Disaster-Prediction Based Virtual Network Mapping against Multiple Regional Failures

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Abstract—**Survivable virtual network mapping (SVNM) has been extensively investigated to guarantee that the mapped virtual network (VN) works normally against substrate failures. The existing studies of SVNM mainly focus on single node or single link failure. Since natural disasters usually cause severe substrate failures in geographic regions, some work addressing SVNM against regional failures has been studied. However, the current approaches only solve the mapping problem against single regional failure. When there are multiple regional failures aroused by natural disasters, such approaches are not effective. In this paper, we first design a regional failure model with the knowledge of risk assessment. Then we propose two effective mapping algorithms based on the disaster-prediction scheme with the regional failure model. One is the minimum link risk prior selection algorithm and the other is the asymmetric parallel flow allocation algorithm. Simulation results show that both approaches can reduce the capacity loss of virtual networks caused by regional failures and can effectively increase the average VN acceptance ratio.**

Keywords—virtualization; survivable virtual network mapping; multiple regional failures; disaster-prediction

I. INTRODUCTION

With the increasing demand for deploying multiple applications, two core virtualization services - cloud computing and grid computing - emerge as a revolution to free data center network from the heavy burden of inflexibility, complexity and high costs. The evolution toward cloud computing and grid computing as observed for over a decennium illustrates the importance of network virtualization in supporting today's distributed applications [1]-[2]. Network virtualization is an advanced technology which allows multiple virtual networks (VNs) to coexist on a shared substrate network (SN). These VNs are on behalf of different services and applications which can be provisioned by network service providers.

Virtual network mapping (VNM), which aims at effectively calculating allocation of the substrate resources for the virtual network requests, provides technical support toward the network virtualization. Researchers in [3]-[9] have studied some classic approaches on VNM. However, sudden failures occur inevitably during normal operation and these failures may cause service interruption of the VNs which have been mapped on the failed substrate network component. Therefore, we also need to map a VN to a substrate efficiently while guaranteeing that the VNs survive the failures. Recently some achievements about survivable virtual network mapping (SVNM) have been obtained in [10]-[18]. Based on the assumption that a single node or link fails at one time, the common approach of SVNM is to reserve backup substrate resources against failure. However, natural disaster such as hurricane or tsunami causes the latent regional failures which lead the SN to fail or to be unstable in a geographic region. Based on single regional failure assumption, that only one regional failure occurs at any time, two main approaches of [15]-[16] have been presented. One is protection-based approach by reserving backup resources before the failure. The other is restoration-based approach by remapping the VNs which are mapped on the failed substrate network component after the failure.

Compared with the single regional failure, multiple regional failures are more complicated in the scale of failures and the distribution of the fault-regions. In practice, the protection-based strategy are unpractical because large numbers of backup resources are idle when there are not network disruption caused by disasters. Besides, the migration strategy against the multiple regional failures may be unrealizable when there are not sufficient resources to remap the affected nodes and links out of the affected regions. Thus the solutions against the single regional failure are of limited applicability to solve the problem under the multiple regional failures. Note that this paper only focus on link failures because any node failure-aware virtual network embedding algorithm depends on tolerating adjacent link failures [10].

In this paper, we investigate the VNM against multiple regional failures. A regional failure model and two effective mapping algorithms are proposed. Our goal is to reduce the capacity loss of VNs caused by regional failures and increase the average VN acceptance ratio. To this end, we take advantage of the historical failures statistics to map the VN requests onto the part of substrate network which has fewer latent regional failures. The main contributions are as follows: (1) A disaster-prediction scheme is proposed to evade large amounts of redundant backup resources against the multiple regional failures; (2) A regional failure model with the knowledge of risk assessment is designed to describe the problem space; (3) Two efficient mapping algorithms based on the regional failure model are provided.

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The rest of this paper is organized as follows. Section II reviews the related work. Section III describes the network model and defines the problem. Section IV presents the proposed algorithms. Simulation results are presented in Section V and this paper is concluded in Section VI.

II. RELATED WORK

Virtual network mapping has received great attention in recent years and the classic VNM approaches in [3]-[9] have been studied extensively. Yu et. al in [3] proposed a typical mapping method based on a path-splitting strategy to enhance the VN acceptance ratio and the load balance problem. Although the survivability from the substrate failures is not considered in this method, it implements fault tolerance to some extent. Our work is similar in the context that the strategy of path-splitting in our link mapping phase. However, the main difference is that our work augments the algorithms used in [3] by weighting the selection of links such that they will be less likely to pass through any of a set of multiple regional failure locations.

Since multiple VNs share the substrate network resources during the network operation, even a single failure in the substrate network can affect a large number of VNs and the services they offer [10]. To guarantee the survivability from the substrate link or node failures, authors in [13]-[14] 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 SVNM against large scale of regional failures cannot be solved sufficiently because the shared backup resources which are out of the fault-regions may be not existing in reality. The approaches in [15]-[17] explore the field of regional failure caused by disasters. Based on the single regional failure assumption, the authors of [15]-[16] address the node failures under single regional failure by migrating the failed VN nodes from the fault-region. Considering that multiple regional failures are distributed in larger scale of geographic regions affected by disasters, these methods by reserving backup resources cause the waste of resources when the network disruption does not occur. The authors in [17] explore the influence by disasters in Optical Networks. The risk assessment is adopted to analyze the influence by disasters. In [18], the researchers state the feasibility and reasonability that the prior knowledge can be acquired of the regional failures as the historical information. Illuminated by their study, we introduce the risk assessment to analyze the regional failures caused by disasters.

Different from these related works, we focus on virtual network mapping against multiple regional failures based on disaster-prediction. A regional failure model as well as the path-splitting strategy are employed in the design of the mapping algorithms.

III. REGIONAL FAILURE MODEL AND PROBLEM STATEMENT

In this section, the regional failure model is designed to depict the VNM against multiple regional failures and then the problem space is formulated.

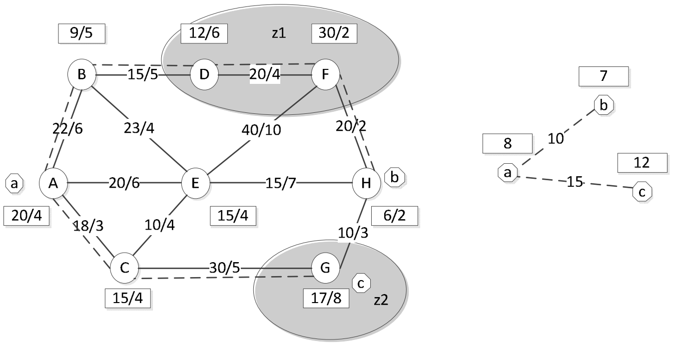
A. Substrate Network

The substrate network can be modeled as an undirected graph $G^\rho = (N^\rho, E^\rho)$, where N^ρ is the set of substrate nodes and E^ρ is the set of substrate links. For each substrate node $n^\rho \in N^\rho$, the node capacity is $\varsigma(n^\rho)$ and the cost of node capacity unit 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 unit is $\lambda l(e^\rho)$. Additionally, substrate link $e^\rho \in E^\rho$ is also denoted as $(n^\rho, n^{\rho\prime})$, where n^ρ and $n^{\rho\prime}$ are a pair of adjacent substrate nodes. We also denote the set of all loop-free paths by $\mathcal{P}$ in the substrate network.

Fig.1 (a) shows an instance of the substrate network, where the number over the link represents the available bandwidth and the cost of bandwidth unit, and the number in the rectangle denotes the available node capacity and the cost of node capacity unit.

B. 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 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. Fig1. (b) shows an example of the VN request with three VN nodes and two VN links, and the related node capacity and bandwidth demands.



(a)Substrate Network

(b)VN Request

Fig. 1. Mapping of VN Request over a substrate network

C. Regional Failure

Regional failures are usually caused by disasters. The disaster can trigger different results of the regional failures. To analyze the influence caused by disasters, the disaster-factor can be denoted as d. A list of possible disaster-factors is denoted by D, where $d \in D$.

Regional failure refers to the latent substrate failure in a limited geographic region. Lists of possible regional failures are denoted by the set of F. Each regional failure $f_i \in F$ represents a kind of latent substrate failure. The relationship between disaster-factors and regional failure is defined as a function $\boldsymbol{G}(D')$ from D' to a set of F.

$$\boldsymbol{G}: D' \mapsto f_i$$

where $D' \subseteq D$ and $f_i \in F$.

The fault-region refers to the region covering the latent failed substrate component. It is denoted by $\boldsymbol{z}$. Accordingly, lists of fault-regions can be denoted by the set Z. Each $\boldsymbol{z} \in Z$ involves one or more latent failed substrate components. The fault-region can be modeled as an undirected graph $G^z = (N^z, E^z)$, where $N^z \subset N^\rho$ and $E^z \subset E^\rho$. To simplify the problem space, we assume that the fault-regions are mutually non-overlapped. For example, in Fig. 1(a), there are two fault-regions z1 and z2, which are mutually non-overlapped. The substrate node D and F as well as the substrate link (B,D) and (F,H) in fault-regions may fail. Similarly, the substrate nodes or links may fail in z2.

In this paper, the latent regional failures are analyzed by computing the empirical failure probability which can be obtained by the historical failures statistics. Some relevant notions are defined as follows.

Definition 1: **(Link Latent-fault Probability)** is an empirical probability to describe the possibility of the latent substrate link failure affected by disasters. It can be calculated by the empirical function $p_{e^z}(f)$ based on historical failures statistics, where $p_{e^z}(f) \in [0,1]$, $f \in F$ and $e^z \in E^z$. F and E^z is the set of regional failures and the set of latent substrate failed edges in $\boldsymbol{z}$, respectively. For simplicity, $p_{e^z}(f)$ is denoted as p_{e^z}.

Definition 2: **(Region Risk Probability)** is defined to describe the degree of regional failures in the specific fault-region. It can be calculated by the empirical function $p_z(f)$ based on the Link Risk Probability p_{e^z}, where $p_z(f) \in [0,1], f \in F, e^z \in E^z$. F and E^z is the set of regional failures and the set of latent substrate failed edges in $\boldsymbol{z}$, respectively. For simplicity, $p_z(f)$ is denoted as p_z.

Definition 3: **(Expected Capacity Loss)** is a mathematical expectation to evaluate the total capacity loss of VNs under the multiple regions Z when regional failures happen. It is denoted as *ECL*. The *ECL* ,which can be calculated in (1), means that the allocated capacity of VNs will be lost if the regional failures happen.

$$ECL = \sum_{z \in Z, f \in F} \sum_{\gamma \in \Gamma} \boldsymbol{C}(\gamma) \cdot p_z \tag{1}$$

where Γ is the set of VNs which have been mapped on the substrate network, Z and F is the set of fault-regions and regional failures, respectively. $\boldsymbol{C}(\gamma)$ represents the allocated capacity to the VN γ.

The regional failure model with the risk assessment can depict the problem under the multiple regional failures scenario. This model provisions predictable information about the latent regional failures for the VNM.

D. Disaster-Prediction Scheme

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 multiple regional failures because the redundant resources for backing up are so large. Moreover, due to the complexity of multiple regional failures, the circumstance exists that there are not available substrate components out of the fault-regions to remap the affected VN after the failure. Therefore the disaster-prediction scheme is proposed to maintain the weak survivability, which refers to the failure-resilient ability that the VNs evades the latent failures in the initial mapping phase. The proposed scheme can judge the latent regional failures based on the analysis of the historical failure statistics. Directed by the result of the judgment, the VNs are mapped on the substrate network component which has lower failure possibility to guarantee the survivability.

E. Problem Statement

Given: a SN $G^\rho = (N^\rho, E^\rho)$, lists of VN requests, the set of regional failures F caused by disasters and $|Z|$ number of fault-region Z.

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

IV. DISASTER-PREDICTION BASED VNM ALGORTHIMS

In this section, we discuss the VNM algorithms based on the disaster-prediction scheme. This scheme is adopted to map the VNs with the analysis of the historical failures information during the VN mapping phase. Our algorithms provide the solutions in two ways: (1) The greedy strategy is adopted to select the substrate links with minimum expected bandwidth loss to map the VN requests; (2) The asymmetric parallel flow allocation algorithm is presented to allocate bandwidth to the substrate branches with the objective of reducing the expected capacity loss. To this end, the Minimum Link Risk Prior Selection (MLRPS) Algorithm and the Asymmetric Parallel Flow Allocation (APFA) Algorithm are presented. In this paper, we focus on the improvement of link mapping algorithm, the node mapping algorithm is out of our scope. The classic scheme of node mapping can be computed by reference to the solutions provided in [3].

A. Minimum Link Risk Prior Selection

Link risk is a metric to evaluate the capacity loss of substrate links when the regional link failures happen. The MLRPS is an improved VNM algorithm against multiple regional failures based on the regional failure model. The main idea is that the greedy strategy is adopted to improve the link selection algorithm with the objective of minimizing the sum of link risk attribution. In each iteration, the MLRPS selects a substrate link with the current minimum link risk for optimal solution. It will achieve the satisfactory global solution by accumulating several times of the local optimal solutions when the algorithm stops.

The MLRPS algorithm is divided into two stages: In the first stage, it maps all VN nodes to the available SN nodes. The node mapping algorithm maps the virtual nodes to the substrate nodes with the maximum available substrate node capacity at each iteration. As the node mapping stage ends, the MLRPS executes the second stage: link mapping stage. In order to minimize the total bandwidth loss caused by regional failures, the MLRPS is adapted from the shortest path algorithm provided by Dijkstra [19]. The shortest substrate mapping path is selected based on the link-risk attribution. For a substrate link e_{ij}, two variables about link-risk attribution are defined:

- $\boldsymbol{R_{i,j}}$: A variable that evaluates the latent link fault ratio of the substrate link e_{ij} in the overall substrate network comprehensively.
- $\boldsymbol{h_{i,j}}$: A variable that evaluates the capacity loss of substrate link e_{ij} when substrate link e_{ij} fails in the substrate network.

Since the link-risk attribution represents the capacity loss of e_{ij} when the regional failures happen, it includes the bandwidth capacity cost for VN mapping and the link-risk assessment. Besides the knowledge of the **Region Risk Probability** and **Link Latent-fault Probability** for link e_{ij}, the bandwidth cost of link e_{ij} for VN mapping should also be considered. $\boldsymbol{R_{i,j}}$ and $\boldsymbol{h_{i,j}}$ are formulated as follows:

$$\boldsymbol{R_{i,j}} = \begin{cases} \dfrac{p_z p_{e_{ij}} + \sum_{e_{ij} \in E^z} p_{e_{ij}}}{\sum_{e_{ij} \in E^z} p_{e_{ij}}} & , \ e_{ij} \in E^z \\ 1 & , \ e_{ij} \in E^\rho - E^z \end{cases} \tag{2}$$

where $p_{e_{ij}}$ is **Link Latent-fault Probability** and p_z is **Region Risk Probability** as defined in Section III. If candidate link e_{ij} is located in the fault-region $\boldsymbol{z}$, $\boldsymbol{R_{i,j}} > 1$; if not, $\boldsymbol{R_{i,j}} = 1$.

$$\boldsymbol{h_{i,j}} = \lambda l(e_{i,j}) \cdot M^{G^v}(e_{i,j}) \cdot \boldsymbol{R_{i,j}} \tag{3}$$

where $\lambda l(e^\rho)$ and $\lambda c(n^\rho)$ are detailed in Section III. The function $M^{G^v}(e_{i,j})$ is the allocated bandwidth of substrate link $e_{i,j}$ when the VN request G^v has been mapped, $e_{i,j} \in E^\rho$. According to (3), $\boldsymbol{R_{i,j}} = 1$ when the substrate link $e_{i,j}$ is not located in fault-region **z**. Based on this condition, the variable $\boldsymbol{h_{i,j}}$ is equivalent to the cost produced by the normal link mapping. The algorithm preferentially selects the substrate link which is not located in the fault-regions. The sum of $\boldsymbol{h_{i,j}}$ in substrate path $\mathcal{P}$ is denoted as value $H_{\mathcal{P}}$. It reflects the sum of the latent capacity loss when the VN link is mapped onto substrate path. It can be calculated as (4):

$$H_{\mathcal{P}} = \sum_{e_{i,j}}^{\mathcal{P}} \boldsymbol{h_{i,j}} \quad , \ e_{i,j} \in \mathcal{P} \tag{4}$$

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

A pseudo code for the MLRPS is as follows. The algorithm uses three Queues Q, $L < \boldsymbol{h_{i,j}} >$ and $\mathcal{P}$ to keep track of arrived VN requests, the $\boldsymbol{h_{i,j}}$ value of each SN 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 $\boldsymbol{h_{i,j}}$ are calculated in (3) and then the $L < \boldsymbol{h_{i,j}} >$ is sorted in the ascend order. Firstly, the MLRPS selects a VN request with the largest revenue from the queue Q (step 4). For the VN request which is taken from Q, the process of VNM is divided into two stages: node mapping (step 5) and link mapping (step 5-14). Since 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 E' is used to contain candidate substrate links which meet the bandwidth constraint (step 6). Aimed at minimizing $H_{\mathcal{P}}$, the MLRPS selects available substrate link $e_{i,j}$ with minimum $\boldsymbol{h_{i,j}}$ in E' to compose the substrate candidate path $\mathcal{P}$ (step 10). If all of the virtual link are mapped, the VNR is accepted; else the VNR is rejected. Finally, the number of accepted VNs is returned.

Algorithm A. Minimum Link Risk Prior Selection (MLRPS)

```
INPUT:   $G^\rho$, $n$ numbers of VN Requests (VNRs) in Queue
         $Q$ , regional failures $F$ fault-Regions $Z$
OUTPUT: $Accepted\_Num$
BEGIN:
1.  Initialize: $index$=1; $Accepted\_Num$=0; $\mathcal{P} = \emptyset$;
       $L < \boldsymbol{h_{i,j}} >$;
2.  Sort the VNRs in $Q$ with the revenue in descend order;
3.  While(index<=n& $Q! = \emptyset$){
4.      Take one VNR from the Q with the largest revenue;
5.      Execute node mapping
6.      Find the subset E' ($E' \subseteq E^\rho$) that satisfy restriction and
        available capacity(larger than that specified by the
        request );
7.      If ($E' == \emptyset$)  {Store this VNR in the queue Q ;
8.                     GOTO step 15;}
9.      Else {
10.         For each virtual link (a, b){
11.             Select the $e_{i,j}$ with min $\boldsymbol{h_{i,j}}$ to map the VN link;
12.             If (all of the virtual link are mapped)
13.             Accept the VN request ; $Accepted\_Num$ ++;
14.             Else  reject the VNR;  }//End for  }//End else
15. $index$ ++}//End While
16. Return $Accepted\_Num$;
END
```

Consider an example of the MLRPS algorithm in Fig. 2. There are four fault-regions, which is denoted as z1, z2, z3 and z4, respectively. The numbers over the substrate links represent the cost of bandwidth and the link-risk attribution value $\boldsymbol{h_{i,j}}$. Suppose that the virtual node $\boldsymbol{a}$ and node $\boldsymbol{b}$ is mapped on the substrate node A and K, respectively. We assume node A as the start node and K as the end node. The value $\boldsymbol{h_{i,j}}$ can be calculated in (3). For example, the link-risk value for substrate link $e_{A,B}$ and substrate link $e_{A,F}$ is $\boldsymbol{h_{A,B}}$ =2*1.5=3.0 and $\boldsymbol{h_{A,F}}$=1*1.0=1.0, respectively. In each iteration, the algorithm selects the substrate link e_{ij} with the minimum $\boldsymbol{h_{i,j}}$ as a part of substrate path which the VN link $(\boldsymbol{a}, \boldsymbol{b})$ will be mapped on, when the end node is found, the $H_{\mathcal{P}}$ of the path $\mathcal{P}$ is minimum. In Fig. 2, when the substrate path for virtual link (a, b) which can be denoted as $< A, F, J, L, K >$is found, the sum of the link-risk attribution value for the substrate path $\mathcal{P}$ is

$H_{\mathcal{P}}$=1∗1.0+3∗1.0+2∗1.0+1∗1.0=7.0 . As is shown in Fig.2, the substrate path $< A, F, J, L, K >$ is the substrate path to map for the virtual link $(\boldsymbol{a}, \boldsymbol{b})$ with the minimum link risk.

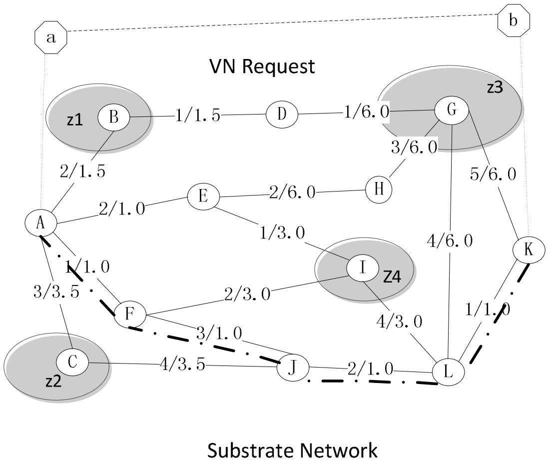


Fig. 2. Illustration of MLRPS

The MLRPS algorithm has two advantages against multiple regional failures:1) it needs no backup resources 2) it adopts a greedy strategy to optimize the solution with the objective of reducing the bandwidth capacity loss expectation. The MLRPS solves the VNM problem efficiently under the condition that the virtual link is not allowed to split or there is no idle substrate resources to be allocated.

B. *Asymmetric Parallel Flow Allocation*

The MLRPS has good efficiency when the number of fault-region is small. However, with the increase of regional failures, the efficiency of MLRPS decreases because many substrate links with higher risk attribution are selected. To further enhance the efficiency of the VNM against multiple regional failures, another algorithm based on the path-splitting strategy is provisioned, which is called as the Asymmetric Parallel Flow Allocation Algorithm.

In this paper, we use flow to depict the bandwidth allocation for VNM. 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 fewer bandwidths to the substrate branch traveling severer fault-region so that it can reduce the sum of bandwidth loss caused by disaster. The core steps of this algorithm is as follows. Firstly, it computes the severity of each fault-region, then two substrate path branches as the solution of the path-splitting for the virtual link is 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 travelling lower severity of fault-regions. The flows are asymmetric because the bandwidth of two branches are unequal. When the failure happens, the mapped VNs can merely loss a little bit of bandwidth. With this approach, the bandwidth capacity can largely be saved because it does not demand backup resources.

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

- s_z : It is a variable to evaluate the severity degree of the fault-region $\boldsymbol{z}$. It is calculated in (5) .
- $x_{i,j}^{z}$: 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 fault-region $\boldsymbol{z}$, $x_{i,j}^{z}$=1, else $x_{i,j}^{z}$=0. The formal description is in (6).
- $\mathcal{S}_{\mathcal{P}}$: A variable to denote the sum of the fault-region severity that the substrate path travels through. It is calculated in (7) .
- $\alpha_{\mathcal{P}_k}$: It is a coefficient that set the proportion of the flow allocation for the substrate branch $\mathcal{P}_k$. It is calculated in (8).
- $flow_{\mathcal{P}_k}$: A variable to reflect the bandwidth constraint about the substrate branch $\mathcal{P}_k$. It is calculated in (9).

Hence, we calculate these variables by the following formula:

$$s_z = p_z \sum_{e_z \in E_z} \lambda l(e_z) \omega(e_z) p_{e_{ij}} \quad , z \in Z \tag{5}$$

where $\lambda l(e_z)$ is the cost of bandwidth unit and $\omega(e_z)$ is the available bandwidth capacity, $p_{e_{ij}}$ is **Link Latent-fault Probability** and p_z is **Region Risk Probability**, Z is the set of fault-regions.

$$x_{i,j}^{z} = \begin{cases} 1 & , if\ e_{i,j} \in \mathcal{P}\ and\ e_{i,j} \in E^{z} \\ 0 & , others \end{cases} \tag{6}$$

$$\mathcal{S}_{\mathcal{P}} = \sum_{e_{i,j} \in \mathcal{P}}^{\mathcal{P}} (x_{i,j}^{z} \cdot s_z) \tag{7}$$

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

$$\alpha_{\mathcal{P}_k} = \mathcal{S}_{\mathcal{P}_k} / \mathcal{S}_{\mathcal{P}} \tag{8}$$

where $\mathcal{P}_k$ represents the branch k of the substrate path $\mathcal{P}$, $\mathcal{P} = \bigcup \mathcal{P}_k$. k is a binary variable $k = 0{,}1$.

$$flow_{\mathcal{P}_k} = \left(1 - \alpha_{\mathcal{P}_k}\right) \cdot \varrho(e^{v}) \tag{9}$$

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

In the link mapping stage, we map the virtual links into multiple paths with the knowledge of fault-regions severity to prevent the virtual links from losing all their capacity. The comparison algorithm re-VNM is provided in [3], which supports path-splitting to enable efficient VNM by utilizing the substrate fragment which cannot provide sufficient resources for a virtual link. Under flexible splitting over the multiple paths, the re-VNM can be reduced to the Multi Commodity Flow (MCF) problem [8]. Different from their work, the APFA simplifies the process of path-splitting to two substrate branches with the K-shortest path algorithm akin to [9] and optimizes the path-splitting strategy by the adjustment of $\alpha_{\mathcal{P}_k}$to reduce the loss of bandwidth caused by the regional failure.

A pseudo code is presented to illustrate the APFA. Similar to the MLRPS, the APFA uses three Queues $Q, \mathcal{P}_0$ and $\mathcal{P}_1$ to keep track of arrived VN requests, the two candidate mapping substrate branches, respectively. The variable $index$ indicates 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, both $\mathcal{P}_0$ and $\mathcal{P}_1$ are empty, let $index = 1$ and $Accepted\_Num = 0$.

```
Algorithm B.    Asymmetric Parallel Flow Allocation (APFA)
INPUT: $G^{\rho}$, $n$ numbers of VN Requests (VNRs) in Queue $Q$,
       regional failures $F$, $|Z|$ of Fault-regions $Z$ with fault-
       regions severity $\boldsymbol{s}_z$.
OUTPUT: $Accepted\_Num$
BEGIN:
1. Initialization: $index = 1, Accepted\_Num = 0; \mathcal{P}_0 = \emptyset$ and
   $\mathcal{P}_1 = \emptyset$
2. Sort the VNRs in $Q$ with the revenue in descend order;
3. While(index<=n& $Q != \emptyset$){
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 $\mathcal{P}$ to two branch $\mathcal{P}_0$ and $\mathcal{P}_1$;
8.       Compute $\mathcal{S}_{\mathcal{P}_k}$, $\alpha_{\mathcal{P}_k}$ and $flow_{\mathcal{P}_k}$ of each branch $\mathcal{P}_k$ with
           the $\boldsymbol{s}_z$ then allocate requested bandwidth $flow_{\mathcal{P}_k}$ for
           each branch $\mathcal{P}_k$;}
9.     If all virtual links are allocated successfully, accepted the
       VNR, $Accepted\_Num$ ++ ;
10.    Else reject the VNR;
11. $index$++;}//End While
12. Return $Accepted\_Num$;
END
```

The APFA selects a VN request with largest revenue from the queue Q (step 1-3). For the VN request which is taken from Q, the process of the VNM is also divided into two stages: node mapping (step 5) and link mapping (step 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 $\mathcal{P}$ to two branch. One is with the minimum cost and the other is with subminimum cost (step 6). Note that “the subminimum cost” means that 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 the 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, the VNR is accepted; else the VNR is rejected. Then return the number of accepted VNs.

Fig. 3 illustrates the basic idea of the APFA. There are three fault-regions, which is z1, z2 and z3 with fault-region severity s_{z1} =2.5, s_{z2} =23.4 and s_{z3} =36.6, respectively. Supposed that the bandwidth demand of the virtual link (**a, b**) is 20. The algorithm has split the substrate path $\mathcal{P}$ into the branch $\mathcal{P}_1$ which is denoted as $< A, F, J, L >$ and the breach $\mathcal{P}_2$ which is denoted as $< A, C, I, L >$. To allocate the appropriate flow to each branch, the algorithm computes $\alpha_{\mathcal{P}_k}$ and $flow_{\mathcal{P}_k}$ for each branch $\mathcal{P}_k$ and the results are shown in the rectangle of Fig. 3. When the substrate link of branch $\mathcal{P}_2$ fails, the lost bandwidth of $\mathcal{P}_2$ is only 0.8. The result show that the proportion of the capacity loss occupies a little bit of Only a small percentage of bandwidth capacity will be lost when the regional failures happen.

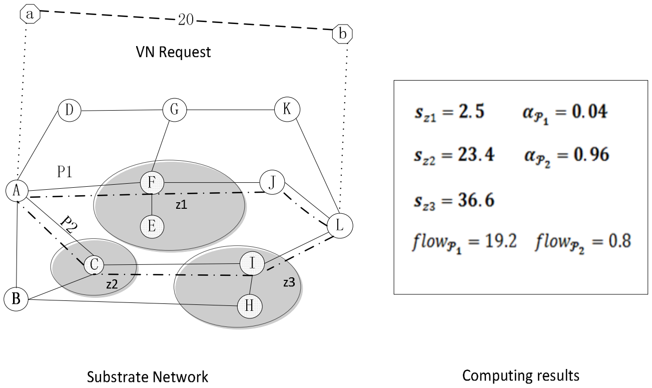


Fig. 3. Illustration of APFA

Compared with the MLRPS, the APFA has approximate efficiency on reducing the capacity loss of VN caused by disaster and increasing the average VN acceptance ratio when the number of fault-region is small. Furthermore, the APFA has better efficiency than the MLRPS when the number of fault-region is large.

V. SIMULATION AND EXPERIMENT

In this section, we describe the simulation environment and present our simulation results. Compared with the single regional failure, the multiple regional failures affect wider range of the substrate network. Based on this reason, the approaches on reserving backup resources and remapping the VNs under single regional failure are not suitable to the scenario of multiple regional failures. While the classic VNM algorithm in [3] has certain fault-tolerance capability, it is selected by us as comparison. The basic principle of their work has been sketched in section IV(B). For simplicity, the VNM algorithm in [3] is called as the re-VNM. The performance of the proposed algorithms is evaluated in a comparison of the MLRPS, the APFA and the re-VNM under the multiple regional failures scenario.

A. Simulation Environment

We use the GT-ITM tools [20] to generate the substrate network topology, which is configured to have 100 nodes, 500 links generated on average. The node capacity at substrate nodes and bandwidth capacity on the links follow a unified distribution from 50 to 100. We assume the unit node capacity cost to be 3 and unit bandwidth cost to be 1. The substrate network topology covers 5-20 fault-regions which are mutually non-overlapped. For each fault-region, we randomly configure the **Link latent-fault Probability** and **Region Risk Probability** of substrate links from 0 to 1.

Each of VN requests varies between 2-10 nodes and the average degree of VN is 2. The node 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 an parameter λ=5, which means that the VN requests arrive with average 5 VN requests per time window. Here the holding time μ=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*= λ/ μ. The experiment is tested with 500 requests. The time of the regional failures is triggered randomly.

B. Performance Metrics

Three performance metrics are defined to evaluate the efficiency of algorithms. The first two are adopted when the amount of the available computing and bandwidth resources is sufficient. The number of the fault-region is constant while the last is adopted when the number of fault-region is variable.

- 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 performance has been defined in Section III. It evaluates the degree of allocated substrate capacity loss.
- Average Region fault density (RFD): It reflects the ability that system resists in the regional failures. It is calculated in (10), where num_F is the number of failed VN request when the number of fault-region is $|Z|$.

$$RFD = num_F/|Z| \tag{10}$$

C. Comparison of MLRPS, APFA and re-VNM

First, we look at the case that the number of fault-region is constant (|*Z*|=5) and compute the acceptance ratio (Fig.4), the expected capacity loss (Fig.5) and the acceptance ratio (Fig.6) of MLRPS, APFA and re-VNM.

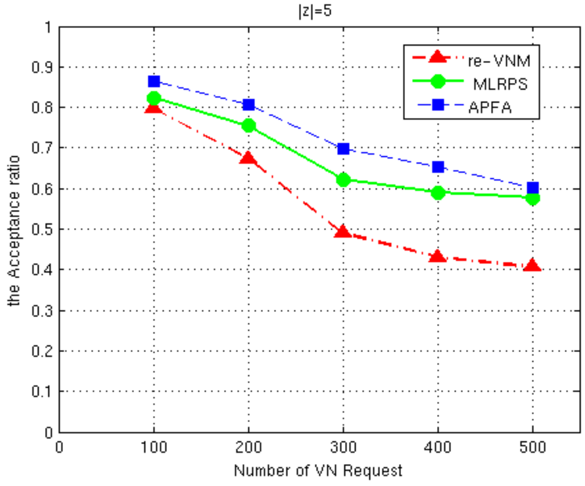


Fig. 4. Comparison in VN acceptance ratio

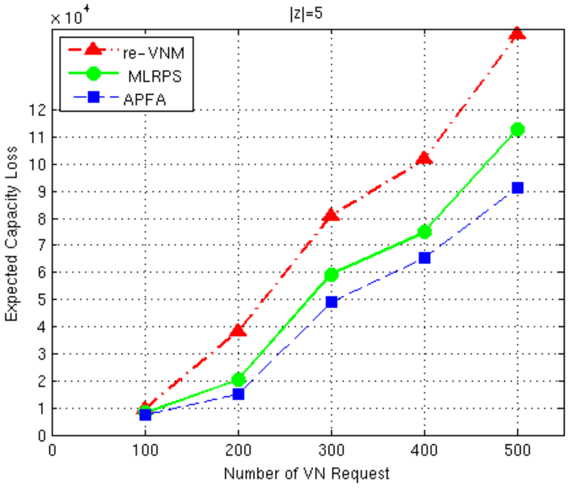


Fig. 5. Comparison in Excepted Capacity Loss

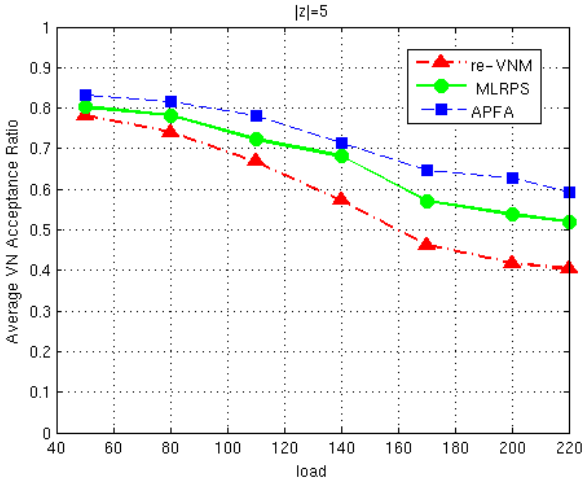


Fig. 6. Comparison in acceptance ratio varying from load

Fig. 4 shows the acceptance ratio influenced by 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 multiple regional failures scenario and the APFA is superior to the MLRPS under the condition that the number of fault-region is small. The reason is that our algorithms adopt disaster-prediction scheme which can evade the latent failures caused by disasters. The APFA has higher acceptance ratio than MLRPS because asymmetric parallel flow strategy in APFA guarantees that only a little bit of bandwidth is lost when the branch goes through severer fault-region. 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 fault-region obviously.

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

Fig. 6 shows that the acceptance ratio of three algorithms varies from the variable ***load***. As the figure reveals, the acceptance ratio decreases when the load increases. The APFA is also better than MLRPS and re-VNM. The main reason is that APFA handles not only VNM problem based on the regional failure model but also can implement the strategy of path-splitting to increase the acceptance ratio in comparison of the MLRPS.

Then consider the circumstance that when the number of fault-region varies. For simplicity, the varied number of fault-region can be denoted as $|Z|$. We study RFD (Fig.7) of three algorithms under the variable $|Z|$. We gather the samples under the condition that the number of the arrived VN request is 200.

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

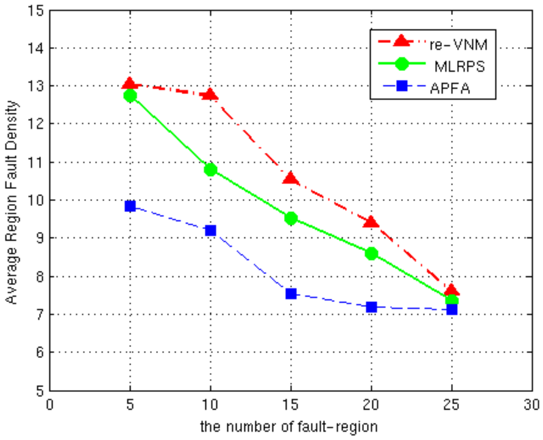


Fig.7. Comparison in region fault denisty varying from |Z|

VI. CONCLUSION

In this paper, the VNM against multiple regional failures has been investigated. A disaster-prediction scheme has been adopted to survive the multiple regional failures. The solution is implemented by two algorithms called as the Minimum Fault-region Prior Selection (MLRPS) Algorithm and the Asymmetric Parallel Flow Allocation (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 multiple regional failures. In the future, we plan to improve the proposed algorithms by adjusting the substrate candidate path selection in a dynamic way.

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