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Survivable Multipath Virtual Network Embedding Against Multiple Failures for SDN/NFV

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ABSTRACT Network virtualization holds a great promise for next-generation network, because it enables sharing of physical infrastructure among different users/services, in a logical isolated way, to achieve higher efficiency and greater flexibility of resources. By using optical network of extremely large capacity, more services can be carried out, but that leads to increase in substrate failures. This problem can be addressed by using survivable virtual network embedding (SVNE), more commonly with single-path provisioning (SPP) than multipath provisioning (MPP), although the former consumes more resources. However, only a few schemes consider using one-to-multi node mapping in SVNE. Now, one-to-multi node mapping and MPP scheme can be easily implemented in SVNE for software defined network (SDN) and network function virtualization (NFV) technology. So, this paper investigates the feasibility of implementing the SVNE scheme, with MPP and one-to-multi node mapping, to achieve higher reliability and better efficiency in elastic optical network. This scheme considers four key points: 1) the number and resource requirement of physical nodes that carry one virtual node, 2) the spectrum requirement of each path of one virtual link, 3) the number of paths considering shared risk group, and 4) graph theory, which are used in the scheme. Three contrasting schemes are formulated as integer linear programming models and their simulation are carried out. The results show that the proposed survivable multipath virtual network embedding scheme against multiple failures, with SDN/NFV, achieves significant gain in terms of spectrum efficiency and survivability.

INDEX TERMS Virtual network embedding, survivability, routing and resource assignment, multipath provisioning, multiple failures.

I. INTRODUCTION

In recent years, network virtualization has been widely accepted as a promising approach for sharing of physical infrastructure among different users/services in a logical isolated way. With the development of optical network, such as elastic optical networks (EON) [1], the capability of physical substrate network has started growing. This paved the way for carrying out more virtual networks (VNs) and services, but they entail increase in substrate failures. Therefore, Survivable Virtual Network Embedding (SVNE) [2], which aims to survive physical failures, has become a big breakthrough in network virtualization. SVNE maps virtual networks onto physical substrate network resources and determines the efficiency of substrate-network-resources utilization and the survivability of virtual networks.

Network survivability literature can be broadly categorized into two main methods: protection method and restoration method [3]. They can be both used and complementary, but the techniques of them are different. The protection method reserves the backup resource before failure occurs, whereas the restoration method finds the resource for the influenced traffic, after failure occurs. The focus of this study is, however, on protection method to achieve fast recovery. Virtual networks are mostly of two types: overlay network (logical layer, WDM layer, etc.) and virtual private network (VPN) [4]. The scenarios of these networks were studied by several researchers of SVNE [5]–[15]. At the same time, SVNE has been studied as a solution to provide high QoS with less cost and energy [16]–[19]. Graph theoretic and protection path routing are two major approaches for SVNE. The graph theoretic focuses on the structure of logical and physical layers to ensure that VN topology remains connected even after the failure of physical substrate network. Such mapping is referred to as survivable mapping [6]. As the

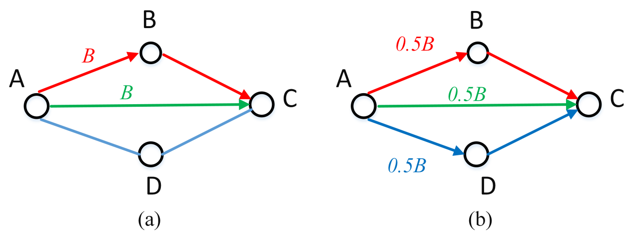

FIGURE 1. Spectrum consumption of traffic A-C: (a) SPP (b) MPP.

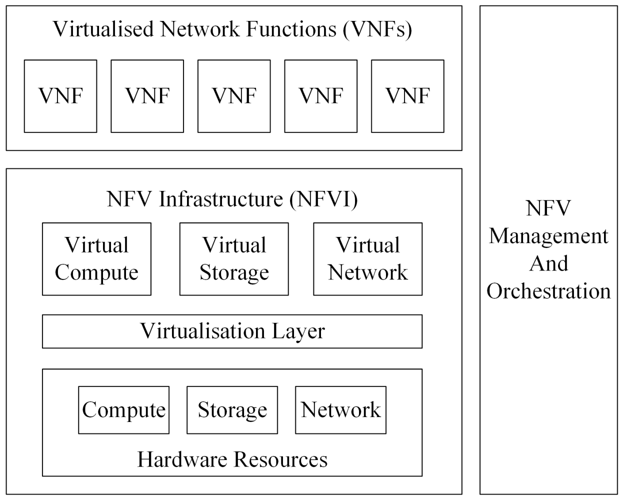

FIGURE 2. High-level NFV framework [39].

VN remains connected, traffic can be restored in the event of physical failure. The graph-theoretic approach is failure-independent and provides a structural foundation for the recovery or protection of traffic. For efficient and scalable survivable mapping, Kurant and Thiran [6] proposed a Survivable Mapping Algorithm using Ring Trimming (SMART) algorithm with subgraph, ring and contraction. For survivable nodes mapping, cut sets were used for handling double-node failures [7] and double-link failures [8], by applying the concept of clique [9]. Protection-path-routing approaches, which try to find link-disjoint or node-disjoint end-to-end paths for each traffic [10]–[15], have been proved to be NP-hard [20].

Generally, networks are vulnerable to multiple failures because of natural disasters, such as earthquake, hurricane, tsunami, and tornado, or even because of human-made disasters, such as weapons of mass destruction and electromagnetic pulse attacks [21], [22]. As the impact of multiple failures is usually great, many research workers are engaged in studying SVNE against multiple failures. Some of them proposed SVNE approaches that can work against double-node failures [7], double-link failures [8], [23], Shared Risk Group (SRG) [7], [24], and regional failures [15]. The problem of SVNE against multiple failures is addressed essentially by establishing disjoint backup paths. However, all of them use single-path provisioning (SPP), which consumes more resource than does multipath provisioning (MPP).

In MPP, a data stream is split into multiple lower rate streams, each of which is routed and assigned to a separate path [25]. As can be seen from Fig.1, the spectrum consumption against one failure is $\mathbf{2}\boldsymbol{B}$ with SPP [see Fig. 1(a)] and $\mathbf{1.5}\boldsymbol{B}$ with MPP [see Fig. 1(b)]. This shows that using MPP results in a saving of 25% spectrum.

Internet multipath routing has been widely used in the form of packet splitting at the network layer (equal-cost multipath in Open Shortest Path first (OSPF) [26] and Intermediate System to Intermediate System (IS-IS) [27]). Although multipath provisioning can be implemented at different layers, transport layer proves to be the best place to provision the end-to-end connection of an application over disjoint paths [28]. It was demonstrated that MPP can provide full or partial protection with better efficiency than SPP can [29], [30], and the same was confirmed by the present authors in their previous work [25]. Even without failures, MPP reduces network cost in EONs [31]. Several research works, including [1] and [32]–[34], tried to mitigate the impact of failures by embedding each virtual link into multiple disjoint paths, and some of them could find the optimal trade-off between VN survivability and path splitting overhead [32], [33]. Shahriar *et al.* [35] bring in shared protection and the simulation result shows resource can be well saved. However, these researches considered the situation that virtual node (Vnode) is one-to-one mapped to the substrate node (Snode) only. Consequently, the number of link-disjoint or node-disjoint paths, between the source and the destination node, is limited by the connectivity of physical substrate network. Nevertheless, many of the benefits of the "diversities" that are brought by MPP, such as load balancing, efficiency, higher throughput, context-aware services, anonymization for privacy [36]. And, with the help of Software Defined Network (SDN) [37] and Network Function Virtualization (NFV) [38] technology, it is possible to get higher reliability and better efficiency with node one-to-multi mapping and survivable multipath VNE.

The purpose of NFV is to decouple the physical network equipment from the functions that run on them [40]. In view of the potential of NFV to address the challenges of future services, a large number of experts have been working on its development. The European Telecommunications Standards Institute (ETSI) created an Industry Specification Group (ISG) for NFV to achieve the common architecture required to support Virtual Network Functions (VNFs) through a consistent approach [38]. The NFV Architecture comprises three key elements: Network Function Virtualization Infrastructure (NFVI), VNFs, and NFV Management and Orchestration (NFV MANO) [41]. The high-level architectural framework of NFV is illustrated in Fig. 2. The NFV has two mapping problems: (1) how to map NFVI to hardware resources (i.e., CPU, storage, and switches); (2) how to efficiently map and schedule the VNFs of a given service onto VN. To solve the first problem, this paper focuses on studying the SVNE problem, with MPP and one-to-multi node mapping. Solutions to the second problem have already been provided by some research works [42]–[45]. As the network service can be separated into a number of VNFs running on different pieces of equipment, mapping one Vnode to different Snodes is more significative and practicable.

For this study, the authors propose a survivable multipath virtual network embedding scheme (SMVNE) against multiple failures in EON, with SDN/NFV. The proposed scheme can solve the SVNE problem, with one-to-multi node mapping and MPP, in such a way that the communication between Vnodes would not be disrupted under a given number of link failures; besides it utilizes the minimal spectrum. The details of the scheme, including the required number of paths, considering SRG and the number of pysical nodes mapped to one virtual node, are investigated, and then an integer linear programming (ILP) model is presented to adapt new demands of RSA with MPP and one-to-multi node mapping. To the best of the authors' knowledge, this is the first attempt to consider MPP and multiple nodes mapping simultaneously in EONs against multiple failures.

The rest of this paper is organized as follows. Section II defines the problem and presents the proposed SMVNE approach against multiple failures, including determination of the number of paths, considering SRG and the number of Snodes that one Vnode should be mapped to; the contrasting schemes are also introduced in this section. Section III details the ILP model for SMVNE scheme. Section IV provides the numerical results to investigate the benefits of the proposed scheme. Finally, Section V presents the conclusions drawn from this study.

II. SMVNE SCHEME AGAINST MULTIPLE FAILURES

Till now, there has been no scheme that can work against any number of failures, but the one proposed here can work against a given number of failures. If M means the total number of failures, then $M \geq 2$ refers to a multiple failures scenario. $M_1 (M_1 \geq 1)$ is the number of link failures, $M_2 (M_2 \geq 0)$ is the number of source or destination node failures, and $M = M_1 + M_2$. Link failures are provided by multiple disjoint paths. If source node or destination node is down, then only backup substrates will be helpful. When a virtual node is mapped to enough number of multiple substrates nodes, then VNE will help in case of multiple nodes failures, but it consumes more resource of substrates nodes. With MPP and partial protection, a lot of the resource of substrates nodes can be saved.

The proposed SMVNE scheme provides protection against multiple failures in EONs. In MPP, there are multiple link disjoint paths between the source virtual node and the destination virtual node of virtual link. EON contains not only the wavelengths but also more flexible resources, and the term " slot" was used to describe the spectrum bands or subcarriers, used as minimum units for spectrum assignment in EON. The resource assignment is done following the common rules [17]:

a) The slots that are used by one path on different links should be continuous, as in the case of wavelength continuity constraint (the continuity constraint).
b) The slots that are used by one path on the same link should be contiguous, that is the slots should be near to each other (the contiguity constraint).
c) Except in shared protection, a slot should be used by, at the most, one path.
d) On one link, between two slot segments used by two paths, there should be guard bands.

For this study, it is assumed that VN requires partial protection. The physical layer topology $G(V, L)$ consists of node set V and link set L. VN is represented by $G'(V', L')$, and the virtual layer topology consists of virtual node set V' and virtual link set L'. Virtual link is represented by $l' =< s', d', \rho, b >$, where, s' is the source virtual node, d' is the destination virtual node, b is the spectrum requirement of l' (the number of slots), and ρ is the partial protection requirement.

- $\rho = 0$ indicates no protection (not discussed in this paper);
- $\rho = 1$ indicates full protection;
- $0 < \rho < 1$ indicates partial protection, and ρ represents the percentage of traffic to be protected.

$N(v')$ is the number of physical nodes that carry virtual node v', and $N(l')$ is the number of link-disjoint paths of virtual link l'. $N(s, d, l')$ is the number of paths of virtual link l' between physical nodes s and d. The relationship between $N(l')$ and $N(s, d, l')$ is shown by (1). $l'_{s,d}(b)$ is used to represent the sum of spectrum requirement of paths between physical nodes s and d. $B^{l'}_{s,d}$ refers to the slot requirement of the path between physical s and d of virtual link l'. We have proved that, for the same l', $B^{l'}_{s,d}$ shsould be the same to consume fewest slots [25].

$$N(l') = \sum_{s,d} N(s, d, l') \quad (N(l') \geq 2) \tag{1}$$

The CPU requirement of virtual node v' is represented by $\boldsymbol{R}_{v'}$, and that of virtual node v' at physical node v is represented by $R^{v'}_{v}$. $\boldsymbol{G}$ is the slot requirement of guard bands.

This Section (II) presents the implementation details of SMVNE against multiple failures. Subsection II A deals with the number and resource requirement of physical nodes that carry one virtual node, Subsection II B with the spectrum requirement of each path of one virtual link, Subsection II C with the number of paths, considering SRG and graph theory and Subsection II D with the contrastive schemes.

A. DETERMINATION OF THE NUMBER AND RESOURCE REQUIREMENT OF NODES

When $M_2 \neq 0$, to protect against M_2 failures, the number of backup nodes should be M_2; so, the total number of physical nodes should be $M_2 + 1$ at least. Although the increase in the number of nodes may decrease the consumption of resource, the more the nodes mapped to the virtual node, the higher would be the cost. As the cost of control and time delay are important in NFV network, the number of physical nodes that

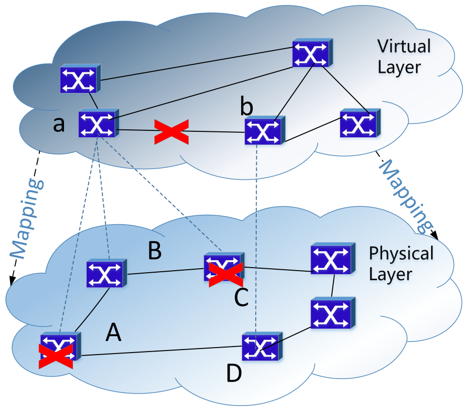

FIGURE 3. Illustrations of virtual node mapping with $M_2 = 2$.

carry virtual node v' should be

$$N(v') = M_2 + 1. \tag{2}$$

At the same time, whether the available physical nodes ($M_2 + 1$) are enough to carry one virtual node depends on the physical layer topology. As shown in Fig.3, $M_2 = 2$, 3 physical nodes (A, B, C) carry the virtual node a. But when physical node A and C break down, the virtual link a-b is down too, and $M_2 + 1$ physical node cannot provide enough protections against M_2 node failures. This means the physical layer topology determines whether or not the network can tolerate M_2 failures.

When there are enough nodes with (2), the resource requirement of each physical node $R_v^{v'}$ is

$$R_v^{v'} = \rho \boldsymbol{R_{v'}}. \tag{3}$$

When the nodes with (2) are not enough, the source node and destination node cannot be adequately protected against M_2 failures, and the $R_v^{v'}$ of (3) is the best that can be provided.

When $M_2 = 0$, more than one physical node may be needed, because there may not be enough paths between two nodes (shown in Fig. 4 (a)). The number of nodes should be minimum to get enough disjoint paths against M_1.

With MPP the resource requirement of each node should be the same to ensure least consumption of resource. However, with NFV, because the VNFs that run on nodes are different, and their resource requirement based on the type of VNF. For this study, to simplify the problem, with the same v', $R_v^{v'}$ is assumed to be equal to each other.

$$R_v^{v'} = \boldsymbol{R}_{v'}/N(v') = \boldsymbol{R_{v'}}/(M_2 + 1) \tag{4}$$

B. DETERMINATION OF THE SPECTRUM REQUIREMENT OF EACH PATH

SRG and M_2 will influence the number of paths, but not the spectrum requirement directly. The influence of SRG will be discussed later in Subsection II C.

When $N(v') = 0$ **or** $M_2 = 0$, all the paths have the same spectrum requirement, which is $B_{s,d}^{l'} = B^{l'}$, and they should be link-disjoint to each other. Then

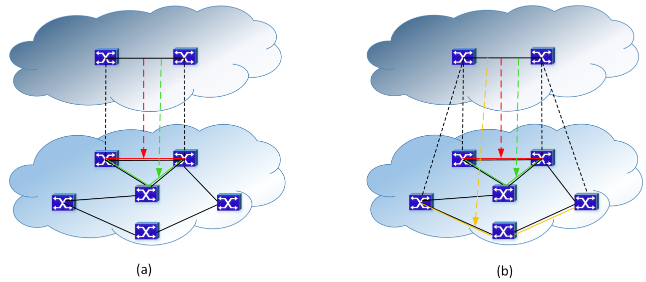

FIGURE 4. Illustrations of Mapping with $M_1 = 2$ and $M_2 = 0$: (a) the number of disjoint paths is not enough to protect the virtual link against 2 failures (b) the number of disjoint paths is enough to protect the virtual link against 2 failures.

$$l'_{s,d}(b) = N(s, d, l') \cdot B^{l'}. \tag{5}$$

where,$B^{l'}$ is determined by $M_1, N(l')(M_1 < N(l'))$ and $l'(b)$. According to [25]:

1) WHEN $0 < \rho < 1$,

If $N(l') \geq M_1/(1-\rho)$,

$$B^{l'} = l'(b)/N(l'). \tag{6}$$

Otherwise, if $N(l') < M_1/(1-\rho)$ or $\rho = 1$

$$B^{l'} = l'(b)/(N(l') - M_1). \tag{7}$$

2) WHEN $\rho = 1$,

$$B^{l'} = l'(b)/N(l'). \tag{8}$$

Formulation (8) can be seen as a special case of (7). As the spectrum of each path is the same, the total consumption of spectrum of link l' is

$$SumB(l') = N(l') \cdot (B^{l'} + \boldsymbol{G}). \tag{9}$$

If $N(l') \geq M_1/(1-\rho)$,

$$SumB(l') = l'(b) + \boldsymbol{G} \cdot N(l'). \tag{10}$$

Otherwise, if $N(l') < M_1/(1-\rho)$ or $\rho = 1$

$$SumB(l') = \rho \cdot N(l') \cdot l'(b)/(N(l') - M_1) + \boldsymbol{G} \cdot N(l'). \tag{11}$$

When $M_2 \neq 0$, to maintain the communication between the pairs of nodes under failures, for each node pairs $l'_{s,d}(b) \geq l'(b)$, (6) and (7) are changed to (12) and (13).

If $N(s, d, l') \geq M_1/(1-\rho)$,

$$B_{s,d}^{l'} = l'(b)/N(s, d, l'). \tag{12}$$

Elseif $N(s, d, l') < M_1/(1-\rho)$ or $\rho = 1$

$$B_{s,d}^{l'} = \rho l'(b)/(N(s, d, l') - M_1). \tag{13}$$

If all $N(s,d,l') \geq M_1/(1-\rho)$

$$SumB(l') = \sum_{s,d} l'_{s,d}(b) = \frac{1}{2}\cdot N(v')\cdot l'(b) + \sum_{s,d} \boldsymbol{G}\cdot N(s,d,l'). \quad (14)$$

Otherwise, if all $N(s,d,l') < M_1/(1-\rho)$ or $\rho = 1$

$$SumB(l') = \sum_{s,d} \rho\cdot N(s,d,l')\cdot l'(b)/(N(s,d,l')-M_1) + \boldsymbol{G}\cdot N(s,d,l'). \quad (15)$$

Otherwise, if $N(s,d,l') < M_1/(1-\rho)$ and $N(s',d',l') \geq M_1/(1-\rho)$

$$SumB(l') = \sum_{s,d} \rho\cdot N(s,d,l')\cdot l'_{s,d}(b)/(N(s,d,l')-M_1) + \sum_{s',d'} l'(b) + \sum_{s,d} \boldsymbol{G}\cdot N(s,d,l'). \quad (16)$$

C. DETERMINATION OF THE NUMBER OF PATHS

The number of paths, such as $N(s,d,l')$ and $N(l')$, depends on the connectivity of topology, because the paths should be link-disjoint. When it comes to SRG, there would be some extra paths, whose failures should be protected [46]. In this subsection two questions are discussed: (i) How does the number of SRG affect spectrum consumption, (ii) How to calculate $N(s,d,l')$ with graph theory.

1) SRG AND SPECTRUM CONSUMPTION

When $0 < \rho < 1$, considering $l'_{s,d}(b)$ and $\boldsymbol{G}$, from (6)-(16) and the investigation in [25],

If $N(l') \geq M_1/(1-\rho)$

$$N(l') = \lceil M_1/(1-\rho) \rceil, \quad (17)$$

$$N(s,d,l') = \lceil M_1/(1-\rho) \rceil. \quad (18)$$

(6) and (12) are used to calculate $B^{l'}$ and $B^{l'}_{s,d}$. And

$$SumB(l') = l'(b) + \lceil M_1/(1-\rho) \rceil \cdot \boldsymbol{G}. \quad (19)$$

If the disjoint routes are not enough, $N(l') < M_1/(1-\rho)$ or $\rho = 1$

$N(l')$ may be less than $M_1/(1-\rho)$, in which case $N(l')$ should be rounded to the nearest integer of $M_1 + \sqrt{\rho M_1 l'(b)/\boldsymbol{G}}$.

$$N(l') = round(M_1 + \sqrt{\rho M_1 l'(b)/\boldsymbol{G}}) \quad (20)$$

The same applies to

$$N(s,d,l') = round(M_1 + \sqrt{\rho M_1 l'(b)/\boldsymbol{G}}) \quad (21)$$

$B^{l'}$ is calculated by (7). And

$$SumB(l') = \rho l'(b) + \sqrt{\rho \boldsymbol{G} M_1 l'(b)} \quad (22)$$

When there are ss paths in the same SRG, $M_1{}' = M_1 + ss$ $\lceil M_1{}'/(1-\rho) \rceil$ disjoint paths should be found for (17) so that $N(s) = \lceil (M_1+ss)/(1-\rho) \rceil$, and the number of required slots for data is constant. However, from (19) it can be seen that $SumB(l')$ increases with increase in ss.

If there are not enough paths, one has to refer to (20). And from (11) it is

$$\begin{aligned} SumB(l') &= \rho\cdot N(l')\cdot l'(b)/(N(l')-M_1{}') + \boldsymbol{G}\cdot N(l') \\ &= \rho l'(b)\cdot(M_1{}' + \sqrt{\rho M_1{}' l'(b)/\boldsymbol{G}})/\sqrt{\rho M_1{}' l'(b)/\boldsymbol{G}} \\ &\quad + \boldsymbol{G}(M_1{}' + \sqrt{\rho M_1{}' l'(b)/\boldsymbol{G}}) \\ &= \rho l'(b) + M_1{}'\boldsymbol{G} + 2\sqrt{\rho l'(b) M_1{}'\boldsymbol{G}} \\ &= \rho l'(b) + M_1\boldsymbol{G} + \boldsymbol{G}\cdot ss + 2\sqrt{\rho l'(b)(M_1+ss)\boldsymbol{G}} \end{aligned} \quad (23)$$

So $SumB(l')$ also increases as the ss grows. And this suits (22) and (14), (15). **These indicate the paths should be SRG-disjoint**.

In summary, if $l'(b) + \lceil M_1/(1-\rho) \rceil \cdot \boldsymbol{G} < \rho l'(b) + \sqrt{\rho \boldsymbol{G} M_1 l'(b)}$, when $M_2 \neq 0$, one has to try to make the number of paths between different node pairs as in (18) and use (12) to $B^{l'}_{s,d}$; if there are not enough paths or $\rho = 1$ or $l'(b) + \lceil M_1/(1-\rho) \rceil \cdot \boldsymbol{G} \geq \rho l'(b) + \sqrt{\rho \boldsymbol{G} M_1 l'(b)}$, (21) paths are needed and (13) is used to calculate $B^{l'}_{s,d}$; if the number is not enough even for (21), then the number of paths between the nodes is the same as largest number of SRG-disjoint routes, which depends on the topology, and $B^{l'}_{s,d}$ is calculated with (13); if the number is less than even $M_1 + 1$, more node pairs are needed. When $M_2 = 0$, considering SRG too, the number of paths is decided by (17), (20) and the connectivity of topology. The spectrum requirement of each path is calculated by (6) or (7). When the number of paths is less than (20), more nodes are used to carry the virtual nodes and the total number of paths is $M_1 + 1$. And the number of paths between different node pair depends on resources of the nodes and the topology.

2) GRAPH THEORY AND NUMBER OF PATHS

It is well known that, because of the fundamental constraint of topology, there is no such SVNE strategy that can keep virtual networking operational against all types of failures. The connectivity of topology has great influence on the number of disjoint paths. With this in view, it is attempted to get the maximum number of disjoint paths between node pairs by using the graph theory.

The following theorems provide some simple, but useful conditions that are required for the survivability of a network. First, the following notions are defined. A cut is partitioning of the set of nodes into two parts, S and $\overline{S} = V - S$. Each cut defines a set of edges consisting of those edges in L with one endpoint in S and the other in $\overline{S}$. This set of edges is referred to as cut-set associated with cut $< S, V - S >$, or simply as $CS(S, V - S)$. The number of edges in the cut-set, $|CS(S, V - S)|$ is the size of cut-set. Using the size of the minimum cut set with Menger's Theorem [47], the maximum number of disjoint paths can be obtained between node pairs. Let v_1 and v_2 be two distinct vertices.

Menger's Theorem states that the size of the minimum cut-set for v_1 and v_2 (the minimum number of edges whose removal disconnects v_1 and v_2) is equal to the maximum number of link-disjoint paths between v_1 and v_2.

The theorem can be derived from the Max-Flow-Min-Cut Theorem [48]. Also, the max-flow-min-cut theorem proves that the maximum network flow and the size of minimum cut-set are equal. The min-cut problem can be solved and the maximum number of link-disjoint paths between two nodes obtained, by using the well-known Edmonds-Karp algorithm [49], a polynomial-time method.

D. COMPARISON SCHEMES

To compare the spectrum efficiencies of MPP and SPP, one-to-one node mapping and one-to-multi node mapping, three schemes are modeled (see the next section): survivable single-path virtual network embedding scheme (SSVNE), one-to-one multipath virtual network embedding scheme (OMVNE) and one-to-one single-path virtual network embedding scheme (OSVNE). Figure 5 shows these three schemes, as also the SMVNE scheme.

With SMVNE, each virtual node is mapped to one or multi physical nodes, and each virtual link is mapped to one or multi physical links too. Whereas, with SSVNE each virtual node is mapped to one or multi physical nodes, but each virtual link is mapped to only one physical link. When it comes to OMVNE, each virtual node is mapped to only one physical node, and each virtual link is mapped to one or multi physical links. As well as, with OSVNE, each virtual node is mapped to only one physical node, and each virtual link is mapped to only one physical link.

The VN shown in Fig. 5 is simple, comprising two nodes and one link. The resources are assumed to be enough under $M = 2$, $M_1 = 1$,and $M_2 = 1$. In SMVNE scheme, each Vnode is mapped to 2 Snodes, and the Vlink to 3 disjoint paths (see Fig 5a), whereas in SSVNE, each Vnode is mapped to 2 Snodes, because of which there are 2 disjoint paths between each pair of nodes and 4 paths are mapped to the Vlink (see Fig. 5b). In OMVNE and OSVNE schemes, each Vnode can be mapped to only one Snode. With MPP, 3 disjoint paths are used (see Fig. 5c), and with SPP, 2 disjoint paths (see Fig. 5d).

III. ILP FORMULATIONS

In this section, mathematical models are presented for the proposed SMVNE scheme and the three contrasting schemes. Following the above approaches, the ILP formulations can achieve the most efficient resource assignment. The link-disjoint paths between the physical nodes s and d are calculated with Bhandari's disjoint paths algorithm [50], and their slot requirements are computed with (6), (7), (12), and (13). Then, the ILP model is used to map nodes, choose paths (SRG disjoint) and accomplish the spectrum assignment.

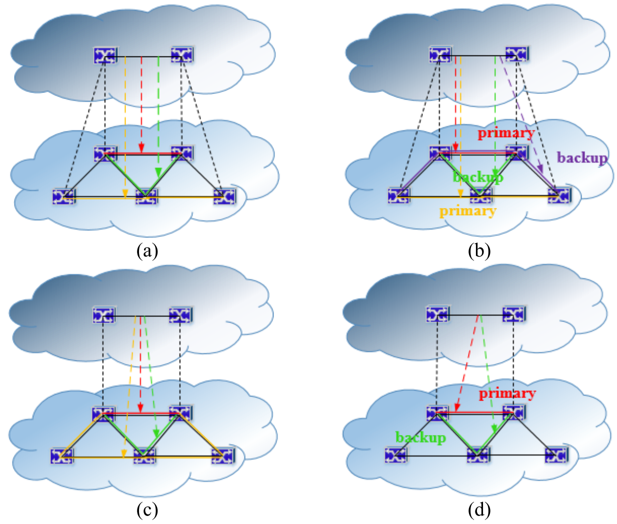

FIGURE 5. Illustrations of VNE schemes (a) SMVNE (b) SSVNE (c) OMVNE (d) OSVNE.

A. SMVNE SCHEME

Given:

$G(V, L)$: The physical topology consisting of node set V and link set L.

$G'(V', L')$: The physical topology consisting of node set V' and link set L'.

l_m: A physical link $l_m \in L, m \in \{1, 2, \cdots, |L|\}$, and $l_m =< s, d > s, d \in V$.

l'_i: A virtual link $l'_i \in L', i \in \{1, 2, \cdots, |L'|\}$, and $l'_i =< s', d', \rho, b > s', d' \in V'$, where ρ is protection level, and b is the slot requirement of the link.

v_m: A physical node $v_m \in V, m \in \{1, 2, \cdots, |V|\}$.

v'_i: A virtual node $v'_i \in V', m \in \{1, 2, \cdots, |V'|\}$.

$\boldsymbol{R}_{v'_i}$: The CPU requirement of virtual node v'_i.

SRG: The set of srg_i, which means a set of the links with the same risk.

$\boldsymbol{W}$: The number of slots on each physical link.

$\boldsymbol{G}$: The slot requirement of guard bands.

$\boldsymbol{R}$: The resource of CPU on each physical node.

$\boldsymbol{K}$: The set of $k_{s,d}$, which is the maximal number of link-disjoint paths between physical nodes s and d. $k_{s,d} = k_{d,s}$.

$\boldsymbol{P}$: The set of $p^k_{s,d}$, which denotes the kth path between physical nodes s and d, besides being a set of physical link,. $k \in \{1, 2, \cdots, k_{s,d}\}$.

$p^k_{s,d}$: A set of physical links, the links make up the kth path between physical s and d.

$p_{s,d}(srg_m)$: Positive integer value that denotes the number of paths between physical s and d, which include the links in SRG srg_m.

$p_{s,d}(srg)$: Positive integer value that is the maximum of $p_{s,d}(srg_m)$.

$p^k_{s,d}(l_m)$: Boolean value that denotes whether l_m is included in $p^k_{s,d}$, and if it does, $p^k_{s,d}(l_m) = 1$, or else $p^k_{s,d}(l_m) = 0$.

$p^k_{s,d}(srg_i)$: Boolean value that denotes whether path includes the links in srg_i, and if it does, $p^k_{s,d}(srg_i) = 1$, or else $p^k_{s,d}(srg_i) = 0$.

NN_1: The set of $nn_{s,d}^1$, which if a Boolean value that denotes whether $k_{s,d} - p_{s,d}(srg)$ is larger than $\lceil M_1/(1-\rho)\rceil$, and if it is $nn_{s,d}^1 = 1$, or else $nn_{s,d}^1 = 0$.

NN_2: The set of $nn_{s,d}^2(l_i')$, which if a Boolean value that denotes whether $k_{s,d} - p_{s,d}(srg)$ is less than $\lceil M_1/(1-\rho)\rceil$ and larger than $round(M_1 + \sqrt{\rho M_1 l'(b)/\boldsymbol{G}})$, and if it is, $nn_{s,d}^2(l_i') = 1$, or else $nn_{s,d}^2(l_i') = 0$.

M_1: The number of link failures, $M_1 \geq 1$.

M_2: The number of node (the endpoint of a physical link) failures, $M_2 \geq 0$.

M_{node}: Boolean value that denotes whether $M_2 > 0$, and if it is, $M_{node} = 1$, or else $M_{node} = 0$.

KK: The set of $kk_{l_i'}$, which is a Boolean value that denotes whether $\rho \neq 1$ and $l_i'(b) + \lceil M_1/(1-\rho)\rceil \cdot \boldsymbol{G}$ is smaller than $\rho l_i'(b) + \sqrt{\rho \boldsymbol{G} M_1 l_i'(b)}$, and if they are, $kk_{l'} = 1$, or else $kk_{l'} = 0$.

Objective: Achieving maximum spectrum efficiency with minimum node mapping cost.

Variables:

S_{l_m}: Positive integer variable that denotes the maximum used slot index on physical link l_m.

$N(v_i')$: Positive integer variable that denotes the number of physical nodes, which carry virtual node v_i'.

$N(l_i')$: Positive integer variable that denotes the number of SRG-disjoint paths of virtual link l_i'.

$N(s,d,l_i')$: Positive integer variable that denotes the number of SRG-disjoint paths of virtual link l_i', between physical nodes s and d.

$v_i'(v_m)$: Boolean variable that denotes whether the physical node v_m carries the virtual node v', and if it carries, $v_i'(v_m) = 1$, or else $v_i'(v_m) = 0$.

$R_{v_m}^{v_i'}$: Positive integer variable that denotes the CPU requirement of virtual node v_i' at physical node v_m.

$B_{s,d}^{l_i'}$: Positive integer variable that denotes the slot requirement of paths between physical nodes s and d for virtual link l_i'.

$l_i'(p_{s,d}^k)$: Boolean variable that denotes whether the kth physical path between physical nodes s and d carries the virtual link l_i', and if it carries $l_i'(p_{s,d}^k) = 1$, or else $l_i'(p_{s,d}^k) = 0$.

$sl_i'(l_m)$: Positive integer variable that denotes the index of the slot, which is the first slot used by virtual link l_i' on link l_m. $sl_i'(l_m) \in [0, W]$. If $sl_i'(l_m) = 0$, it means that virtual link l_i' is not carried by link l_m.

$el_i'(l_m)$: Positive integer variable that denotes the index of the slot, which is the last slot used by virtual link l_i' on link l_m (including guard bandwidth). $el_i'(l_m) \in [0, W]$. If $el_i'(l_m) = 0$, it means that virtual link l_i' is not carried by link l_m.

$\varphi(l_m, l_1', l_2')$: Boolean variable that denotes whether the slots used by l_1' on link l_m is behind the slots used by l_2'. If it is, $sl_1'(l_m) > sl_2'(l_m)$ and $\varphi(l_m, l_1', l_2') = 1$, or else $\varphi(l_m, l_1', l_2') = 0$.

Objective Function:

$$Min \sum_{m=1}^{|L|} S_{l_m} + \alpha \sum_{n=1}^{|V'|} N(v_n') \tag{24}$$

where, α is a variable for weighting the importance of minimizing the number of physical nodes for the same virtual node. The objective function includes two parts: (i) minimize the sum of S_{l_m}, which means less fragmentation, less slot consumption and higher spectrum efficiency; (ii) the usage count of physical nodes; the smaller the count, the less would be the node mapping cost.

The objective function is subjected to the following constraint conditions: concept constraint conditions (25)-(30), the position relationship between used slot conditions (31), (32), the survivable constraint conditions (33), (34), the number of nodes and paths conditions (35)-(40), slot contiguity conditions (41), slot unique conditions (42)-(45), link resource requirement conditions (46)-(48), node resource requirement conditions (49), (50), SRG-disjoint conditions (51), (52) and the slots continuity conditions, which form part of the variables design.

Constraints:

$$S_{l_m} \geq el_i'(l_m) l_m \in L, l_i' \in L' \tag{25}$$

Equation (25) guarantees that S_{l_m} is the maximum of the used slots' index on link l_m. The smaller S_{l_m}, the more compact and fewer would be the used slots.

$$N(v_i') = \sum_{v_m \in V} v_i'(v_m) \tag{26}$$

$$N(l_i') = \sum_{s,d} N(s,d,l_i') \tag{27}$$

$$N(s,d,l_i') = \sum_{k} l_i'(p_{s,d}^k) \tag{28}$$

Equations (26)-(28) ensure that $N(v_i')$, $N(l_i')$ and $N(s,d,l_i')$ are coincident with their definitions.

$$sl_i'(l_m) < el_i'(l_m) \quad (sl_i'(l_m) \neq 0) \tag{29}$$

$$sl_i'(l_m) = el_i'(l_m) \quad (sl_i'(l_m) = 0) \tag{30}$$

Equation (29) ensures for the Vlink l_i' that the first used slot is not at the back of the last used slot on the same Slink.

$$sl_1'(l_m) - sl_2'(l_m) < \boldsymbol{W} \cdot \varphi(l_m, l_1', l_2') \quad l_1' \neq l_2' \tag{31}$$

$$sl_2'(l_m) - sl_1'(l_m) < \boldsymbol{W} \cdot [1 - \varphi(l_m, l_1', l_2')] \quad l_1' \neq l_2' \tag{32}$$

Equations (31) and (32) ensure that the relationship, in terms of position, between the slots used by two Vlinks on the same Slink is coincident with $\varphi(l_m, l_1', l_2')$.

$$N(v_i') \geq M_2 + 1 \tag{33}$$

$$N(l_i') \geq (M_2 + 1) \cdot (M_1 + 1) \tag{34}$$

Equation (33) ensures that enough Snodes have been mapped to Vnodes against M_2 node failures, and equation (34) ensures that there are enough paths against M_1 link failures.

$$N(l_i') \geq kk_{l_i'} \cdot M_1/(1-\rho) \tag{35}$$

$$N(l_i') \geq (1 - kk_{l_i'}) \cdot [M_1 + \sqrt{\rho M_1 l_i'(b)/\boldsymbol{G}}] \tag{36}$$

$$N(s,d,l'_i) \geq [s'(s)\cdot d'(d) + d'(s)\cdot s'(d)] \cdot M_{node}\cdot kk_{l'_i}\cdot nn^1_{s,d}\cdot M_1/(1-\rho) \quad s\neq d, s,d\in V \tag{37}$$

$$N(s,d,l'_i) \geq [s'(s)\cdot d'(d) + d'(s)\cdot s'(d)] \cdot (1-kk_{l'_i})\cdot M_{node}\cdot nn^2_{s,d}\cdot [M_1+\sqrt{\rho M_1 l'_i(b)/\boldsymbol{G}}] \quad s\neq d, s,d\in V \tag{38}$$

$$N(s,d,l'_i) \geq [s'(s)\cdot d'(d) + d'(s)\cdot s'(d)] \cdot M_{node}\cdot (1-nn^2_{s,d})\cdot [k_{s,d}-p_{s,d}(srg)] \quad s\neq d, s,d\in V \tag{39}$$

Equations (35)-(39) constrain the number of paths in accordance with the decision in Section II.C.(1).

$$N(s,d,l'_i) \leq [s'(s)\cdot d'(d) + d'(s)\cdot s'(d)] \cdot [k_{s,d}-p_{s,d}(srg)] \quad s\neq d, s,d\in V \tag{40}$$

Equation (40) constrains the number of disjoint paths in conformity with the graph theory and SRG.

$$p^k_{s,d}(l_n) = 1, \quad p^k_{s,d}(l_m) = 1, \; l'_i(p^k_{s,d}) = 1 \quad l_m\neq l_n, \quad l_m, l_n\in L \quad el'_i(l_m) = el'_i(l_n) \tag{41}$$

Equation (41) ensures that the slots used by any one path on different links are continuous.

$$l_m\neq l_n, \quad l_m,l_n\in L \; sl'_1(l_m)\neq 0, \; sl'_2(l_m)\neq 0 \quad el'_1(l_m)\neq 0, \quad el'_2(l_m)\neq 0$$

$$sl'_1(l_m) - el'_2(l_m) < \boldsymbol{W}\cdot\varphi(l_m, l'_1, l'_2) \tag{42}$$

$$el'_2(l_m) - sl'_1(l_m) < \boldsymbol{W}\cdot[1-\varphi(l_m, l'_1, l'_2)] \tag{43}$$

$$sl'_2(l_m) - el'_1(l_m) < \boldsymbol{W}\cdot[1-\varphi(l_m, l'_1, l'_2)] \tag{44}$$

$$el'_1(l_m) - sl'_2(l_m) < \boldsymbol{W}\cdot\varphi(l_m, l'_1, l'_2) \tag{45}$$

Equations (42)-(45) ensure that each slot is used by one path only, without any overlapping.

$$el'_i(l_m) - sl'_i(l_m) \geq p^k_{s,d}(l_m)\cdot l'_i(p^k_{s,d})\cdot (B^{l'_i}_{s,d} + \boldsymbol{G}) - 1 \tag{46}$$

Equation (46) ensures that enough slots are used by the Vlink l'_i on the Slink l_m for the slot requirement $B^{l'_i}_{s,d}$ and guard band $\boldsymbol{G}$.

$$el'_i(l_m) \leq \boldsymbol{W} \tag{47}$$

Equation (47) ensures that the used slots are not more than the number of slots on each link.

$$\begin{aligned} B^{l'_i}_{s,d} \geq{}& (1-M_{node})\cdot kk_{l'_i}\cdot(1-\rho)\, l'_i(b)/M_1 \\ &+ (1-M_{node})\cdot(1-kk_{l'_i})\cdot\sqrt{\rho\cdot\boldsymbol{G}\cdot l'_i(b)/M_1} \\ &+ M_{node}\cdot nn^1_{s,d}\cdot kk_{l'_i}\cdot(1-\rho)\, l'_i(b)/M_1 \\ &+ M_{node}\cdot nn^1_{s,d}\cdot(1-kk_{l'_i})\cdot\sqrt{\rho\cdot\boldsymbol{G}\cdot l'_i(b)/M_1} \\ &+ M_{node}\cdot nn^2_{s,d}\cdot\sqrt{\rho\cdot\boldsymbol{G}\cdot l'_i(b)/M_1} \\ &+ M_{node}\cdot(1-nn^2_{s,d})\cdot(1-nn^1_{s,d})\cdot \\ &\rho l'_i(b)\big/(k_{s,d} - p_{s,d}(srg) - M_1) \end{aligned} \tag{48}$$

Equation (48) constrains the bandwidth of paths in conformity with the decision in Section II B.

$$R^{v'_i}_{v_m} = v'_i(v_m)\cdot[M_{node}\cdot\rho\boldsymbol{R}_{v'_i} + (1-M_{node})\cdot\boldsymbol{R}_{v'_i}\big/(M_2+1)] \tag{49}$$

Equation (49) constrains the requirement of node resource in conformity with the decision in Section II A.

$$\sum_{v'_i} R^{v'_i}_{v_m} \leq \boldsymbol{R} \tag{50}$$

Equation (50) ensures that the used resources are not more than the resources of CPU on each physical node.

$\forall srg_i, l'_j$

$$\sum\nolimits_{s,d,k} p^k_{s,d}(srg_i)\cdot l'_j(p^k_{s,d}) \leq 1 \tag{51}$$

$$\sum\nolimits_{s,d,k} p^k_{s,d}(l_m)\cdot l'_i(p^k_{s,d}) \leq 1 \tag{52}$$

Equations (51), (52) ensure that the paths of the same Vlink are SRG-disjoint.

B. SSVNE SCHEME

The survivable single-path virtual network embedding scheme (SSVNE) has both primary and back-up paths. In this section, the differences between the models of SSVNE and SMVNE schemes are described.

When $M_2 = 0$, the SSVNE scheme requires $M_1 + 1$ paths to protect against M_1 failures. So (35), (36) change to formulation (53), which can be seen as a special case of (34).

$$N(l'_i) \geq M_1 + 1 \tag{53}$$

One of them is the primary path, and the others are back-up paths.

Given:

NN_3: The set of $nn^3_{s,d}$, which is a Boolean value, denotes whether $k_{s,d} - p_{s,d}(srg)$ is larger than M_1+1; if it is $nn^3_{s,d} = 1$, or else $nn^3_{s,d} = 0$.

Variables:

$B^{l'_i,k}_{s,d}$: Positive integer variable that denotes the slot requirement of the kth paths between physical nodes s and d for virtual link l'_i.

$pl'_i(p^k_{s,d})$: Boolean variable that denotes whether the kth path is the primary path of the virtual link l'_i between physical node s and d; if it is $pl'_i(p^k_{s,d}) = 1$, or else $pl'_i(p^k_{s,d}) = 0$.

Constraints:

$$\sum_k pl'_i(p^k_{s,d}) \leq 1 \tag{54}$$

$$pl'_i(p^k_{s,d}) \leq l'_i(p^k_{s,d}) \tag{55}$$

Equations (54), (55) ensure that each virtual link has only one primary path.

$B_{s,d}^{l'_i,k}$ of the primary path is $l'_i(b)$, while the $B_{s,d}^{l'_i,k}$ of back-up path is $\rho l'_i(b)$. So, (48) changes to (55), and (46) to (57).

$$B_{s,d}^{l'_i,k} \geq \rho l'_i(b) + pl'_i(p_{s,d}^k) \cdot (1-\rho) l'_i(b) \quad (56)$$

$$el'_i(l_m) - sl'_i(l_m) \geq p_{s,d}^k(l_m) \cdot l'_i(p_{s,d}^k) \cdot (B_{s,d}^{l'_i,k} + \boldsymbol{G}) - 1 \quad (57)$$

When there are not enough disjoint paths for the virtual link, more Snodes can be mapped. In SSVNE scheme, when $M_2 \neq 0$,to protect against M_2 failures, $M_2 + 1$ Snodes should be mapped to one Vnode, and $M_2 + 1$ paths between each pairs of node. The constraint conditions (37), (38) change to (58), (59), and (49) to (60).

$s \neq d, s, d \in V$

$$N(s,d,l'_i) \geq [s'(s) \cdot d'(d) + d'(s) \cdot s'(d)] \cdot M_{node} \cdot nn_{s,d}^3 \cdot (M_1 + 1) \quad (58)$$

$$N(s,d,l'_i) \geq [s'(s) \cdot d'(d) + d'(s) \cdot s'(d)] \cdot M_{node} \cdot (1 - nn_{s,d}^3) \cdot [k_{s,d} - p_{s,d}(srg)] \quad (59)$$

$$R_{v_m}^{v'_i} = v'_i(v_m) \cdot \boldsymbol{R}_{v'_i} \quad (60)$$

The constraint conditions of SSVNE include the concept constraint conditions (25)-(30), the positional relationship between the used slot conditions (31), (32), the survivable constraint conditions (33), (34), the number of nodes and paths conditions (40), (58), (59), the slot contiguity conditions (41), the slot unique conditions (42)-(45), the link resource requirement conditions (47), (56), (57), the node resource requirement conditions (50), (60), the primary path conditions (54), (55), and the SRG-disjoint conditions (51), (52), while the design of variables includes the slots continuity condition.

C. OMVNE SCHEME

In one-to-one multipath virtual network embedding scheme (OMVNE), each virtual node can be mapped to only one substrate node. This section describes the differences between the models of OMVNE and SMVNE schemes.

So (33) changes to (61).

$$N(v') = 1 \quad (61)$$

When $M_2 \neq 0$, in OMVNE scheme, the Vlinks may be down under node failures, because not enough node protection is available for source or destination node, and the number of path is restricted to the topology. So, in modeling the scheme $M_2 \neq 0$ is not considered.

When $M_2 = 0$, the OMVNE scheme requires $M_1 + 1$ paths to protect against M_1 failures. But, if there are not enough disjoint paths, then the Vlinks may be down with failures. For survivable VN, one must try to map enough paths to Vlinks and keep the number of Vlinks without enough paths to the minimum.

Given:

NN_3: The same as in SSVEN.

Variables:

$nl'_{s,d}$: Boolean variable that denotes whether the number of SRG-disjoint paths of virtual link l', between physical nodes s and d, is larger than $M_1 + 1$; if it is, $nl'_{s,d} = 0$, or else $nl'_{s,d} = 1$.

Objective Function:

$$Min \sum_{m=1}^{|L|} S_{l_m} + \alpha \sum_{n=1}^{|V'|} N(v'_n) + \beta \sum_{i=1}^{|L'|} \sum_{s,d} nl'_{s,d} \quad (62)$$

where, β is a variable for weighting the importance of minimizing the number of Vlinks without enough protection.

When the number of Vlinks without enough protection is taken into consideration, (24) changes to (62).

Constraints:

So, (35)-(39) change to (63)-(66), and (49) to (60).

$s \neq d, s, d \in V$

$$N(s,d,l') \geq [s'(s) \cdot d'(d) + d'(s) \cdot s'(d)] \cdot [1 - nn_{s,d}^3] \cdot [k_{sd} - p_{s,d}(srg)] \quad (63)$$

$$N(s,d,l') \geq [s'(s) \cdot d'(d) + d'(s) \cdot s'(d)] \cdot (1 - nn_{s,d}^1(l')) \cdot nn_{s,d}^3 \cdot (M_1 + 1) \quad (64)$$

$$N(s,d,l') \geq [s'(s) \cdot d'(d) + d'(s) \cdot s'(d)] \cdot kk_{l'_i} \cdot nn_{s,d}^1(l') \cdot M_1 / (1-\rho) \quad (65)$$

$$N(s,d,l') \geq [s'(s) \cdot d'(d) + d'(s) \cdot s'(d)] \cdot (1 - kk_{l'_i}) \cdot nn_{s,d}^2(l') \cdot [M_1 + \sqrt{\rho M_1 l'(b) / \boldsymbol{G}}] \quad (66)$$

Equation (67) ensures that $nl'_{s,d}$ is coincident with its definition.

$$nl'_{s,d} \geq [s'(s) \cdot d'(d) + d'(s) \cdot s'(d)] \cdot (1 - nn_{s,d}^3) \quad (67)$$

If $nl'_{s,d} = 1$, $B_{s,d}^{l'}$ should be $l'(b)$, for best survivability of the VN.

Formulation (48) changes to (68).

$$B_{s,d}^{l'} \geq nn_{s,d}^3 \cdot l'(b) + nn_{s,d}^1 \cdot (1 - nn_{s,d}^3) \cdot kk_{l'_i} \cdot (1-\rho)\, l'_i(b)/M_1 + nn_{s,d}^1 \cdot (1 - kk_{l'_i}) \cdot (1 - nn_{s,d}^3) \cdot \sqrt{\rho \cdot \boldsymbol{G} \cdot l'_i(b)/M_1} + nn_{s,d}^2 \cdot \sqrt{\rho l'_i(b) \boldsymbol{G} / M_1} \quad (68)$$

The constraint conditions of OMVNE include the concept constraint conditions (25)-(30), (67), the position relationship between the used slot conditions (31), (32), the number of node constraint conditions (61), the number of paths conditions (63)-(66), (40), the slot contiguity conditions (41), the slot unique conditions (42)-(45), the link resource requirement conditions (46), (47), (68), the node resource requirement conditions (50), (60), and the SRG-disjoint conditions (51), (52), while the design of variables includes the slots continuity condition.

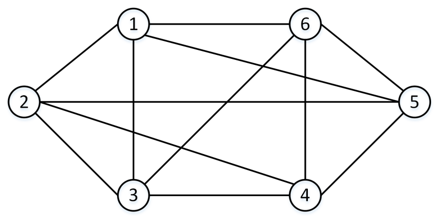

FIGURE 6. Illustration of physical topology.

D. OSVNE SCHEME

OSVNE scheme is a traditional scheme without MPP and one-to-multi mapping. So, this scheme has no protection for node failures, besides, its disjoint paths may not be enough for M_1 link failures. So, the objective is (62). The number of nodes condition is as given by (61), and the number of paths should be $M_1 + 1$. If $nn^3_{s,d} = 0$ does not give enough disjoint paths, then the best way is to try to map the most disjoint paths. So, the number of path condition is (69), (70) and (40).

$$N(s, d, l'_i) \geq [s'(s) \cdot d'(d) + d'(s) \cdot s'(d)] \cdot nn^3_{s,d} \cdot (M_1 + 1) \quad (69)$$

$$N(s, d, l'_i) \geq [s'(s) \cdot d'(d) + d'(s) \cdot s'(d)] \cdot (1 - nn^3_{s,d}) \cdot [k_{s,d} - p_{s,d}(srg)] \quad (70)$$

These include the prime and back paths; so, the primary path condition is given by (54), (55), and link resource requirement condition by (47), (56) and (57).

The other constraint conditions of OSVNE include concept constraint conditions (25)-(30), (67), the position relationship between the used slot conditions (31), (32), slot contiguity conditions (41), the slot unique conditions (42)-(45), the node resource requirement conditions (50),(60), and the SRG-disjoint conditions (51),(52), while the design of variables includes the slots continuity condition.

IV. NUMERICAL ANALYSIS

This section investigates the performance of the proposed SMVNE by simulations and comparisons. To compare the spectrum efficiency (SE) of MPP and SPP, multi-node and single-node mapping, the other three schemes (SSVNE, OMVNE, OSVNE) are also simulated. The physical topology, which is used for simulation, is shown in Fig. 6.

The ILP models are implemented and solved using MATLAB with the YALMIP toolbox [51]. The bandwidth of each slot is assumed to be 6.25 GHz, with 700 slots on each fiber ($\boldsymbol{W} = 700$). The real number of CPU resources of the substrate nodes is 80 ($\boldsymbol{R} = 80$). The CPU resource requirement of each virtual node is 4, which means $R_{v'_i} = 4$. Table 1 shows the simulation parameters and the performance data. To show the partial protection we assume $\rho = 0.8$ in most simulations. The parameter α and β mean the weight of overhead of node split and the weight of survivability. Considering the banlance of the scheme and the order of magnitude, they are assumed to be $\alpha = 10$ and $\beta = 5$.

TABLE 1. Simulation parameters and performance data.

Notation	Description
Parameter: vV	The average number of Vnodes.
Parameter: vL	The average number of Vlinks.
Parameter: $l'(b)$	The number of slot requirement of Vlink l'. The number of $l'(b)$ can be 8, 16, and 32, which represent 100, 200 and 400 Gbps.
Parameter: ρ	The protection level.
Parameter: SRG	Whether the SRLG is considered.
Parameter: $\boldsymbol{G}$	The slot number of guard bands.
Parameter: M_1	The number of link failures.
Parameter: M_2	The number of node failures.
Parameter: α	The weight of overhead of node split.
Parameter: β	The weight of survivability.
Data: S	The sum of S_{l_m}, $S = \sum_{m=1}^{\|L\|} S_{l_m}$.
Data: NV	The sum of $N(v'_i)$, $NV = \sum_{n=1}^{\|V'\|} N(v'_i)$.
Data: NL	The sum of $N(l'_i)$, $NL = \sum_{n=1}^{\|V'\|} N(l'_i)$.

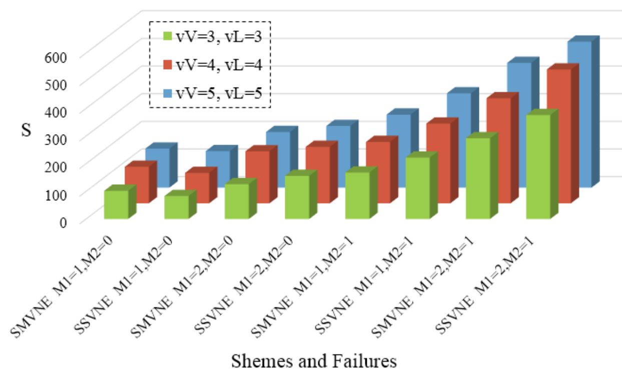

FIGURE 7. Comparison of the sum of the maximum used slot index (*S*) with different numbers of failures. *vV* is the average number of Vnodes and *vL* is the average number of Vlinks.

The probelm is a NP-hard promblem. The number of variables of the proposed model is $O(\left|L'\right|^2 \cdot |L| + |V|^2 \cdot \left|L'\right|)$ and the number of conditions is 27.

A. PERFORMANCE OF SMVNE

To investigate the performance of the proposed SMVNE scheme against multiple failures, the solutions of ILP are compared with different schemes or variables. It is assumed that $\alpha = 10$.

1) SPECTRUM EFFICIENCY

Figure 7, which shows the SE results of SMVNE and SSVNE with different numbers of failures, illustrates the effect of MPP on SE. In the simulations, it is assumed $l'(b) = 16$, no SRG, $\rho = 0.8$, $\boldsymbol{G} = 1$.

S is the sum of the maximum used slot index on physical links. So, it can reflect both the slot consumption and spectrum efficiency. With single link failure ($M_1 = 1, M_2 = 0$), SPP consumes fewer slots than does MPP. In this case, with MPP, the number of guard-band slots added, and the total number of the incremental slots is more than the number of

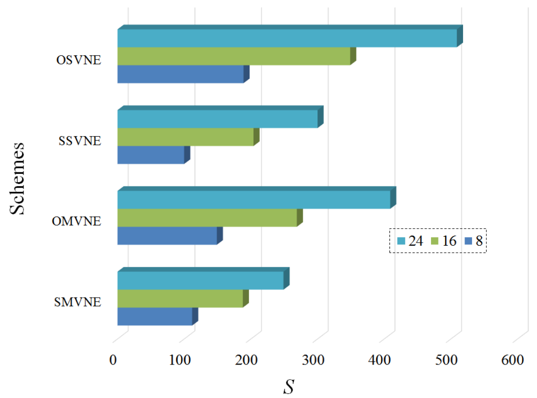

FIGURE 8. Comparison of the sum of the maximum used slot index (S)with different schemes with different number of slot requirement of virtual link ($l'(b)$ = 8, 16, 24).

saved slots. In the other cases, S with MPP is less than that with SPP. This means that multipath transportation can very well improve the spectrum efficiency under multiple failures, and it should be used considering the whole consumption. The results show that SMVNE can reduce the sum of S_{l_m} by approximately 22 % than SSVNE at the best.

Figure 8 shows that the SE results of SMVNE, OMVNE, SSVNE, OSVNE for different values of $l'(b)$. It reflects the SE effect of multiple node. For simulations, it is assumed that $vV = 4, vL = 4$, no SRG, $\rho = 0.8$, $\boldsymbol{G} = 1$. The result shows that the sum of S_{l_m} with SMVNE is always less than that with OMVNE, and the sum of with SSVNE is always less than that with OSVNE. The results show that multiple node scheme can significantly reduce the sum of S_{l_m}.

2) CONSUMPTION OF CPU RESOURCE

The consumptions of CPU source (CCS) under different number of failures with different schemes, is simulated, and the results are shown in Fig.9. As OMVNE and OSVNE cannot protect traffic against multiple node failures, only CCS under $M_1 = 2, M_2 = 0$ is considered. In the simulations, it is assumed that $vV = 4, vL = 4, l'(b) = 16$, no SRG, $\rho = 0.8$, $\alpha = 10$, $\beta = 5$ and $\boldsymbol{G} = 1$. From the results, it can be seen that the CCS remains the same even as the number of failures changes, and the CCS of SSVNE is less than the CCS of SMVNE. For less spectrum consumption Vnodes are mapped to multiple Snodes, regardless whether $M_2 = 1$ or not. In other words, the proposed scheme achieves higher SE by sacrificing part of the node resources.

3) SURVIVABILITY

The results in Fig. 10 illustrate the survivability performance of SMVNE, OMVNE, SSVNE, OSVNE. The red color of the grid indicates that, with that scheme, the VN failed as the number of failures changed, whereas the green color indicates that, with that scheme, the VN is survivable even as the number of failures changed. It is assumed that $vV = 4, vL = 4, l'(b) = 16$, no SRG, $\rho = 0.8$, and $\boldsymbol{G} = 1$. Considering seven different scenarios, it can be seen that the

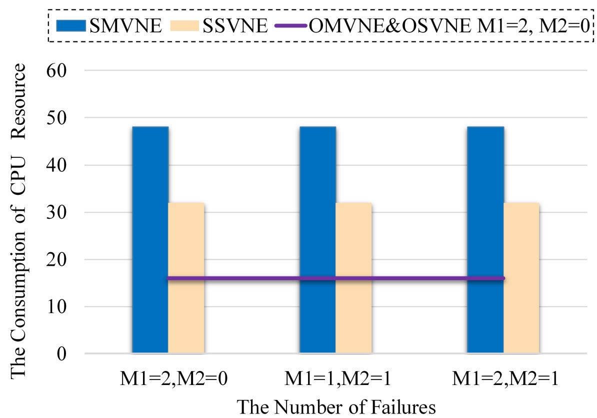

FIGURE 9. The consumption of CPU resource with different number of failures.

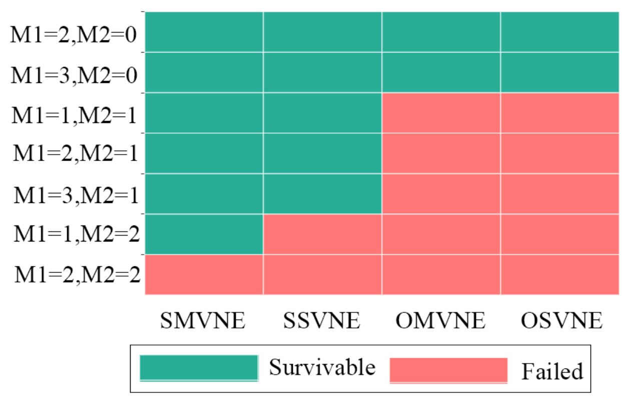

FIGURE 10. Comparison of the survivability with different schemes.

survivable rate is 85.7% for SMVNE, 71.4% for SSVNE, and 28.6% for OMVNE and OSVNE. This shows that the SMVNE algorithm has significant survivability, which can effectively increase the network survivability.

B. INFLUENCE OF PARAMETER

To investigate the influence of parameters on the proposed SMVNE scheme, models with different parameters are solved. When the parameters are not under investigation, it is assumed that $vV = 4, vL = 4, l'(b) = 16$, no SRG, $\rho = 0.8$, $\alpha = 10$, $\beta = 5$ and $\boldsymbol{G} = 1$.

1) INFLUENCE OF DEMAND

For this simulation, it is assumed that $M_1 = 2, M_2 = 1$. From Fig. 11, it can be seen that with increasing traffic demand, S ($S = \sum_{m=1}^{|L|} S_{l_m}$) increases. With SMVNE, S is always less than that with SSVNE. It is obvious from the figure that SE improves with increase in demand, because, with fixed $\boldsymbol{G}$, the higher the demand, the more would be the saving in slots.

2) INFLUENCE OF GUARD-BAND BANDWIDTHS

As can be seen from Fig.12, with different bandwidths of guard band ($\boldsymbol{G}$), S increases with increasing traffic demand.

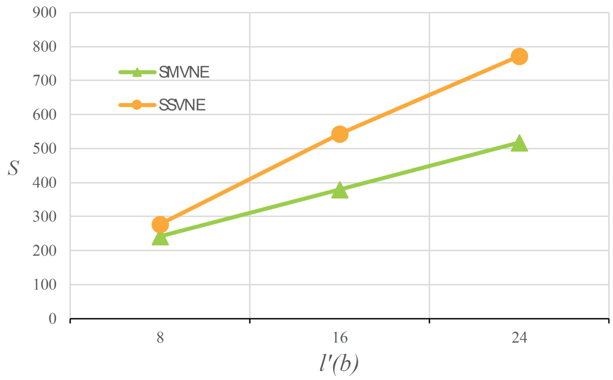

FIGURE 11. Comparison of the sum of the maximum used slot index (*S*) with changing demands the number of slot requirement of virtual link ($l'(b)$).

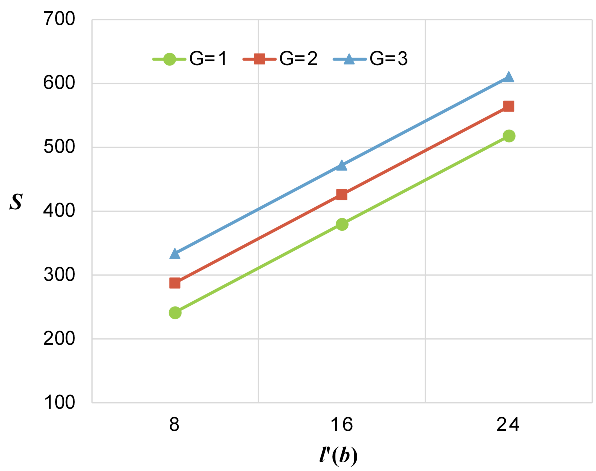

FIGURE 12. Comparison of the sum of the maximum used slot index (*S*) between different guard-bands bandwidths (*G*) and $l'(b)$ is the number of slot requirement of virtual link.

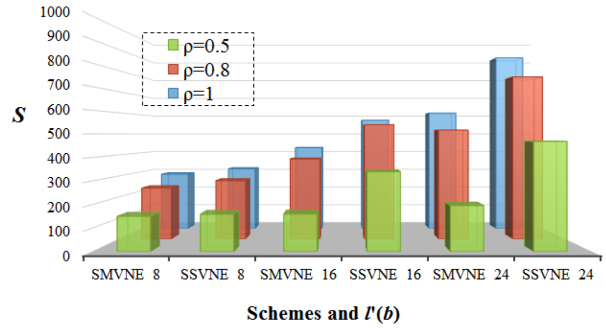

FIGURE 13. Comparison of the sum of the maximum used slot index (*S*) between different protection levels.

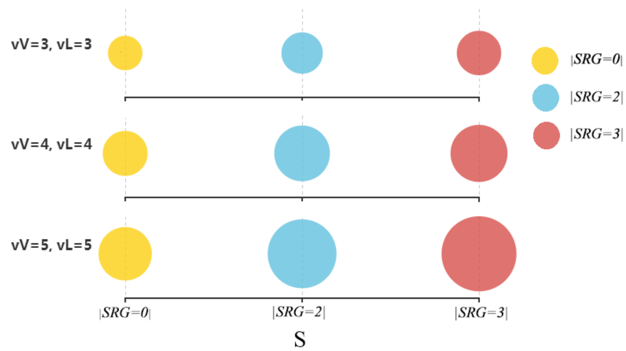

FIGURE 14. Comparison of the sum of the maximum used slot index (*S*) with different SRG.

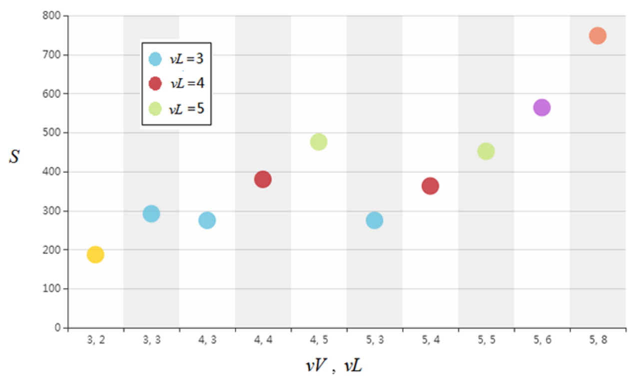

FIGURE 15. Comparison of the sum of the maximum used slot index (*S*) with different VN scales. *vV* is the average number of Vnodes and *vL* is the average number of Vlinks.

The increment of S is the same, with the same increment of $\boldsymbol{G}$ (i.e. $\Delta\boldsymbol{G} = 1$), even under different bandwidth demand condition. This is because the number of multipaths remains same with different bandwidth demand, and the influence of $\boldsymbol{G}$ also is the same.

3) INFLUENCE OF PROTECTION LEVEL

The influence of protection level is investigated with $vV = 4, vL = 4$, no SRG, and $\boldsymbol{G} = 1$, and the results are shown in Fig. 13. The results show that, with different traffic demands, S increases proportionally to the level of increases in protection, because the higher the protection level, the more would be the number of slots needed for protection. And, it can be seen that the consumption of SMVNE is less than that of SSVNE.

4) INFLUENCE OF SRLG

In Section II C, it is shown that SRG influences the bandwidth demand. The influence of SRG is investigated with different numbers of links in one SRG (see Fig. 14). As the number of links included in the SRG increases, also increases, because the more the number of links in one SRG, the less would be the number of links that can be mapped to Vlinks at the same time.

5) INFLUENCE OF *vV* AND *vL*

As can be seen in Fig.15, the scale of VN will influence S. With vV remaining the same, S increases with increasing vL. However, with vL remaining the same, S reduces with increasing vV. This is because, the VLinks can be mapped to

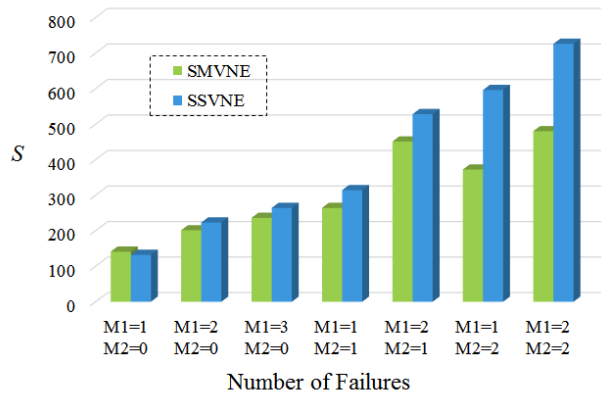

FIGURE 16. **Comparison of the sum of the maximum used slot index (*S*) under different numbers of failures.**

more pairs of Snodes, as vV increases; besides, the guardband consumption decreases, following which S also decreases.

6) INFLUENCE OF M_1 AND M_2

Moreover, the S of schemes is also compared under different numbers of failures and the simulation results are shown in Fig.16. It can be seen that the number of failures significantly influences the SE of SMVNE. As the number of node failures increases, the advantages of SMVNE increase more quickly than those with link failures. This is because the node failures may influence more virtual links, and the SMVNE scheme can protect them better.

V. CONCLUSION

In this paper, an SMVNE scheme is proposed against multiple failures to achieve higher spectrum efficiency and better survivability with SDN/NFV in EON. For minimal resource consumption, the authors analyzed the number and resource requirement of physical nodes that carry one virtual node, the spectrum requirement of each path of one virtual link, the number of paths considering SRG, and the graph theory with SMVNE scheme against multiple failures. Menger's Theorem is used to get the maximum number of disjoint paths between node pairs. It is found that the requirement of bandwidth is related to the number of paths, the number of failures, and the protection levels. To compare the spectrum efficiencies of MPP and SPP, one-to-one node mapping and one-to-multi node mapping, three other schemes are modeled: SSVNE, OMVNE and OSVNE. ILP models are used to describe the four schemes.

The proposed SMVNE scheme is evaluated with numerical simulations. The simulation results of the four schemes show the spectrum efficiency and survivability performance of SMVNE. The performance of SMVNE scheme also is investigated against multiple failures with different parameters, namely the bandwidth of guard band, the level of protection, the number of failures, the scale of VN etc. The simulation results show that the proposed SMVNE scheme against multiple failures, with SDN/NFV, achieves significant gain in terms of spectrum efficiency and survivability.

The proposed approach based on ILP, and it is not implementable for large networks. Because the computational complexity is exponentially increasing with the increase of network size. The heuristic algorithm will be developed and studied in the future.

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