. B is the bandwidth requirement, and the guard band is included.

B. SPECTRUM CONSTRAINS

Compared with the fixed-grid technology, two features can be concluded from flexible-grid technology based on elastic optical networks, whose rigid wavelength is further divided into finer spectrum slots, and light path is established by provisioning a certain number of consecutive spectrum slots. However, there are two spectrum constrains being assumed as follows:

- Spectrum contiguity constraint: allocating the same spectral resources on each link along the routing path;
- Spectrum continuity constraint: the spectrum slots allocated on the routing path must be consecutive.

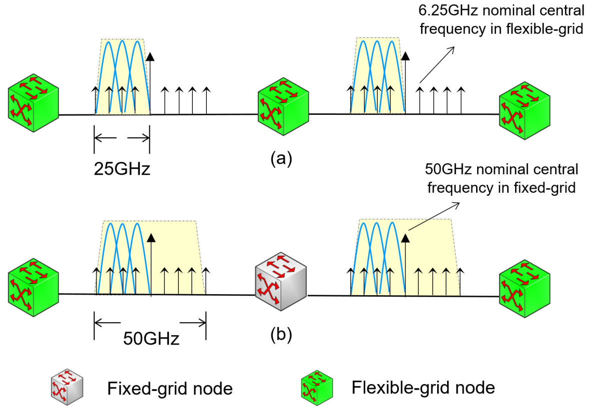

FIGURE 2. Spectrum allocation: (a) lightpath through the nodes those are all upgraded nodes; (b) lightpath goes through the fixed-grid node.

Except for the above two constraints, spectrum backward compatibility constraint also plays an important role in spectrum allocation during the measurable migration, since fixed-grid nodes and flexible-grid nodes utilize different technologies and require different reconfigurable optical add/drop multiplexers (ROADMs):

- Spectrum backward compatibility constraint: spectrum allocation must meet the spectrum constraint of the previous technology, such as fixed-grid technology and the elastic super-channel, which can only be established between adjacent upgraded flexible-grid nodes.

Figure 2 shows two scenarios of co-existing fixed-grid nodes and flexible-grid nodes to illustrate the three spectrum constraints when allocating spectrum resources for services, especially the spectrum backward compatibility which means that the elastic super-channel can only be established between adjacent upgraded flexible-grid nodes. In Figure 2, the wavelength of the fixed-grid node is 50 GHz, and the spectrum granularity of flexible-grid node is 6.25 GHz. Figure 2 (a) depicts a lightpath, where all the flexible-grid nodes are there. It can be seen that the whole lightpath just occupies 25 GHz spectrum resources. Figure 2(b) shows a lightpath, where the source node and the destination node are flexible-grid nodes, and the intermediate node is a fixed-grid node. It can be seen that the link from a flexible-grid node to a fixed-grid node needs to be assigned 50 GHz spectrum, and the link from a fixed-grid node to a flexible-grid node also needs to be assigned 50 GHz spectrum resource. The reason is that the switching granularity of the flexible-grid node cannot be less than 50 GHz. From the comparison, it can be noted that when flexible-grid nodes and fixed-grid nodes coexist, the required spectrum resource will be different if a lightpath passes through a fixed-grid node.

C. UPGRADE PROBABILITY

In previous investigations, we find that different fixed-grid nodes have different necessary levels to be upgraded to flexible-grid nodes, and we should consider many factors, such as network bottleneck, network load, traffic profile, network topology and so on [21]. The different selection of upgraded nodes can achieve various performance. To make the migration process manageable, we define the term of upgrade probability to accurately describe the node requirement for upgrading, during optical network migrating from fixed-gird to flexible-grid. Normalized factor p_i represents the upgrade probability of node i.

As the basis of the measurable migration, the upgrade probability is evaluated by the following two aspects. One is self-influence of a node, exampled by its traffic load, named intra-influence, and denoted as u_i. The other is the interaction between the node and its adjacent node, considering the link connection between a pair of adjacent nodes. Apparently, the influence from the upgraded nodes has an impact on the selection of the nodes which are to be upgraded, because a high bandwidth and spectrum-efficient super-channel can only be established between two adjacent flexible-grid nodes as shown in Fig. 1. v_i is used to represent the interaction that has a close relationship with the connectivity, called the inter-influence of nodes. Hence, the definition of formula (1) consisting of u_i and v_i is as follows,

$$p_i = \alpha \cdot u_i + \beta \cdot v_i, \tag{1}$$

where α and β are influenced parameters of the intra-influence and the inter-influence, and $\alpha + \beta = 1$.

On intra-influence u_i, traffic distribution is regarded as the most vital factor. Based on this, plenty of network information, such as network load, network bottlenecks, can be included. In order to clarify the migration model, we formulate u_i with the traffic of node i in formula (2). t_i and T_{total} represent the traffic volume of node i and the sum of the traffic of all nodes, respectively.

$$u_i = \frac{t_i}{T_{total}} \tag{2}$$

The inter-influence v_i is divided into the influence of regional traffic and the influence of regional flexibility. T_{adj} signifies the sum of the traffic from the adjacent nodes i and denote $pair(i, j)$ to describe the influence of flexibility between node i and node j. Therefore, v_i is formulated to describe the inter-influence by formula (3). d_i is the degree of node i, and the parameter γ denotes the influence coefficient of the regional traffic parts whose boundary is from 0 to 1.

$$v_i = \gamma \cdot \frac{t_i}{T_{adj}} + (1-\gamma) \cdot \frac{\sum_{d_i} pair(i, j)}{d_i} \tag{3}$$

With three variable parameters α, β and γ in the formulation, we are not able to decide which nodes should be upgraded from fixed-grid to flexible-grid. Then four solutions are proposed to investigate the procedure to manage the calculation of nodes upgrading probability, and they are separated into two classes:

- Self-influence Dominant (SD): Upgrade probability is calculated with the dominant part of intra-influence, such as setting $\alpha = 0.8$ and $\beta = 0.2$. Wherein, SD-Flexibility (SD-F) represents that the influence of regional flexibility is more important than regional traffic. It means that γ must be small enough to highlight the influence of regional flexibility, such as $\gamma = 0.2$. SD-Traffic (SD-T) indicates the influence of regional traffic is more important than regional flexibility.
- Inter-influence Dominant (ID): Upgrade probability is calculated with the dominant part of inter-influence, such as setting $\alpha = 0.2$ and $\beta = 0.8$. Wherein, ID-Flexibility (ID-F) and ID-Traffic (ID-T) signifies the ratio of the regional flexibility and the ratio of the regional traffic in the inter-influence portion is larger, respectively.

D. POTENTIAL UPGRADE NODES GROUP (PUNG)

In order to schedule the migration, especially, to upgrade the sequence of fixed-gride nodes, we design a Potential Upgrade Nodes Group (PUNG) which determines the nodes order to be upgraded from fixed-grid optical networks to flexible-grid optical networks following their upgrade probabilities. Three PUNG construction schemes which have significant influence on service path establishment during the measurable migration are proposed:

- Maximum Value Scheme (MVS) -The highest upgrade probability nodes will be chosen to be upgraded firstly. The node with high upgrade probability may have an urged demand for being upgraded to flexible-grid, resulting in a positive impact on the upgrade performance.
- Connected Nodes Scheme (CNS) - The connected nodes with the high upgrade probabilities will be chosen first to be upgraded. Apart from the benefits from the nodes with high upgrade probability, the elastic lightpath connected by two adjacent nodes will improve the network performance obviously.
- Largest Weighted Link Scheme (LWLS) - Calculating the upgrade probabilities of the link's terminal nodes, and selecting the link whose upgrade probability of pair of terminal nodes is the largest as the largest weighted link.

III. MIGRATION-AWARE SERVICE PROVISIONING SCHEME

In this section, a novel Migration-aware Service Provisioning (MSP) scheme based on PUNG is proposed to cope with the traffic stability issue during the measurable migration from fixed-grid to flexible-grid in optical networks. It can provide high quality service and reduce the connection interruption. This section consists of three parts. First, an example is presented to illustrate the traffic stability issue. Then, the MSP scheme is proposed based on PUNG. Last, a case study is presented to illustrate the comparison of the MSP scheme and the Non-migration-aware Service Provisioning (NSP) scheme in the measurable migration.

A. TRAFFIC STABILITY

As illustrated in Fig. 3, there is a network migration scenario where four nodes have already been upgraded to flexible-grid. Fixed-grid nodes and flexible grid nodes are co-existing in the optical networks. Three lightpaths can be established from the source node A to the destination node L,

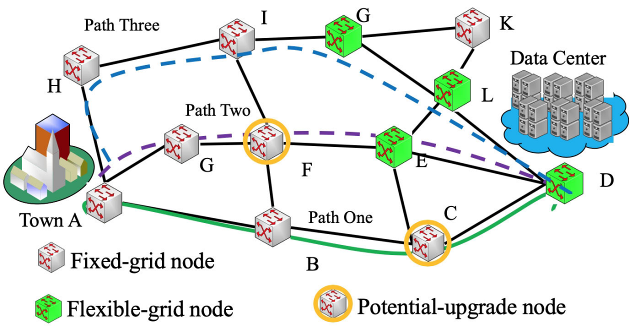

FIGURE 3. Migration scenario with traffic stability issue.

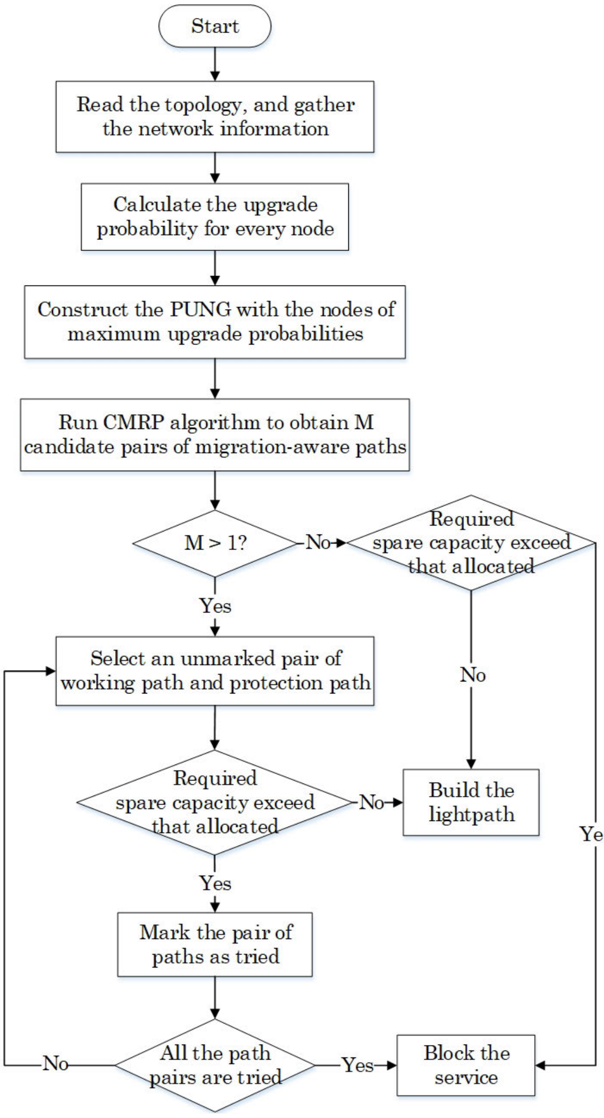

FIGURE 4. Flowchart of MSP scheme.

i.e. the lightpath A-B-C-D, the lightpath A-G-F-E-D, and the lightpath A-H-I-G-L-D. One of them is the most promising candidate path to carry the service from node A to node L. When fixed-node F and fixed-node C are planned to be upgraded, the lightpath A-B-C-D and the lightpath A-G-F-E-D will be broken up when the node facilities are replaced, while the other path A-H-I-G-L-D, will not be affected. Some traffic losses will be caused if we route the path A-G-F-E-D or the path A-B-C-D during network migration. It means we can maintain the level of traffic stability during the network migration period. Thus, in this paper, the problem of "how to resist the traffic losses caused by connection interruption during the migration" can be solved by a migration-aware pair of primary and backup paths. Compared with the existing technologies, which cannot easily differentiate the paths which have the risk to be damaged during the measurable migration, a novel service provisioning scheme which can select a pair of migration-aware primary and backup paths is urgently desired.

Algorithm 1 Candidate Migration-Aware Routing Pairs (CMPR)

```
KSP algorithm is allocated to find K-shortest paths.
while the candidate path ($k > 0$) do
    Gather the paths in a working path set $V(x_n)$ for $x_n \in x_1, x_2, \ldots, x_k$ and a protection path set $V(y_n)$ for $y_n \in y_1, y_2, \ldots, y_k$, respectively.
    for each working path $x \in V(x_n)$
        for each protection path $y \in V(y_n)$
            Make a pair of working path $x$ and protection path $y$.
            if the pair is PUNG disjoint then
                Mark the pair as a candidate pair for MSP.
            end if
        end for
    end for
end while
```

B. MIGRATION-AWARE SERVICE PROVISIONING SCHEME

To achieve the objective that resists connection interruption with a migration-aware pair of primary path and protection path, we propose a Migration-aware Service Provisioning (MSP) scheme with Candidate Migration-aware Routing Pairs (CMRP) algorithm to provide high-quality service. The proposed migration scheme includes three stages. The first stage is to model the measurable migration, as the MSP scheme is based on PUNG, in which we need to analyze the network state, to evaluate the upgrade demands of fixed-grid nodes, and to calculate upgrade probability. Then based on a constructing strategy, we select the corresponding fixed-grid nodes to construct a PUNG. The second stage is to calculate the route of the candidate paths. This stage adopts the CMPR algorithm to calculate k shortest path ($k = 3$ in the simulation) as the migration-aware candidate working paths and the candidate protection paths for the requests. Then two paths are selected as a pair of primary path and protection path. These two paths must be PUNG disjoint. The definition of PUNG disjoint is that each node of the two selected paths is not included in the same PUNG. In other words, when the nodes in one selected path belong to a PUNG, the nodes

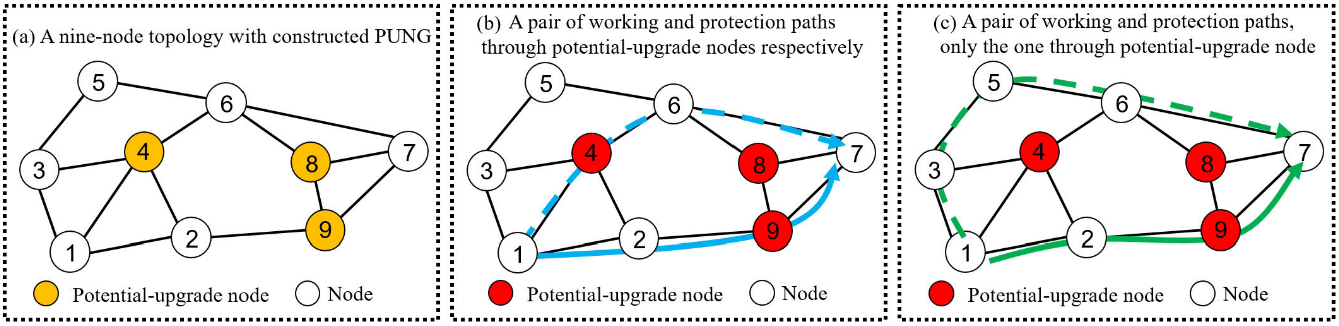
(a) A nine-node topology with constructed PUNG
(b) A pair of working and protection paths through potential-upgrade nodes respectively
(c) A pair of working and protection paths, only the one through potential-upgrade node

FIGURE 5. An illustration example: (a) A 9-node topology; (b) The NSP scheme; (c) The MSP scheme.

in other selected path are not included in this PUNG at the same time. The third process is service connection establishment, which reserves the spectrum resources for the candidate pairs of selected migration-aware working and protection paths. And, establishing a pair of primary and backup paths whose spectrum resources are available and costless. For more details of scheme MSP, please refer to Fig. 4.

Fig. 5 illustrates how to provision a high-quality service with MSP scheme. A 9-node coexisting network topology is presented in Fig. 5(a) to simulate the network migration process. According to their upgrade probabilities, node 4, node 8 and node 9 are selected to form PUNG with MVS. As shown in Fig. 5(b), two paths can be established from node 1 to node 7, where the primary path is 1-2-9-7 and the backup path is 1-4-6-7 by NSP scheme, for its unawareness of migration. From Fig. 5(c), MSP scheme selects the pair of path 1-3-5-6-7 and path 1-2-9-7, instead of the former pair. The different pairs of primary and backup paths between the NSP scheme and MSP scheme have been shown, comparing Fig. 5(b) with Fig. 5(c). In Fig. 5(b), we can see clearly that the NSP scheme does not make a difference between the nodes in PUNG, i.e. the lightpath 1-4-6-7 is established through node 4 while the lightpath 1-2-9-7 is established through node 9, and they would break, if the potential upgrade nodes start to be upgraded to flexible-grid nodes. What is worse, the service provisioned by this pair of paths will be interrupted. Fig. 5(c) shows that the primary and backup paths are disjoint, and one of them does not pass through an upgrade node. In this way, MSP scheme is suitable for network migration and it can provision high-quality service maintaining reliable connections.

IV. NUMERICAL RESULTS

In this section, the simulation setup is introduced, then we describe the performance of the measurable migration in detail, and compare the results of the proposed MSP scheme with the NSP scheme.

A. SIMULATION SETUP

The simulation is carried on an Intel Core PC equipped with a 3.6GHz CUP and 16 GBytes RAM. National Science Foundation Network (NSFNet) is allocated as the substrate network shown in Fig. 6, where 14 nodes with corresponding cities and 22 links with 5000GHz spectrum resources, to evaluate the performance. The simulation platform is set up using JAVA language. 100,000 connections are simulated each time, and we run the simulation for ten times. The simulation results were the average of these ten times of simulation results. These connections are generated following the Poisson process, and their bandwidth requirements follow uniform distribution between 40Gbps, 100Gbps, 200Gbps, and 400Gbps. For different bandwidth requirements, the corresponding number of slots is shown in Table. 1 [20], [21]. For fixed-grid technology, we consider the spectrum bandwidth of 50 GHz as a lambda; for flexible-grid technology, a slot of the frequency grid is 12.5GHz. In addition, in this paper, the non-uniform traffic model, where the traffic between two nodes depends on not only their populations but also the distance between them, has been considered.

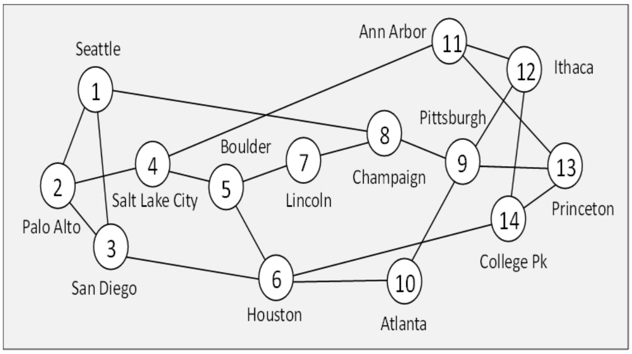

FIGURE 6. NSFNET topology.

TABLE 1. Chennal in co-existing fixed/flexible grid networks.

	Fixed Grid		Flexible Grid	
Channel	Spectrum	lambda	Spectrum	slot
40Gbps	50GHz	1	25GHz	2
100Gbps	50GHz	1	37.5GHz	3
200Gbps	100GHz	2	75GHz	6
400Gbps	200GHz	4	125GHz	10

During the measurable migration, firstly, we have a discussion about the four solutions of parameter α, β, and γ, shown in Fig. 7. Then, we contrast the four solutions, such as SD-T, SD-F, ID-T, and ID-F, with each other in Fig. 8.

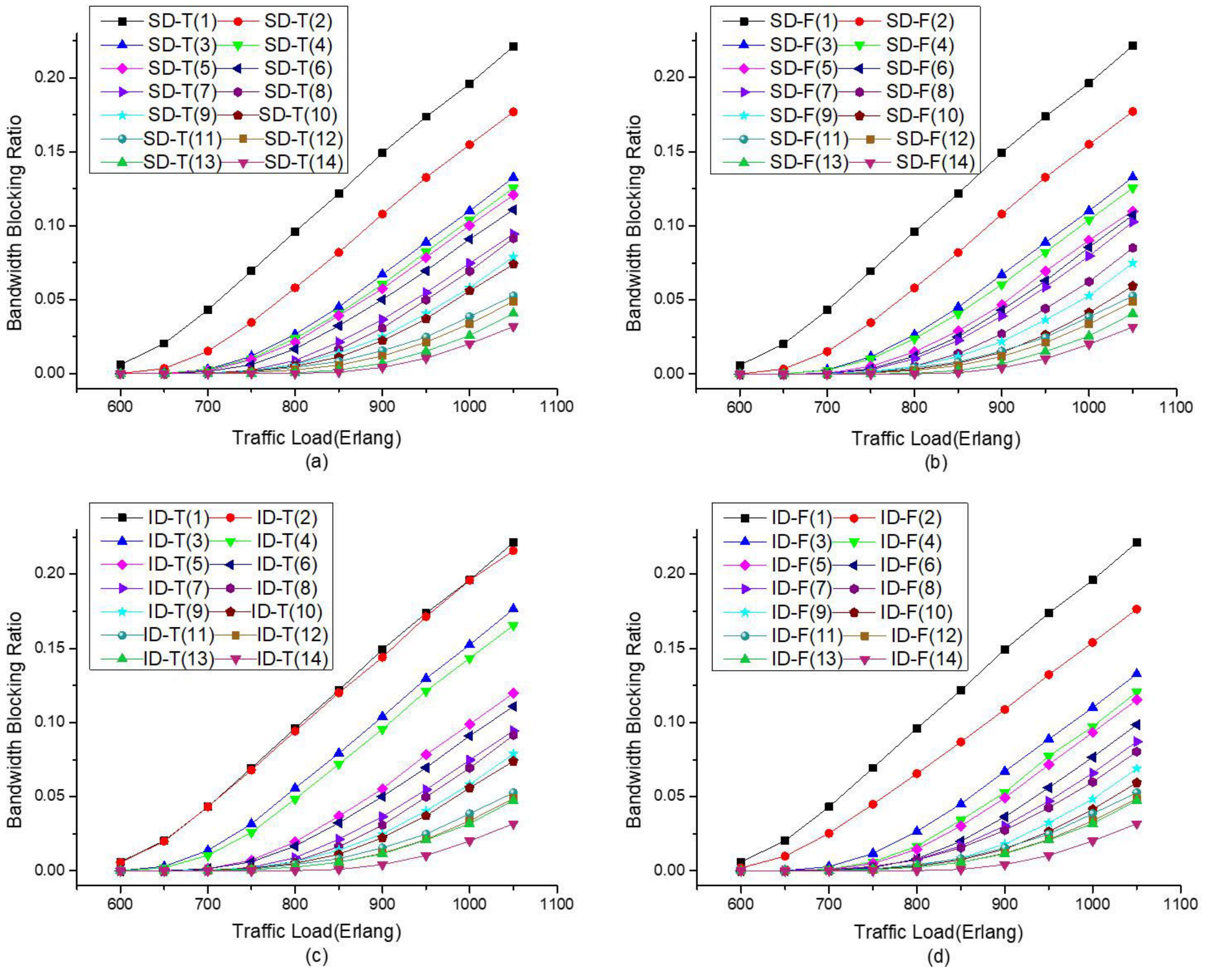

FIGURE 7. **BBR of different parameter solutions with different flexible nodes: (a) SD-T parameter solution; (b) SD-F parameter solution; (c) ID-T parameter solution; (d) ID-F parameter solution.**

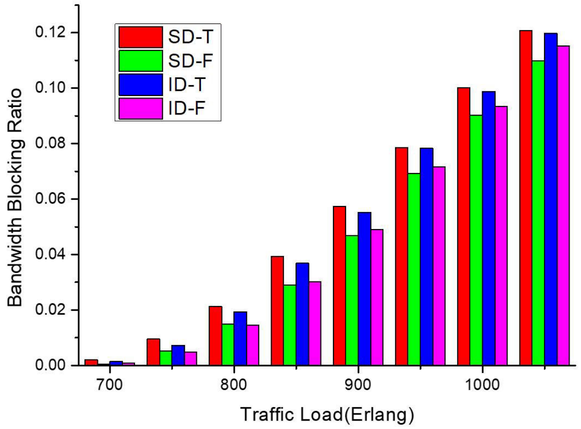

FIGURE 8. **BBR of four parameter solutions when 5 nodes are upgraded.**

The selection of parameter α, β and γ, has been introduced in Sec. II. A. Next, we assess the performance of measurable migration with different PUNG schemes. Finally, the proposed MSP scheme is evaluated compared with the NSP scheme.

In this part, three indexes are adopted to evaluate the performance of the migration scheme, Bandwidth Blocking Ratio (BBR), Bandwidth Gain Per Upgraded Node (BGP), and Connection Interrupted Ratio (CIR).

B. RESULTS AND DISCUSSION

We start by examining the performance and present the results. In Fig. 7, Fig. 8 and Fig. 9, the measurable migration is performed with different parameter solutions and different PUNG schemes.

In Fig. 7, we can see the BBR performance of different solutions, SD-T, SD-F, ID-T, and ID-F. SD-T and SD-F are the upgrade solutions that give priority to self-influence dominant of the nodes. ID-T and ID-F are the upgrading solutions that give priority to the inter-fluence dominant of the nodes. SD-T and ID-T solutions mean the traffic of a domain is more important than the flexibility. SD-F and ID-F mean that flexibility is more important than the traffic. The detailed parameter settings of these solutions are described in Section II. We can note that BBR of all the solutions increase with the increment of the traffic load. For the same traffic load, the BBR is decreased further with the increasing

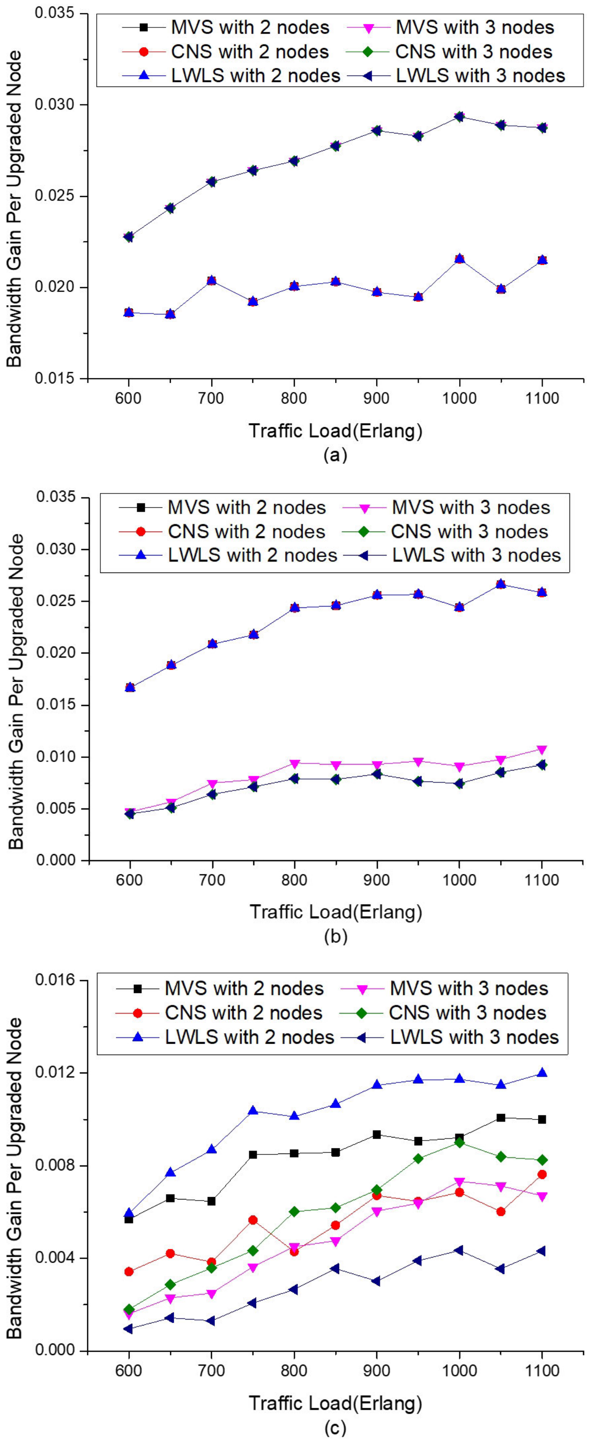

FIGURE 9. BGP of different PUNG scheme with various nodes size: (a) the first upgrade; (b) the second upgrade; (c) the third upgrade.

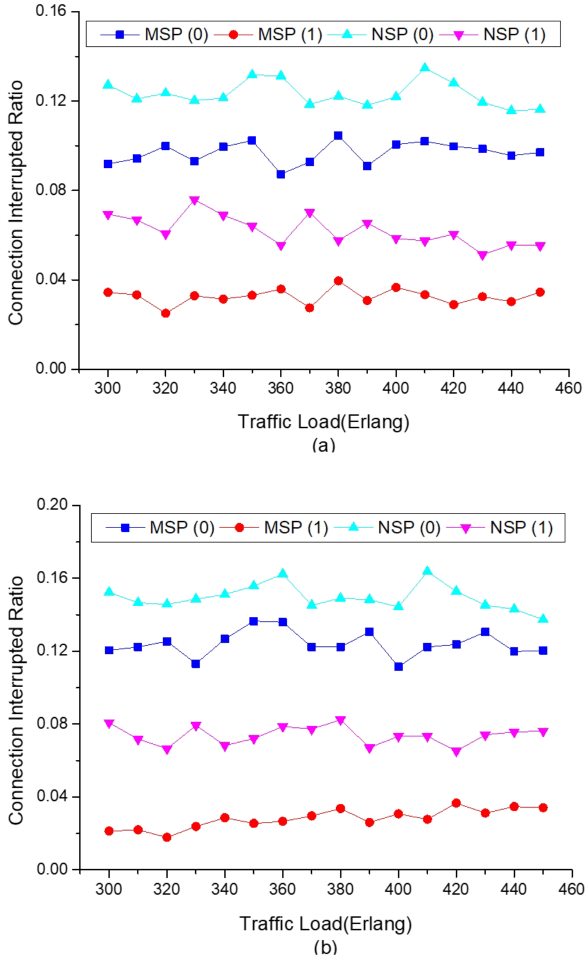

FIGURE 10. CIR of different service provisioning schemes with upgrade time: (a) 2 nodes PUNG size; (b) 3 nodes PUNG size.

upgrade nodes. It shows that these upgrade solutions can increase the network capacity effectively. We can also note that the decrease level is different for an upgrade solution with the increment of upgraded nodes. For example, in Fig. 7(a), SD-T(3) upgrades extra 2 nodes compared with SD-T(1), and BBR decreases almost ten percentages. At the same time, SD-T(5) also upgrades extra 2 nodes compared with SD-T(3). However, BBR only decreases 3 percentages. It indicates that after upgrading certain important nodes, the increased performance is not so obvious. It provides a reference for the service provider to balance the benefit and the expense. It can also be noted that some selected adjacent upgraded nodes can achieve high bandwidth benefit, and it is not easy to tell the difference by the performance of some selected adjacent upgraded nodes. The reason is that these different upgrade solutions have different upgrade nodes sequences, and these diverse upgrade sequences make them have different performance. Thus, we can conclude that the proper setting of the weights can improve the network performance obviously with fewer upgraded nodes for network migration. It provides a reference for the practice of measurable network migration.

Figure 8 shows BBR vary with the traffic load in the situation, where 5 fixed-grid nodes are upgraded during the measurable migration. We can note that the parameter solution of SD-T performs the best while the SD-F solution performs the worst. Besides, in the parameter solutions of SD and ID, traffic always plays a more significant role in comparison with flexibility. However, we can note that the BBR of SD-T is higher than the BBR of SD-F and the BBR of ID-T is also higher than the BBR of ID-F. It means that

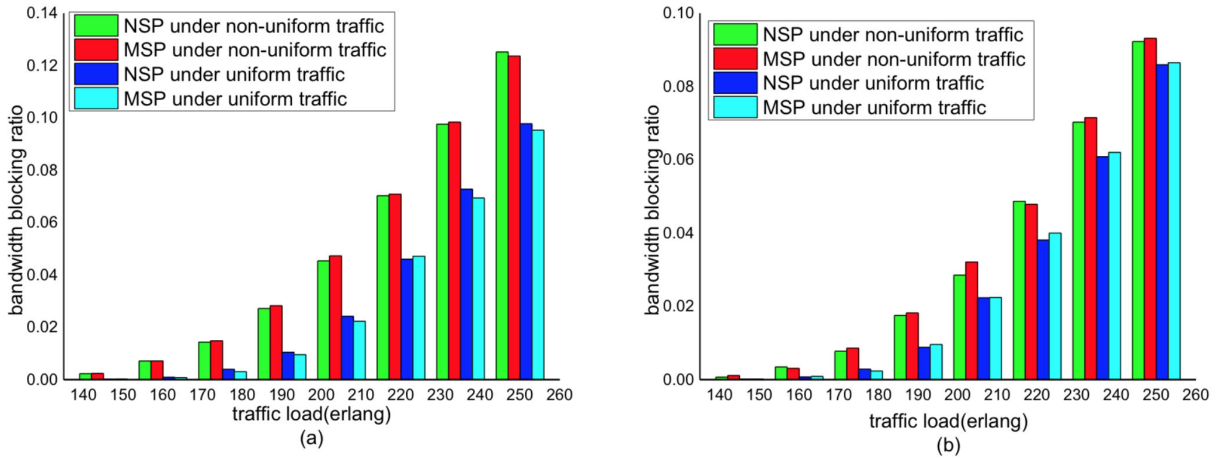

FIGURE 11. **Migration scenario: several nodes have been upgraded to flexible-grid nodes.**

compared with regional traffic, regional flexibility is more effective in achieving better BBR performance and points out that a flexible district is necessary for network migration.

Figure 9(a)-9(c) illustrate how the BGP of different PUNG schemes with different sizes vary with the traffic load. We can observe that as the traffic load increases, the trend of BGP from measurable migration increases in general. From Fig. 9(a), the BGP of PUNG with 3 nodes is higher than the BGP of PUNG with 2 nodes. But from Fig. 9(b), the BGP of PUNG with a smaller size is higher than the BGP of PUNG with the larger size. The reason is that the BGP increases sharply at the beginning of migration, when only a few nodes are upgraded. However, with the increment of upgraded nodes, the benefit level of network upgrading will decrease. Then the performance of BGP will decrease after a few migration steps. Fig. 9(c) displays the different BGP after 3 times upgrade. We can notice that the BGP of PUNG with 2 nodes MVS gain the highest benefits on account of its optimal link selection.

Figure 10 shows the performance of CIR of different service provisioning schemes for PUNG with different node sizes based on different traffic loads. Fig. 10(a) depicts the CIR performance of CIR for MSP scheme and NSP scheme at the first round upgrading and the second round upgrading, when the size of PUNG is two nodes. Fig. 10(b) shows the CIR performance of CIR for MSP scheme and NSP scheme at the first round upgrading and the second round upgrading, when the size of PUNG is three. From Fig. 10(a) and Fig. 10(b), it can be noted that the CIR fluctuates within limits, and CIR of MSP scheme is lower than that of the NSP scheme with the traffic load increasing for the same upgrading. Besides, CIR performance is also impacted by the size of PUNG, as the CIR performance of Fig. 10(a) is different from the CIR performance of Fig. 10(b). The reason is that during network migration process, a tradeoff appears between the affected range and performance improvement. Thus MSP scheme can provide more reliable connections compared with the traditional scheme, especially when the size of PUNG is smaller.

Figure 11 depicts the BBR performance of the MSP scheme and Non-migration-aware Service (NSP) with a uniform traffic distribution model and non-uniform traffic distribution model. It can be noted that BBR will increase with the increment of the traffic load. Fig. 10(a) shows the BBR performance of MSP and NSP schemes in these two traffic distribution models in the first upgrading round. Fig. 10(b) shows the BBR performance of the second upgrading round. From the results, Fig. 10(a) and Fig. 10(b) have a similar trend under different traffic models. Thus, it can be concluded that the MSP scheme does not sacrifice BBR to get the benefits of the target performance. For a service providing scheme with different traffic distribution models, it can be found that the non-uniform traffic distribution model can get better in network upgrading performance. The reason is that the bottleneck for network performance is more obvious for the non-uniform traffic distribution model.

From these numerical results, we have three conclusions. First, at the beginning of measurable migration, the benefits from nodes upgraded to flexible-grid are supreme. Thus, we can greatly improve the capacity of the network with few flexible-grid nodes. Secondly, the calculation of upgrade probability with the SD-F parameter solution performs better than other solutions with lower BBR. Last but not the least, with the consideration of CIR, MSP scheme can provide safer connections than traditional NSP scheme, and the fewer size of PUNG is more prominent.

V. CONCLUSION

The gradual evolution from fixed-grid optical networks to flexible-grid optical networks has been investigated with a measurable model for fog computing. The evolution has been ensured as an efficient technique to improve network performance and enlarge network capacity. This paper proposes a novel Migration-aware Service Provisioning (MSP) scheme to address the measurable migration issue and connection interruption during the migration process. From the numerical results, it is found that with measurable migration, we can realize controllable gradual network evolution (i.e. the sequence of potential upgrade nodes, the number of nodes to be upgraded at one time etc.), with MSP scheme achieving dramatically more benefits of CIRs than the NSP scheme. Moreover, inspired by this paper, it proves that network operators can achieve no-break services provisioning when the network migration happens.

REFERENCES

[1] J. Pan and J. McElhannon, "Future edge cloud and edge computing for Internet of Things applications," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 439–449, Feb. 2018.

[2] S. N. Shirazi, A. Gouglidis, A. Farshad, and D. Hutchison, "The extended cloud: Review and analysis of mobile edge computing and fog from a security and resilience perspective," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 11, pp. 2586–2595, Nov. 2017.

[3] J. L. Garcia-Dorado and S. G. Rao, "Cost-aware multi data-center bulk transfers in the cloud from a customer-side perspective," *IEEE Trans. Cloud Comput.*, vol. 7, no. 1, pp. 34–47, Jan. 2019.

[4] Y. Zhao, B. Yan, Z. Li, W. Wang, Y. Wang, and J. Zhang, "Coordination between control layer AI and on-board AI in optical transport networks," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 12, pp. A49–A57, Jan. 2020.

[5] Y. Zhao, W. Wang, Y. Li, C. Colman Meixner, M. Tornatore, and J. Zhang, "Edge computing and networking: A survey on infrastructures and applications," *IEEE Access*, vol. 7, pp. 101213–101230, 2019.

[6] J. Wu, M. Dong, K. Ota, J. Li, W. Yang, and M. Wang, "Fog-computing-enabled cognitive network function virtualization for an information-centric future Internet," *IEEE Commun. Mag.*, vol. 57, no. 7, pp. 48–54, Jul. 2019.

[7] X. Lin, J. Li, J. Wu, H. Liang, and W. Yang, "Making knowledge tradable in edge-AI enabled IoT: A consortium blockchain-based efficient and incentive approach," *IEEE Trans Ind. Informat.*, vol. 15, no. 12, pp. 6367–6378, Dec. 2019.

[8] B. Yan, Y. Zhao, X. Yu, W. Wang, Y. Wu, Y. Wang, and J. Zhang, "Tidal-traffic-aware routing and spectrum allocation in elastic optical networks," *J. Opt. Commun. Netw.*, vol. 10, no. 11, pp. 832–842, Nov. 2018.

[9] Q. Yao, H. Yang, A. Yu, and J. Zhang, "Transductive transfer learning-based spectrum optimization for resource reservation in seven-core elastic optical networks," *J. Lightw. Technol.*, vol. 37, no. 16, pp. 4164–4172, Aug. 15, 2019.

[10] H. Yang, J. Zhang, Y. Zhao, Y. Ji, J. Han, Y. Lin, and Y. Lee, "CSO: Cross stratum optimization for optical as a service," *IEEE Commun. Mag.*, vol. 53, no. 8, pp. 130–139, Aug. 2015.

[11] J. Kong, I. Kim, X. Wang, Q. Zhang, W. Xie, H. C. Cankaya, N. Wang, T. Ikeuchi, and J. P. Jue, "Guaranteed-availability network function virtualization in inter-datacenter networks," in *Proc. Opt. Fiber Commun. Conf.*, 2018, pp. 1–3.

[12] H. Yang, Q. Yao, A. Yu, Y. Lee, and J. Zhang, "Resource assignment based on dynamic fuzzy clustering in elastic optical networks with multi-core fibers," *IEEE Trans. Commun.*, vol. 67, no. 5, pp. 3457–3469, May 2019.

[13] Y. Zhao, B. Chen, J. Zhang, and X. Wang, "Energy efficiency with sliceable multi-flow transponders and elastic regenerators in survivable virtual optical networks," *IEEE Trans. Commun.*, vol. 64, no. 6, pp. 2539–2550, Jun. 2016.

[14] S. Behera, A. Deb, G. Das, and B. Mukherjee, "Impairment aware routing, bit loading, and spectrum allocation in elastic optical networks," *J. Lightw. Technol.*, vol. 37, no. 13, pp. 3009–3020, Jul. 1, 2019.

[15] V. Eramo and F. G. Lavacca, "Proposal and investigation of a reconfiguration cost aware policy for resource allocation in muliti-provider NFV infrastructures interconnected by elastic optical networks," *J. Lightw. Technol.*, vol. 37, no. 16, pp. 4098–4114, Aug. 15, 2019.

[16] L. Velasco, P. Wright, A. Lord, and G. Junyent, "Saving CAPEX by extending flexgrid-based core optical networks toward the edges," *J. Opt. Commun. Netw.*, vol. 5, no. 10, p. A171, Oct. 2013.

[17] R. Pastorelli, G. Bosco, S. Piciaccia, and F. Forghieri, "Network planning strategies for next-generation flexible optical networks [Invited]," *J. Opt. Commun. Netw.*, vol. 7, no. 3, pp. A511–A525, Mar. 2015.

[18] M. Ruiz, L. Velasco, A. Lord, D. Fonseca, M. Pioro, R. Wessaly, and J. Fernandez-Palacios, "Planning fixed to flexgrid gradual migration: Drivers and open issues," *IEEE Commun. Mag.*, vol. 52, no. 1, pp. 70–76, Jan. 2014.

[19] K. Christodoulopoulos, P. Soumplis, and E. Varvarigos, "Planning flexible optical networks under physical layer constraints," *J. Opt. Commun. Netw.*, vol. 5, no. 11, p. 1296, Nov. 2013.

[20] X. Yu, M. Tornatore, Y. Zhao, J. Zhang, X. Wang, S. Zhang, R. Wang, J. Wang, J. Zhang, and B. Mukherjee, "When and how should the optical network be upgraded to flex grid?" in *Proc. Eur. Conf. Opt. Commun. (ECOC)*, Sep. 2014, pp. 1–3.

[21] X. Yu, M. Tornatore, M. Xia, J. Wang, J. Zhang, Y. Zhao, J. Zhang, and B. Mukherjee, "Migration from fixed grid to flexible grid in optical networks," *IEEE Commun. Mag.*, vol. 53, no. 2, pp. 34–43, Feb. 2015.

[22] X. Yu, M. Tornatore, M. Xia, Y. Zhao, J. Zhang, and B. Mukherjee, "Brown-field migration from fixed grid to flexible grid in optical networks," *IEEE Commun. Mag.*, vol. 53, no. 2, pp. 34–43, Mar. 2015.

[23] Y. Zhang, Y. Zhang, S. K. Bose, and G. Shen, "Migration from fixed to flexible grid optical networks with sub-band virtual concatenation," *J. Lightw. Technol.*, vol. 35, no. 10, pp. 1752–1765, May 15, 2017.

[24] T. Ahmed, S. Rahman, M. Tornatore, X. Yu, K. Kim, and B. Mukherjee, "Dynamic routing and spectrum assignment in co-existing fixed/flex-grid optical networks," in *Proc. IEEE Int. Conf. Adv. Netw. Telecommun. Syst. (ANTS)*, Dec. 2018, pp. 1–3.

[25] Y. Tan, X. Yu, Y. Zhao, H. Yang, G. Zhang, H. Ding, and J. Zhang, "A novel migration-aware protection scheme in co-existing fixed and flexible grid optical networks," in *Proc. Asia Commun. Photon. Conf.*, 2015, pp. 1–3.

[26] R. Gour, J. Kong, G. Ishigaki, A. Yousefpour, S. Hong, and J. P. Jue, "Finding survivable routes in multi-domain optical networks with geographically correlated failures," *J. Opt. Commun. Netw.*, vol. 10, no. 8, p. C39, Aug. 2018.

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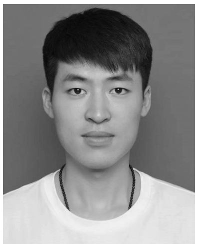

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