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Prediction-based survivable virtual network mapping against disaster failures

Ying Wang,*† Xiao Liu, Xuesong Qiu and Wenjing Li

State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications, Beijing, China

SUMMARY

Survivable virtual network mapping (SVNM) guarantees that the mapped virtual network works normally against substrate failures. Most of the existing solutions are mainly focusing on single node or single link failure. A long-standing challenge in SVNM is to reduce the capacity loss of network when substrate failures happen. Because some regions are frequently attacked by disasters, the disaster failures should be paid attention to. In this paper, we re-consider the existing work on the SVNM and explore the feasible solution of SVNM against disaster failures. We first design the disaster failure model with the knowledge of risk assessment. Then we formulate the problem with the mixed integer programming. Two heuristic algorithms based on the prediction mechanism are proposed. Simulations show that our algorithms increase the average acceptance ratio and reduce the risk of capacity loss in the initial mapping phase compared with previous algorithms. Copyright © 2016 John Wiley & Sons, Ltd.

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1. INTRODUCTION

As a promising technology to support the evolvement of the future networks, the network virtualization has obtained the extensive attention in the last few years, by allowing heterogeneous virtual networks (VNs) to run on a shared substrate network simultaneously [1]. It is considered as an effective way to support the services or applications in emerging areas such as software defined networking, network function virtualization, and cloud computing [2].

In a network virtualization environment, it is possible to create new business model by separating the conventional Internet service provider's role into infrastructure provider (InP) and service provider (SP). The InP is responsible for deploying and maintaining the substrate network that is composed of physical nodes and links. The SP assembles the customized VNs by integrating resources leased from InP according to the end-users' requirements, such as the computing power of the virtual node, bandwidth capacity between the virtual nodes. To make it work, the InP will then allocate substrate resources to the VN according to the requirements. Compared with the traditional Internet SP, the SP can focus on providing various and superior services without the burden of building and maintaining the functional capability of physical infrastructure.

Virtual network mapping (VNM), which aims at effectively calculating allocation of the substrate resources for the VN requests, provides technical support toward the network virtualization [3]. During the process of the mapping, VN requests with resource constraints of node and link must be met. Besides, the admission control and the online nature of VN requests also make the VNM problem difficult [4]. The VNM problem is simplified to the multi-way separator problem [5]. Many existing works have been carried

*Correspondence to: Ying Wang, State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications, Beijing, China. E-mail: wangy@bupt.edu.cn

out for solving the VNM problem [6–9]. However, the circumstance is not considered exhaustively that sudden failures occur during normal operation. These failures result in service interruption of the VNs, which have been mapped on the failed substrate network components. Therefore, we explore to map a VN to a substrate efficiently while guaranteeing that the VNs survive the failures.

Recent progress about survivable virtual network mapping (SVNM) was reported in [10–15]. The fundamental research on the SVNM is based on the assumption that a single node or link fails at one time. The common strategies for solving the problem of SVNM are classified into two categories: one is the protection mechanism by reserving backup substrate resources before the failure. The other is the restoration mechanism by remapping the virtual nodes or links from the failed substrate nodes or links to the normal substrate nodes or links. The problem of the SVNM under the single failure scenario can be solved efficiently by adopting the two mechanisms. However, because the substrate network failures caused by disasters happen occasionally, network survivability has become a major concern. Authors in [10] study the disasters and cascading failures in network. The authors elaborate the characteristics of network failures caused by disasters and debate the feasibility that the disaster information can be obtained to assess the severity of disaster failure in a geographic region. Compared with the traditional single failure scenario [16,17], the disaster failures are boarder in the scope and more destructive. Using protection mechanism to handle the disaster failures may lead to large numbers of idle backup resources when there is not network disruption [13]. Besides, the restoration strategy against the disaster failures may be unrealizable when there are not sufficient resources to remap the affected nodes and links outside of the affected regions. Therefore, the solutions under the single failure scenario are of limited applicability to solve the problem under the disaster failures.

In this paper, we propose two prediction-based SVNM mechanisms in the case of disaster failures. The prediction means that the potential failure risk of substrate network resource can be made aware of based on the historical network failures statistics. Compared with the protection and restoration mechanisms, prediction mechanism achieves the goal that the capacity loss caused by the disaster can be controlled in the initial mapping. A disaster failure model and two effective mapping algorithms are proposed. Our goal is to reduce the capacity loss of VNs caused by disaster failures and increase the average VN acceptance ratio. The main contributions of our work are as follows:

- A prediction mechanism is proposed to reduce the capacity loss of VN against the disaster failures. This mechanism takes advantage of the historical failures statistics to analyze the potential disaster impact area and provide guidance for the VNM in the initial mapping phase. In the part of model construction, we will debate this prediction scheme.
- A disaster failure model with the knowledge of risk assessment is designed to describe the problem space. With this model, we can analyze the impact degree of the disasters on the substrate network.
- Based on the disaster failure model, we propose two efficient mapping algorithms that are called the minimum fault risk prior selection (MFRPS) algorithm and the asymmetric parallel flow allocation (APFA) algorithm, combining the greedy strategy and the path-splitting mechanism in the link mapping stage.

The rest of this paper is organized as follows. Section 2 reviews the related work. Section 3 describes the network model and defines the problem. Section 4 presents the proposed algorithms. Simulation results are presented in Section 5, and this paper is concluded in Section 6.

2. RELATED WORK

Virtual network mapping has received great attention in recent years, and the classic VNM approaches in [4,6,9,18–22] have been studied extensively. Yu *et al.* in [4] proposed a typical mapping method based on a path-splitting strategy to enhance the VN acceptance ratio and achieve load balance effect. Although the survivability from the substrate failures is not considered in this method, it gains fault tolerance to some extent. One of our proposed algorithms (APFA) employs the similar strategy of path splitting. However, the main difference is that our work augments the algorithm used in [4] by introducing the risk assessment in path selection.

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Because VNs are mapped over a shared substrate network during the network operation, even a single failure in the substrate network can affect a large number of VNs and the services they offer. To guarantee the survivability from the substrate link or node failures, authors in [14,22] propose effective approaches by protectively reserving shared backup network provision for a single substrate link or node. The shared backup scheme can increase the utilization of substrate resources effectively and guarantee the survivability against single link or node failure. However, the backup method has limitation in disaster failure scenario. The demand of the backup resources is large, and the available backup resources outside of the disaster impact areas are few after the disaster. Such demand of backup resources is not easy to be satisfied.

There are also some related works about the disaster scenarios in the optical networks. The researchers demonstrate that the disasters can cause severe service disruptions due to large-scale correlated cascading failures in networks [23]. The disaster failures can be classified into two types: horizontal correlated cascading failures and vertical correlated cascading failures [10,24]. The former means that other substrate network failures are caused by some correlated incidents after the initial disasters. The latter means that the VN in the upper layer fails because of the lack of restoration of the substrate network. In the network virtualization environment, we focus on the vertical correlated cascading failures. Network operators and SPs need to adapt their networks to a more disaster-prone environment and be prepared for increasing frequencies of disasters. Related works on how to predict disasters and assess risks of disasters for certain regions have been extensively researched in the fields of climatology, geology, and environmental science [10]. Based on the fundamental research, the novel methods are developed to prevent the networks against severe disaster failures with the knowledge of risk regions. Researchers in [25] provide the failure-dependent protection against the single regional failure in a distinguishing perspective. They use the single regional failure to describe the substrate network failures that caused by the same disaster in a geographic region. In their method, the node failures under single regional failure are addressed by migrating the failed VN nodes from the disaster impact areas. Actually, such approach may require massive bandwidth overprovisioning, which results in the waste of resources. The authors in [23] explore the influence of disasters on optical networks. The risk assessment is adopted to analyze the influence of disasters. The feasibility and reasonability that the historical statistics information of the disaster failures can be acquired are debated [15]. Illuminated by their studies, we introduce the risk assessment to analyze the disaster failures.

Different from these related works, we focus on SVNM against disaster failures based on prediction strategy. A disaster failure model and two algorithms are proposed with the greedy and the path-splitting strategy with the objective of increasing the average acceptance ratio and reducing the capacity loss in the design of the mapping algorithms.

3. DISASTER FAILURE MODEL FORMULATION

3.1. *Substrate network*

Similar to previous works in [7,8], the substrate network can be modeled as an undirected graph $G^\rho = (N^\rho, E^\rho)$, where $N^\rho = N^\rho_H \cup N^\rho_S$ is the set of substrate nodes and E^ρ is the set of substrate links. Note that N^ρ is composed of host devices and switch devices. N^ρ_H is the set of host devices, and N^ρ_S is the set of switch devices. We assume that each node in N^ρ_H is attached to a node of N^ρ_S. Note that the host devices are terminal devices and are connected to the switch devices. When the host devices fail, they can be mapped to another unaffected host devices. To simplify the discussion, the substrate node does not distinguish between N^ρ_H and N^ρ_S. For each substrate node $n^\rho \in N^\rho$, the node computing capacity is $\varsigma(n^\rho)$, and the cost of node computing capacity on substrate node n^ρ is $\lambda c(n^\rho)$. For each link $e^\rho \in E^\rho$, the available bandwidth is $\omega(e^\rho)$, and the cost of bandwidth is $\lambda l(e^\rho)$. Additionally, substrate link $e^\rho \in E^\rho$ is also denoted as $(n^\rho, n^{\rho'})$, where n^ρ and $n^{\rho'}$ are a pair of adjacent substrate nodes. We also denote the set of all loop-free paths by $\mathcal{P}$ in the substrate network.

Figure 1(b) shows an instance of the substrate network, where the number over the link represents the available bandwidth and the cost of bandwidth, while the number in the rectangle denotes the available node computing capacity and the cost of node computing capacity.

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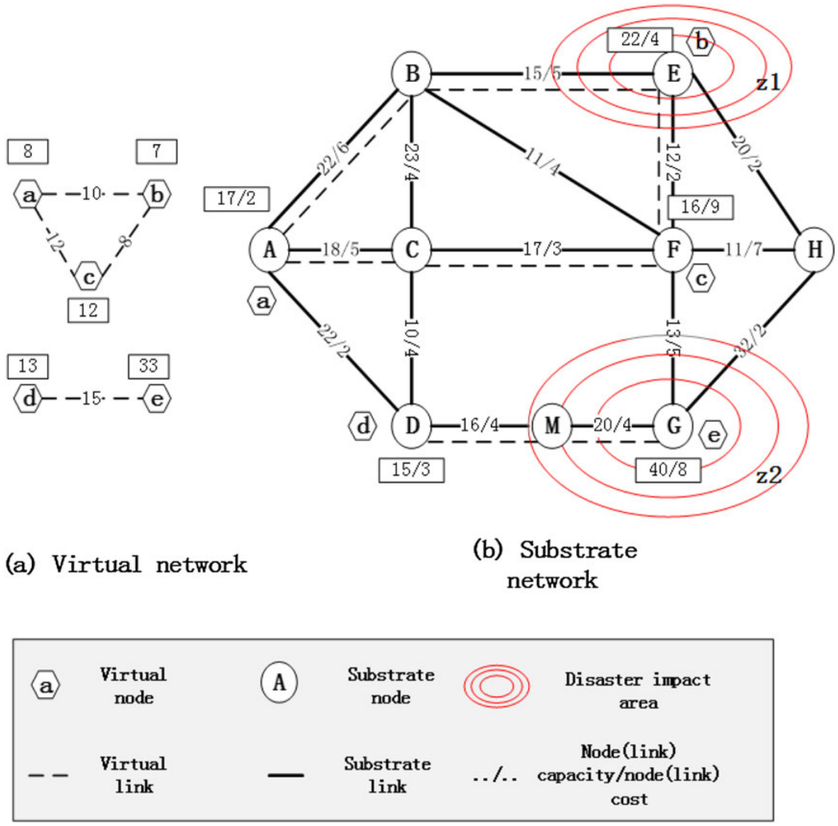

Figure 1. An instance for SVNE against disaster failure

3.2. VN request

A VN request is also modeled as an undirected graph $G^v = (N^v, E^v)$, where N^v is the set of VN nodes and E^v is the set of VN links. Here, each virtual node $n^v \in N^v$ has node computing capacity demands $\varepsilon(n^v)$, and each virtual link $e^v \in E^v$ has bandwidth demands $\varrho(e^v)$. The virtual link $e^v \in E^v$ is also denoted as $(n^v, n^{v\prime})$, just as the definition of the substrate link. Figure 1(a) shows an example of the VN request with three VN nodes and two VN links, and the related node computing capacity demands and bandwidth demands.

3.3. Disaster scenario and disaster failure model

3.3.1. Disaster scenario

Generally, substrate failures are caused by natural disasters such as earthquake, tsunami, tornado, hurricane, or human-made disasters such as weapons of mass destruction and electromagnetic pulse attacks [26–28]. The threats from disasters make the research of the SVNM against disaster failures more crucial in coming years. Compared with the traditional single substrate failure, new features are as follows:

- Failures diversity: Different disasters can cause the substrate network failures in different degrees.
- Broader scope: The range of impact is broader when disaster happens in a geographic region in comparison with the single substrate failure scenario. We should take it into account the broader scope of the failures and depict the disaster impact range in our model.
- Disaster predictability: Based on the reason that some regions may suffer from similar disaster, the historical failure statistics can be used to analyze the failures caused by certain disaster. The substrate network resources can be allocated more reasonably in the initial mapping stage.

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Hence, these aforementioned new requirements are considered in the model with the objective of reducing the capacity loss.

3.3.2. *Disaster failure model*

To study the SVNM under disaster failure scenario, we model the disaster failure from the following aspects.

(1) The classification of the disaster failures

Disaster failure refers to the substrate failure caused by disaster in a limited geographic region. Because some substrate failures caused by the same disaster are similar, we adopt the method that classifies these similar failures into the same group akin to the shared-risk group. The concept of the shared-risk group is introduced to represent a generic set of substrate nodes or links that fail together with a kind of failure feature. For example, in the optical network, the fibers are always laid in bundle to be used. The cut of the bundle results in many fibers that are laid in the bundle fail. The disaster incident that the bundle is cut is defined failure feature that leads the fibers in the bundle to fail. In the disaster failure scenario, the same type of disaster may cause similar feature of the substrate failures. We can adopt the idea of classification to research the disaster failures. In this paper, lists of possible disaster failures are denoted by the set of F. Each disaster failure $f_i \in F$ represents a kind of substrate failure.

(2) Disaster impact area

When the network is attacked by the disaster, it can be damaged severely if the disaster happens in a geographic area and affects many network nodes and links. In consideration of the border scope of disaster, the disaster impact area is defined to depict the relationship between the substrate failures and the disasters. It refers to the geographic region in which the network is affected by disaster. Actually, the disaster impact area can take any shape. In this paper, the disaster impact area is designed to circular shape with the consideration of the convenience.

Formally, the substrate network topology affected by disaster is modeled as an undirected graph $G^z = (N^z, E^z)$, where $N^z \subset N^p$ and $E^z \subset E^p$. The number z identifies the network topology. Let $Dis_{i,j}$ be the Euclidean distance between substrate node i and node j, $1 \le i \le n$, $n = |V|$. For example, in Figure 1(b), there are two disaster impact areas $z1$ and $z2$, which are mutually non-overlapped. The substrate node E as well as the substrate link (B,E), (E,F), (E,H) in disaster impact area $z1$ may fail. Similarly, the substrate nodes or links may fail in $z2$.

Definition 1: (Disaster impact area) is defined by the circular disaster covering area $Z = (Z._c, Z._r)$, where $Z._c$ is the location of the epicenter and $Z._r$ is the radius of the circular disaster covering area. $Dis_{c,j}$ ($Dis_{c,j} \ge 1$) is the distance from component j to the epicenter c, where j is the number of the component. The disaster impact variable DI_j evaluates the disaster impact intensity on the substrate component. The disaster impact variable of the substrate component j after a disaster is defined by the following equation:

$$DI_j = \begin{cases} \dfrac{1}{Dis_{c,j}} & , Dis_{c,j} \le \Lambda_r \\ 0 & , \text{otherwise} \end{cases} \tag{1}$$

The disaster impact value is sensitive to the range of network topology. It decreases with the increasing of distance between the node j and the epicenter after a disaster. Note that the substrate component can be a substrate node or link. In this paper, the disaster failure area and the affected network topology are overlapped in the space. We also use the number z to indicate the affected area.

Definition 2: (Potential fault probability) is a conditional probability to describe the possibility of the potential disaster failure, which is denoted as $p_{c_j^z}(f)$. It is calculated by the empirical function $p_j^h(f)$ based on historical failures statistics, where $p_j^h(f) \in [0,1]$, $f \in F$, and $c_j^z \in G^z$. F and G^z are the set of disaster failures and the affected substrate network topology G^z. For simplicity, $p_{c_j^z}(f)$ and $p_j^h(f)$ are denoted as $p_{c_j^z}$ and p_j^h, respectively. The formula is as follows:

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$$p_{c_j^z}(f) = P\left(c_j^z \text{ fail} \middle| DI_j \leq \frac{1}{n} \cdot \sum_j \frac{1}{Dis_{c,j}}\right) = \frac{\left[1 - \prod_{j \in G^z}\left(1 - p_j^h\right)\right] d_{\max}^2}{d^2} \tag{2}$$

where c_j^z represents the substrate node or link in the affected substrate network topology G^z. j represents the number of the component. d is the average distance of the disaster impact, and $d_{\max}$ is the max distance of the disaster impact.

Definition 3: (Region risk probability) is defined to describe the failure probability of the specific disaster impact area z. It is formulated by the empirical function $p_z(f)$, where $p_z(f) \in [0, 1], f \in F$. F is the set of disaster failures. For simplicity, $p_z(f)$ is denoted as p_z. The formula is as follows:

$$p_z(f) = \frac{1}{n} \sum_{c_j^z \in G^z} p_{c_j^z} \cdot \alpha_j \tag{3}$$

Region risk probability and potential fault probability are empirical probability based on the risk awareness of the disaster failure. The two probabilities are used to find the potential disaster failure area and describe the failure possibility of the network component in the affected area. The severity of each disaster failure area is decided by two factors, one is region risk probability and the other is potential fault probability.

(3) Prediction mechanism

Based on the knowledge of the historical network failures and the aforementioned definitions, each potential substrate failure can be made aware of. This process is called prediction. A newly happened failure will become a part of the failure classification set. It will then impact on the computation of the SVNM and be reflected in the subsequent VNM. In this paper, the design of the algorithms focuses on the initial mapping phase, which adopts a kind of best effort way to decrease the capacity loss when the disaster failure happens.

The SVNM requires that VN maintains transparency. It means that the VN can work normally when the related substrate nodes or links fail. The typical solution is to reserve a backup substrate path as the bypass of the normal work path. However, this solution is not suitable to the disaster failures because the redundant resources for backing up are so large. Moreover, because of the complexity of disaster failures, the circumstance exists that there are not available substrate components outside of the disaster impact areas to remap the affected VN after the failure. Therefore, the prediction mechanism is proposed to maintain the weak survivability. With the mechanism, VNs are mapped on the substrate network component that has lower failure possibility to guarantee the survivability.

3.4. Problem statement

Given: A SN $G^p = (N^p, E^p)$, lists of VN requests, the set of disaster failures F, and $|Z|$ number of disaster impact area Z.

Question: How to map as many incoming VN requests as possible onto G^p based on the disaster failure model to minimize the expected capacity loss and still be able to increase the average VN acceptance ratio?

3.5. Objective

Good efficiency of the resources allocation must be achieved within the period of the VNM. We also want to increase revenue and decrease the cost of the InP in the long run. Along this line, the revenue from providing a VN request is formulated akin to [8] as

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$$\mathbb{R}\left(G^V\right) = \alpha \sum_{e^V \in E^V} \varrho(e^v) + (1-\alpha) \sum_{n^V \in N^V} \varepsilon(n^v) \tag{4}$$

where α is the coefficient of the link resources. It reflects the importance of the nodes' revenue relative to the links' revenue in the overall revenue. $\varrho(e^v)$ is the bandwidth demands, and $\varepsilon(n^v)$ is the computing capacity demands. The revenue of a VN evaluates how much profits an InP will gain by accepting a VN request. Then the cost of accepting a VN is

$$\mathbb{C}(G^v) = \mathbb{C}_{\mathscr{H}}(G^v) + \mathbb{C}_{\mathscr{C}}(G^v) \tag{5}$$

The cost of VN G^V mapped by InP is denoted as $\mathbb{C}(G^v)$; it includes bandwidth consumption cost $\mathbb{C}_{\mathscr{H}}(G^v)$ and computing capacity consumption cost CPU capacity allocation $\mathbb{C}_{\mathscr{C}}(G^v)$, which are defined as follows:

$$\mathbb{C}_{\mathscr{H}}(G^v) = \sum_{e^\rho \in E^\rho} \lambda l(e^\rho) \cdot M^{G^v}(e^\rho) \tag{6}$$

$$\mathbb{C}_{\mathscr{C}}(G^v) = \sum_{n^\rho \in N^\rho} \lambda c(n^\rho) \cdot M^{G^v}(n^\rho) \tag{7}$$

$\mathbb{C}_{\mathscr{H}}(G^v)$ is the total bandwidth cost of the virtual link mapping, and $\mathbb{C}_{\mathscr{C}}(G^v)$ represents the total computing capacity cost of the virtual node mapping. $\mathbb{C}(G^v)$ is the total cost of accepting a VN request; $M^{G^v}(x)$ is a function to demonstrate that the bandwidth or computing resources are allocated on available substrate link or node, $x \in N^\rho \cup E^\rho$. $\lambda l(e^\rho)$ and $\lambda c(n^\rho)$ are detailed in Section 3.1.

Expected capacity loss is a mathematical expectation to evaluate the total capacity loss of VNs under the disaster impact area Z when disaster failures happen. It is denoted as *ECL*. The *ECL*, which can be calculated in 8, means that the allocated capacity of VNs will be lost if the disaster failures happen.

$$ECL = \sum\nolimits_{z \in Z, f \in F} p_z \cdot \sum_{\gamma \in \Gamma} \mathbb{C}(\gamma) \tag{8}$$

where Γ is the set of VNs that have been mapped on the substrate network; Z and F are the set of disaster impact areas and disaster failures, respectively. $\mathbb{C}(\gamma)$ represents the allocated capacity cost to the VN γ.

The disaster failure model with the risk assessment formulates the problem under the disaster failures scenario. This model provides predictable information about the disaster failures for the SVNM.

4. PREDICTION-BASED SVNM ALGORITHMS

In this section, we discuss the SVNM algorithms based on the failure model. This mechanism is adopted to map the VNs with the analysis of the historical failure information during the phase of SVNM. Firstly, we give the fundamental formulation with the mixed-integer problem (MIP). Next, we give two heuristic algorithms in two ways: (i) a greedy strategy is adopted to select the substrate links with minimum expected capacity loss to map the VN requests and (ii) an APFA heuristic is proposed to allocate bandwidth to the substrate branches with the objective of reducing the expected capacity loss. To this end, the MFRPS algorithm and the APFA algorithm are presented.

4.1. MIP formulation

Survivable VNM should also achieve good resource efficiency in the substrate network, that is, to minimize cost. Thus, the SVNM problem can be formulated as a MIP, which is similar to the multi-commodity flow problem [20]. Our objective is to minimize the capacity loss caused by disasters and maximize the revenue of SVNM. We present the MIP formulation as follows.

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Variables:

- $\phi_{u,v}^{e^v}$: indicates the amount of capacity of the virtual link $e^v \in E^v$ to be allocated from substrate link $e_{u,v} \in E^\rho$.
- l_z: numbers of virtual links in the disaster impact area z.

Binary variables:

- $\xi_{\rho,v}^{n}$: it equals 1 if substrate node $n^\rho \in N^\rho$ is used to embed virtual node $n^v \in N^v$; else equals 0.
- $\Theta_{\rho,v}^{\mathcal{P}}$: it equals 1 if path $\mathcal{P}$ containing substrate link $e^\rho \in E^\rho$ is used to map the virtual link $e^v \in E^v$; else equals 0.
- $\chi_{u,v}^{G^V}$: it equals 1 if the virtual link exists from node u to node v in G^V; else equals 0.
- $\mathscr{R}_e^f$: it equals 1 if the virtual link e fails by disaster failure f; else equals 0.
- $t_{e^z}^f$: it equals 1 if the substrate link in the disaster impact area z fails by disaster failure f; else equals 0.
- W_z^f: it equals 1 if all of the virtual links in the disaster impact area z fail by disaster failure f; else equals 0.

The objective:

$$\min \boldsymbol{ECL} \tag{9}$$

The objective function 9 tries to minimize the total capacity loss of all VNs when disasters happen. Subject to:Node mapping constraints:

$$\sum_{\forall n^\rho \in N^\rho} \xi_{\rho,v}^{n} = 1 \tag{10}$$

$$\sum_{\forall n^v \in N^v} \xi_{\rho,v}^{n} \leq 1 \tag{11}$$

Capacity constraints:

$$\sum_{\forall n^\rho \in N^\rho} \xi_{\rho,v}^{n} \cdot \varepsilon(n^\upsilon) \leq \varsigma(n^\rho) \tag{12}$$

$$\sum_{\forall e^\rho \in E^\rho} \Theta_{\rho,v}^{\mathcal{P}} \cdot \varrho(e^\upsilon) \leq \omega(e^\rho) \tag{13}$$

Flow constraints:

$$\sum_{\forall e_{s,u} \in N^\rho} \phi_{s,u}^{e^v} - \sum_{\forall e_{u,d} \in N^\rho} \phi_{u,d}^{e^v} = \chi_{s,d}^{G^V} \cdot \varrho(e^\upsilon) \tag{14}$$

$$\sum_{\forall e_{s,d} \in N^\rho} \chi_{s,d}^{G^V} - \sum_{\forall e_{d,s} \in N^\rho} \chi_{d,s}^{G^V} = 0 \tag{15}$$

Constraints when disaster failure happens:

$$\mathscr{R}_e^f \geq \frac{1}{\delta} \sum_{e^z \in E^Z}^{\mathcal{P}} t_{e^z}^f \Theta_{z,v}^{\mathcal{P}} \tag{16}$$

$$\mathscr{R}_e^f \leq \sum_{e^z \in E^Z}^{\mathcal{P}} t_{e^z}^f \Theta_{z,v}^{\mathcal{P}} \tag{17}$$

$$\mathrm{W}_z^f \leq \frac{1}{l_z} \sum_{e^z \in E^Z} \mathscr{R}_e^f \tag{18}$$

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$$W_z^f \geq \sum_{e^z \in E^Z} \mathscr{R}_e^f - l_z \tag{19}$$

Constraints 10 and 11 guarantee, respectively, that each virtual node is mapped in exactly one substrate node. Constraints 12 and 13 ensure that virtual node and link capacity do not exceed the limitation of the amount of the capacity of substrate node and links. Constraints 14 and 15 ensure that each virtual link is mapped on a substrate path, and it does not pass the same substrate node more than once. Constraints 16–19 denote that the virtual links are affected by disaster failure. Constraints 16 and 17 guarantee that the capacity of the affected virtual link e does not exceed the limitation of the substrate path. δ is a large positive number to make the $\frac{1}{\delta}\sum_{e^z \in E^Z}^{\mathcal{P}} t_{e^z}^f \Theta_{z,v}^{\mathcal{P}}$ verge to zero. Constraints 18 and 19 guarantee that the capacities of all the affected virtual links in the disaster impact area do not exceed the sum of the limitation of all the substrate paths.

Based on the aforementioned definitions, in what follows, we will design algorithms to solve the issue of SVNM based on the disaster failure model. In this paper, our algorithms improve the failure-aware ability in the initial mapping. The algorithms do not adopt remapping after the disaster happens. When the failures happen, our algorithm can control the capacity loss.

4.2. Minimum fault risk prior selection

Fault risk is a metric to evaluate the capacity loss of substrate component when the disaster failures happen. The MFRPS is an improved SVNM algorithm based on the model. The MFRPS algorithm is divided into two stages: In the first stage, it maps all VN nodes to the available substrate network nodes. The node mapping algorithm maps the virtual nodes to the substrate nodes with the maximum available substrate node computing capacity at each iteration. As the node mapping stage ends, the MFRPS executes the second stage: link mapping stage. In order to minimize the total bandwidth loss caused by disaster failures, the MFRPS is adapted from the shortest path algorithm provided by Dijkstra [29]. The shortest substrate mapping path is selected based on the fault risk. Two variables about fault risk are defined:

- $\boldsymbol{R_j}$: a variable that evaluates the potential fault possibility of the substrate link c_j^z in the overall substrate network.
- $\boldsymbol{h_j}$: a variable that evaluates the capacity loss of substrate link c_j^z when substrate link c_j^z fails in the substrate network.

Because the fault risk represents the capacity loss of substrate link when the disaster failures happen, it includes the cost of bandwidth capacity for SVNM and the fault risk assessment. Besides the region risk probability and potential fault probability for link c_j^z, the cost of the bandwidth of link c_j^z for SVNM should also be considered. $\boldsymbol{R_j}$ and $\boldsymbol{h_j}$ are formulated as follows:

$$\boldsymbol{R_j} = \begin{cases} \dfrac{p_z p_{c_j^z} + \sum_{c_j^z \in E^z} p_{c_j^z}}{\sum_{c_j^z \in E^z} p_{c_j^z}}, & c_j^z \in E^z \\ 1, & c_j^z \in E^\rho - E^z \end{cases} \tag{20}$$

where $p_{c_j^z}$ is potential fault probability and p_z is region risk probability as defined in Section 3. Note that the symbol c_j^z that is defined in Section 3 represents the substrate link here. If candidate link c_j^z is located in the disaster impact area z, $R_j > 1$; else, $R_j = 1$.

$$\boldsymbol{h_j} = \lambda l\left(c_j^z\right) \cdot M^{G^v}\left(c_j^z\right) \cdot \boldsymbol{R_j} \tag{21}$$

where $\lambda l(e^\rho)$ and $\lambda c(n^\rho)$ are detailed in Section 3. The function $M^{G^v}\left(c_j^z\right)$ demonstrates the allocated bandwidth of substrate link c_j^z when the VN request G^v has been mapped, $c_j^z \in E^\rho$. According to 20,

$R_j = 1$ when the substrate link c_j^z is not located in disaster impact area z. The variable h_j is equivalent to the cost produced by the normal link mapping. The algorithm preferentially selects the substrate link that is outside of the disaster impact areas. The sum of h_j in substrate path $\mathcal{P}$ is denoted as value $H_{\mathcal{P}}$. It reflects the sum of the potential capacity loss when the VN links are mapped onto substrate path. It can be calculated as 22:

$$H_{\mathcal{P}} = \sum_{c_j^z}^{\mathcal{P}} \boldsymbol{h_j}, \quad e_{i,j} \in \mathcal{P} \tag{22}$$

When the substrate path for mapping is found by the MFRPS, the value $H_{\mathcal{P}}$ of the path is minimum. The sum of capacity loss can be maintained to some lower extent when the disaster failures happen.

A pseudocode for the MFRPS is as Algorithm A. The algorithm uses three queues Q, $L\langle h_j \rangle$ and $\mathcal{P}$ to keep track of the arrived VN requests, the h_j for each substrate network link, and the candidate mapping path, respectively. The variable *index* indicates the number of the VN request, which is handled at present. The variable *Accepted_Num* records the number of the successful mapped VNs. In the phase of initialization, let $index = 1$ and $Accepted\_Num = 0$, and the $\mathcal{P}$ is empty. All of the h_j are calculated in 21, and then the $L\langle h_j \rangle$ is sorted in the ascending order. Firstly, the MFRPS selects a VN request with the largest revenue from the queue Q (step 4). For the VN request that is taken from Q, the process of SVNM is divided into two stages: node mapping (step 5) and link mapping (steps 5–14). Because the algorithm focuses on optimizing the link mapping, it takes a greedy node mapping algorithm at the phase of node mapping. In the link mapping stage, the algorithm finds the subset E' of E^ρ. The set

Algorithm A. Minimum link risk prior selection (MLRPS) algorithm

INPUT: G^ρ, n numbers of VN requests (VNRs) in queue
Q, disaster failures F, disaster impact areas Z
OUTPUT: *Accepted _Num*
BEGIN:
1. Initialize: $index = 1$; $Accepted\_Num = 0$; $P = \varnothing$
$L\langle \boldsymbol{h_j} \rangle$;
2. Sort the *VNRs* in Q with the revenue in descend order;
3. While ($index <= n \& Q != \varnothing$){
4. Take one VNR from the Q with the largest revenue;
5. Execute node mapping
6. Find the subset E′ (E′ ⊆ E^ρ) that satisfy restriction and available capacity (larger than that specified by the request);
7. If (E′ == ∅) {Store this VNR in the queue Q;
8. GOTO step 16;}
9. Else {
10. For each virtual link (a, b){
11. Select the c_j^z with *min* $\boldsymbol{h_j}$ to map the VN link;
12. If (all the virtual networks are computed)
13. Select the path with min
14. Accept the VN request; *Accepted_Num* ++;
15. Else reject the VNR;}//End for}//End else
16. *index* ++}//End While
17. Return *Accepted_Num*

END

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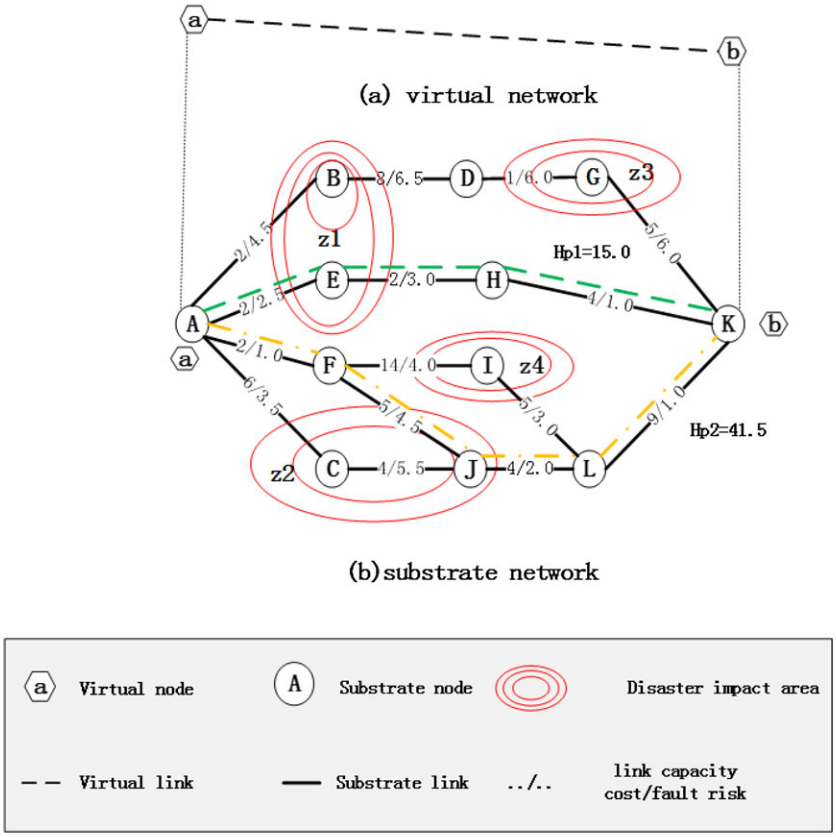

Figure 2. An instance to illustrate the MFRPS algorithm

E' is used to contain candidate substrate links that meet the bandwidth constraint (step 6). Aimed at minimizing $H_{\mathcal{P}}$, the MFRPS selects available substrate link c_j^z with minimum $\boldsymbol{h_j}$ in E' to compose the substrate candidate path $\mathcal{P}$ (step 10). If all of the virtual links are mapped, the VN request is accepted; else, the VN request is rejected. Finally, the number of accepted VNs is returned.

Consider an example of the MFRPS algorithm in Figure 2. There are four disaster impact areas, which are denoted as $z1$, $z2$, $z3$, and $z4$, respectively. The number over the substrate links represents the cost of bandwidth and the fault risk h_j. Suppose that the virtual node a and node b are mapped on the substrate nodes A and K, respectively. We assume node A as the start node and K as the end node. The value h_j can be calculated in 21. In each iteration, the algorithm selects the substrate link j with the minimum $\boldsymbol{h_j}$ as a part of substrate path that the VN link (a, b) will be mapped on. Just as shown in Figure 2, the fault risk for substrate link $e_{A,B}$ and substrate link $e_{A,F}$ is $h_{A,B}=2*4.5=9.0$ and $h_{A,F}=2*1.0=2.0$, respectively. The first candidate substrate path is p1: $\{A \rightarrow F \rightarrow J \rightarrow L \rightarrow K\}$, the fault risk of which is Hp1 = 41.5. When all the candidate substrate paths are found, the substrate path p2: $\{A \rightarrow E \rightarrow H \rightarrow K\}$ with minimum Hp2 = 15.0 will be selected.

The MFRPS algorithm has two advantages against disaster failures: (i) it needs no backup resources and (ii) it adopts a greedy strategy to optimize the solution with the objective of reducing the bandwidth capacity loss expectation.

4.3. *Asymmetric parallel flow allocation*

The MFRPS has good efficiency when the scale of disaster impact area is small. However, with the increase of disaster impact area, the available substrate network resources among the areas become few. The efficiency of MFRPS decreases because many substrate links with higher fault risk will be

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selected. To further enhance the efficiency of the SVNM against disaster failures, another algorithm based on the path-splitting strategy is designed, which is called as the APFA algorithm.

In this paper, we use flow to depict the bandwidth allocation for SVNM. The main idea of the APFA algorithm is to make substrate network support flexible splitting of the virtual links over two branches of the substrate path. Then the APFA allocates less bandwidth to the substrate branch traveling disaster impact area with higher severity, so that it can reduce the sum of bandwidth loss caused by disaster. The core steps of this algorithm are as follows. Firstly, it computes the severity of each disaster impact area. Then two substrate path branches as the solution of the path splitting for the virtual link are designed. Finally, the flow allocation coefficient is defined to set the proportion of the flow allocation based on the regulation that the larger flow is allocated to the substrate branch traveling disaster impact areas with lower severity. The flows are asymmetric because the bandwidth of two branches is unequal. When the failure happens, the mapped VNs can merely loss a little bit of bandwidth. And with this approach, the bandwidth capacity can largely be saved because it does not demand backup resources.

To describe the APFA algorithm, some variables are defined as the following.

- s_z: a variable to evaluate the severity degree of the disaster impact area. It is calculated in 23.
- $x_{i,j}^z$: a binary valuable is defined to describe the process that substrate links are selected. If the substrate link $e_{i,j}$ is located in the substrate path $\mathcal{P}$ and meanwhile $e_{i,j}$ is located in the disaster impact area z, $x_{i,j}^z = 1$; else, $x_{i,j}^z = 0$.
- $\mathcal{S}_{\mathcal{P}}$: a variable to denote the sum of the disaster impact area severity that the substrate path travels through. It is calculated in 24.
- $\alpha_{\mathcal{P}_k}$: a coefficient that set the proportion of the flow allocation for the substrate branch $\mathcal{P}_k$. It is calculated in 25.
- $flow_{\mathcal{P}_k}$: a variable to reflect the bandwidth constraint about the substrate branch $\mathcal{P}_k$. It is calculated in 26.

The aforementioned variables are calculated through the following formulas:

$$s_z = p_z \sum_{c_j^z \in E_z} \lambda l\left(c_j^z\right) \omega\left(c_j^z\right) p_{c_j^z}, \ z \in Z \tag{23}$$

where $\lambda l\left(c_j^z\right)$ is the cost of bandwidth and $\omega\left(c_j^z\right)$ is the available bandwidth capacity, $p_{c_j^z}$ is potential fault probability and p_z is region risk probability, and Z is the set of the affected substrate network topologies.

$$\mathcal{S}_{\mathcal{P}} = \sum_{e_{i,j} \in \mathcal{P}}^{\mathcal{P}} \left(x_{i,j}^z \cdot s_z\right) \tag{24}$$

where $z \in Z$, $e_{i,j} \in \mathcal{P}$ and $e_{i,j} \in E^z$.

$$\alpha_{\mathcal{P}_k} = \mathcal{S}_{\mathcal{P}_k} / \mathcal{S}_{\mathcal{P}} \tag{25}$$

where $\mathcal{P}_k$ represents the branch k of the substrate path $\mathcal{P}$, $\mathcal{P} = \cup \mathcal{P}_{\mathrm{k}}$. k is a variable $k = 1, 2$.

$$flow_{\mathcal{P}_k} = (1 - \alpha_{\mathcal{P}_k}) \cdot \varrho(e^v) \tag{26}$$

where $\varrho(e^v)$ is the bandwidth demand of the virtual link e^v.

In the link mapping stage, we map the virtual links onto paths with the knowledge of disaster impact area severity to prevent the virtual links from losing all their capacity. The comparison algorithm re-VNM is provided in [4], which supports path splitting to enable efficient VNM by utilizing the

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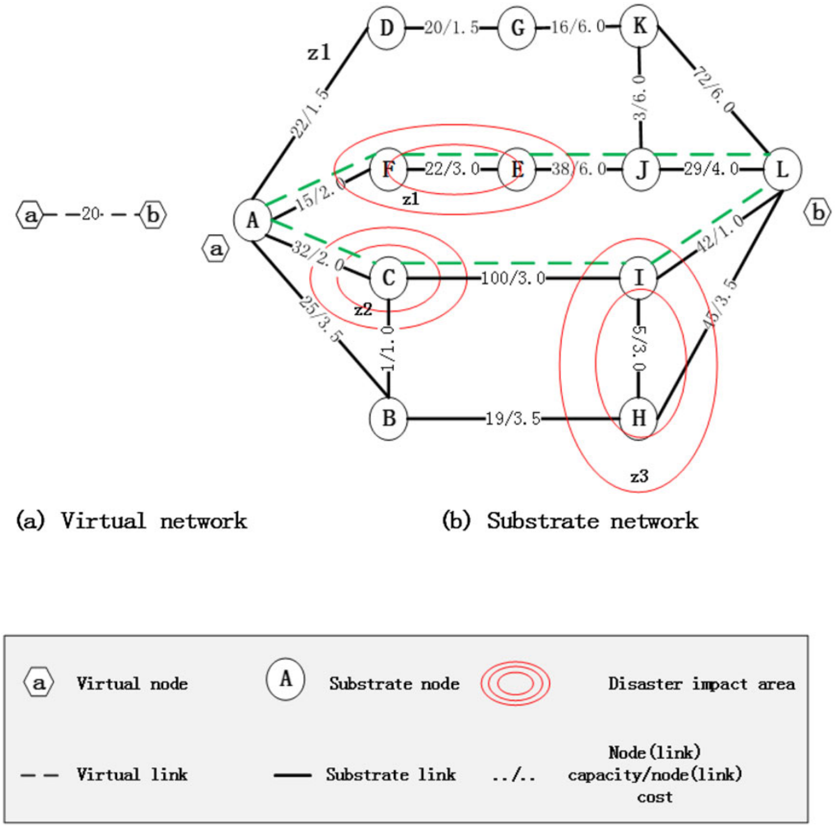

Figure 3. An instance to illustrate the APFA algorithm

substrate fragment that cannot provide sufficient resources for a virtual link. Based on the flexible path splitting, the re-VNM can be reduced to the multi-commodity flow problem [20]. Different from their work, the APFA simplifies the process of path splitting to two substrate branches with the K-shortest path algorithm akin to [21] and optimizes the path-splitting strategy by the adjustment of $\alpha_{\mathcal{P}_k}$ to reduce the loss of bandwidth caused by the disaster failure.

The pseudocode of the APFA algorithm is presented in Algorithm B. Similar to the MFRPS, the APFA uses three queues Q, $\mathcal{P}_1$ and $\mathcal{P}_2$ to keep track of arrived VN requests, and the two candidate mapping substrate branches, respectively. The variable *index* indicates the VN request that is handled at present. The variable *Accepted_Num* records the number of the successful mapped VNs. In the phase of initialization, both $\mathcal{P}_1$ and $\mathcal{P}_2$ are empty; let $index = 1$ and $Accepted\_Num = 0$.

The APFA selects a VN request with largest revenue from the queue Q (steps 1–3). For the VN request that is taken from Q, the process of the SVNM is also divided into two stages: node mapping (step 5) and link mapping (steps 6–11). The process of node mapping can be handled as a node mapping algorithm. In link mapping stage, the algorithm first adopts K-shortest path algorithm to split a substrate path $\mathcal{P}$ into two branches. One is with the minimum cost, and the other is with subminimum cost (step 6). Note that 'the subminimum cost' means the second branch of the substrate path with a subminimum bandwidth capacity cost, which represents the second best path. To decide the ratio of bandwidth allocation, the algorithm computes the $\mathcal{S}_{\mathcal{P}_k}$, the $\alpha_{\mathcal{P}_k}$, and the $flow_{\mathcal{P}_k}$ according to equations 6–10. Based on the computing results, the algorithm allocates the $flow_{\mathcal{P}_k}$ to each branch $\mathcal{P}_k$ according to $\alpha_{\mathcal{P}_k}$. If all of the virtual links are mapped on, the VN request is accepted; else, the VN request is rejected. Then the number of accepted VNs is returned. Figure 3 illustrates the basic idea of the APFA. In the instance of the figure, there are three disaster impact areas, which are $z1$, $z2$, and $z3$ with disaster impact area severity $s_{z1} = 2.5$, $s_{z2} = 23.4$, and $s_{z3} = 36.6$, respectively. Suppose that the bandwidth demand of the virtual link (a, b) is 20. Firstly, the algorithm selects the path $\mathcal{P}_1 : \{A \rightarrow F \rightarrow J \rightarrow L\}$ with the minimum cost and the path $\mathcal{P}_2 : \{A \rightarrow C \rightarrow I \rightarrow L\}$ with the sub-minimum cost as the candidate

Algorithm B. (APFA) Algorithm

INPUT: G^p, n numbers of VN requests *(VN requests)* in queue Q, disaster failures F, $|Z|$ of disaster impact areas Z with disaster impact areas severity s_z.
OUTPUT: *Accepted _Num*
BEGIN:
1. Initialize: $index = 1$, $Accepted\_Num = 0$; $P_1 = \varnothing$ and $P_2 = \varnothing$
2. Sort the *VNRs* in Q with the revenue in descend order;
3. While ($index <= n \& Q != \varnothing$){
4. Take one VNR from the Q with the largest revenue;
5. Execute node mapping
6. For each virtual link:
7. {Adopt K-shortest path algorithm to split the substrate path P to two branch P_1 and P_2;
8. Compute S_{P_k}, a_{P_k} and $flow_{P_k}$ of each branch P_k with the S_z then allocate requested bandwidth $flow_{P_k}$ for each branch P_k;}
9. If all virtual links are allocated successfully, accepted the VN request, *Accepted_Num ++;*
10. Else reject the VN request;
11. *index* ++;}//End While
12. Return *Accepted_Num;*

END

substrate branches. To allocate the appropriate flow to each branch, the algorithm computes $\alpha_{\mathcal{P}_k}$ and $flow_{\mathcal{P}_k}$ for each branch $\mathcal{P}_k$. As a result, $flow_{\mathcal{P}_1} = 19.2$ and $flow_{\mathcal{P}_2} = 0.8$.

Compared with the traditional SVNM against multiple substrate failures, our algorithms need no backup resources, because a best effort way to reduce the capacity loss is adopted. In the initial process of the resource allocation, the algorithms guarantee failure tolerant as much as possible. Our algorithms focus on the awareness of the disaster failures initial mapping. However, when a particular disaster strikes, among the VNs mapped by MFRPS, there will be statistically only small number of VNs be affected and fail. As for the VNs mapped by APFA, for the VNs affected by the disaster, there will be probably only small part of the VN fails due to the splitting strategy. Therefore, after the disaster, both MFRPS and APFA can reduce the capacity loss of the affected VNs in disaster impact area.

5. SIMULATION AND EXPERIMENT

In this section, we describe the simulation environment and present our simulation results. Compared with the single failure, the disaster failures affect wider range of the substrate network. Based on this reason, the approaches on reserving backup resources and remapping the VNs after the failures are not suitable to the scenario of disaster failures. While the classic VNM algorithm in [4] has certain fault-tolerance capability, it is selected by us as comparison. The basic principle of their work has been sketched in Section 4.3. For simplicity, the VNM algorithm in [4] is called as the re-VNM. The performance of the proposed algorithms is evaluated in a comparison of the MFRPS, the APFA, and the re-VNM under the disaster failures scenario.

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5.1. Simulation environment

We use the GT-ITM tools [30] to generate the substrate network topology, which is configured to have 100 nodes, 500 links generated on average. The computing capacity at substrate nodes and bandwidth capacity on the links follow a unified distribution from 50 to 100. We assume the node computing capacity cost to be 3 and bandwidth cost to be 1. The substrate network topology covers 5–20 disaster impact areas, which are mutually non-overlapped.

Each of VN requests varies between 2 and 10 nodes, and the average degree of VN is 2. The node computing capacity and bandwidth capacity demand follows a uniform distribution 0–20 and 50–100, respectively. The VN requests have exponential holding and inter-arrival time, which is denoted by μ and λ, respectively. The VN requests arrive in a Poisson manner with a parameter $\lambda = 5$, which means that the VN requests arrive with average five VN requests per time window. Here, the holding time $\mu = 10$, which means that one holding time occupies 10 time windows. Meanwhile, the variable *load* is defined as the ratio of inter-arrival time and holding time, where $load = \lambda/\mu$. It reflects the throughput rate of the VN requests. The experiment is tested with 500 requests. The disaster failures are triggered randomly.

5.2. Performance metrics

Three performance metrics are defined to evaluate the efficiency of algorithms.

- Average VN acceptance ratio: The average VN acceptance ratio is the ratio that the number of successful mapped VN requests occupies the number of arrived VN requests at time *t*. For simplicity, we call it as acceptance ratio.
- Expected capacity loss: This metric has been defined in Section 3. It evaluates the capacity loss degree of the allocated VNs.
- Average region fault density (RFD): It reflects the ability that system resists in the disaster failures. It is calculated in 27, where num_F is the number of failed VN request when the sum of the disaster impact area is |Z|.

$$RFD = num_F/|Z| \tag{27}$$

5.3. Comparison of MFRPS, APFA, and re-VNM

First, we look at the case that the number of disaster impact area is constant (|Z| = 5) and compute the acceptance ratio (Figure 4), the expected capacity loss (Figure 5), and the acceptance ratio (Figure 6) of MFRPS, APFA, and re-VNM.

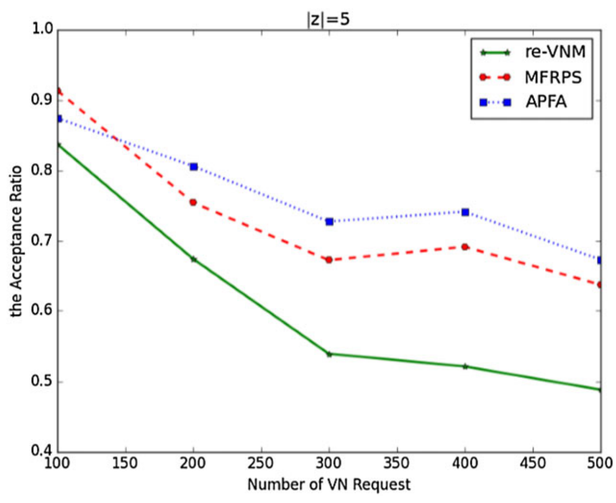

Figure 4. Camparison in VN acceptance ratio

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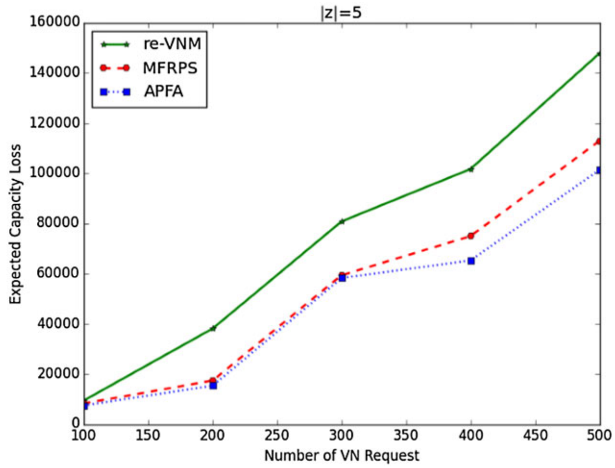

Figure 5. Camparison in expected capacity loss

Figure 4 shows that the acceptance ratio varies from the number of the arrived VN requests in the three algorithms. The figure demonstrates that our algorithms have higher acceptance ratio than re-VNM under the disaster failures scenario and the APFA is superior to the MFRPS under the condition that the number of disaster impact area is small. This is because our algorithms adopt best effort way to reduce the capacity loss of VNs caused by the potential disaster failures. The APFA has higher acceptance ratio than MFRPS because asymmetric parallel flow strategy in APFA guarantees that only a little bit of bandwidth is lost when the branch goes through severer disaster impact area. As the number of arrived VN requests increases, the acceptance ratio of all three algorithms decreases, and the gap between our algorithms and re-VNM increases when the number of arrived VN requests surpasses 300. The main reason is that as the number of VN requests increases, the VN mappings are influenced by the disaster impact area obviously.

Figure 5 shows that the expected capacity loss incurred by re-VNM is higher than our algorithms, and the loss of APFA is the lowest in the three algorithms. The first reason is that our algorithms can evade the potential failures caused by disasters. Secondly, unlike the APFA, the MFRPS cannot split the substrate path so that the failed mappings increase when the number of the arrived VN requests is large.

Figure 6 shows that the acceptance ratio of three algorithms varies with the variable *load*. As the figure reveals, the acceptance ratio decreases when the load increases. But our algorithms with the

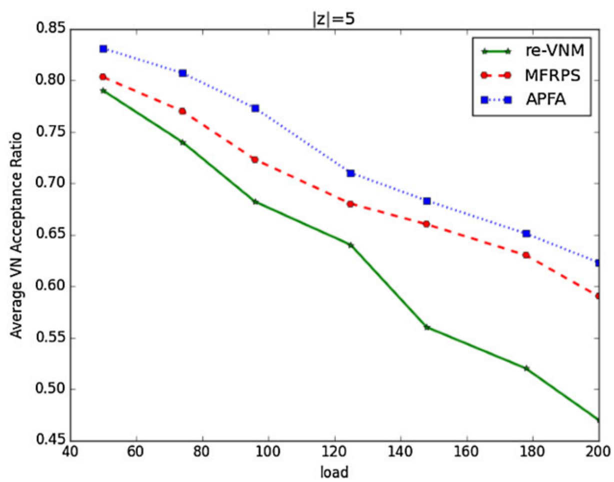

Figure 6. Comparison in acceptance ratio varying with load

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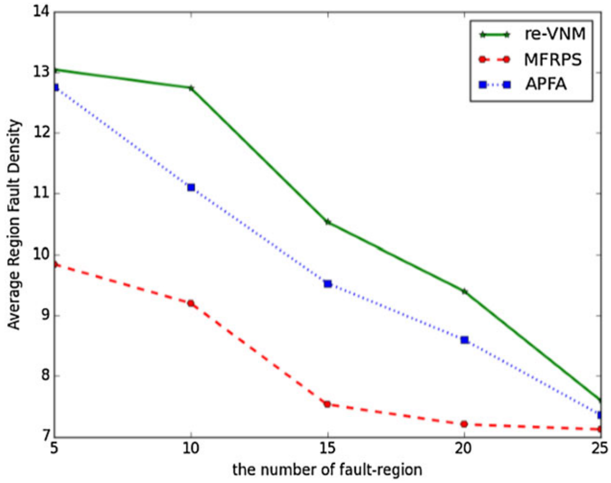

Figure 7. Comparison in region fault density varying with |*z*|

disaster tolerant can protect the already mapped VN requests against disaster failure. Therefore, the VN request acceptance ratio of the proposed algorithms does not deteriorate so much as that of the algorithm re-VNM as the load increases. The APFA is also better than MFRPS. The main reason is that APFA not only handles SVNM problem based on the disaster failure model but also can implement the strategy of path splitting to increase the acceptance ratio in comparison of the MFRPS.

Then consider the circumstance that when the number of disaster impact area varies. For simplicity, the varied number of disaster impact area can be denoted as |*Z*|. We study RFD (Figure 7) of three algorithms with the number of disaster impact area change from 5 to 25. We gather the samples under the condition that the number of the arrived VN request is 500.

As is shown in Figure 7, our algorithms have lower RFD than re-VNM when the number of disaster impact area varies in a certain range. As the variable |*Z*| increases, the decline of the RFD of the APFA slows. The result demonstrates that the APFA is better fault tolerant than the MFRPS and the re-VNM when the variable |*Z*| is in a certain range. The RFD of all three algorithms verges to the same pot when the number of disaster impact area surpasses 25. The main reason is that our experiment scale is limited and when the number of disaster impact area surpasses 25, the number of failed VN requests is so large that the system crashes.

6. CONCLUSION

In this paper, the SVNM against disaster failures has been investigated. A prediction mechanism has been adopted to survive the disaster failures. The solution is implemented by two algorithms called as the minimum disaster impact area prior selection (MFRPS) algorithm and the APFA algorithm. Simulation results have shown that, compared with the classic VNM algorithm, the proposed algorithms can effectively decrease the expected capacity loss and increase the average VN acceptance ratio when the substrate network suffers disaster failures. In the future, we plan to improve the proposed algorithms by providing failover mechanism after disaster.

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AUTHORS' BIOGRAPHIES

Ying Wang received the PhD degree from Beijing University of Posts and Telecommunications in 2006. She is currently an associate professor in the State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications. Her research interests include the management of future network, cloud computing, and IT service management.

Xiao Liu is currently a MS candidate at Beijing University of Posts and Telecommunications. His research interest focuses on future network management.

Xuesong Qiu received the PhD degree from Beijing University of Posts and Telecommunications in 2000. He is currently a professor in the State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications. His major research interests include network management and telecommunication software.

Wenjing Li is currently a professor in the State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications. Her research interests include the management of future network, wireless network and automatic management.

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