Disaster-Resilient Virtual-Network Mapping and Adaptation in Optical Networks

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***Abstract*—Today's Internet applications include grid- and cloud-computing services which can be implemented by mapping virtual networks (VNs) over physical infrastructure such as an optical network. VN mapping is a resource-allocation problem where fractions of the resources (e.g., bandwidth and processing) in the physical infrastructure (e.g., optical network and servers/data-centers) are provisioned for specific applications. Researchers have been studying the survivable VN mapping (SVNM) problem against physical-infrastructure failures (typically by deterministic failure models), because this type of failure may disconnect one or more VNs, and/or reduce their capacities. However, disasters can cause multiple link/node failures which may disconnect many VNs and dramatically increase the post-disaster vulnerability to correlated cascading failures. Hence, we investigate the disaster-resilient and post-disaster-survivable VN mapping problem using a probabilistic model to reduce the expected VN disconnections and capacity loss, while providing an adaptation to minimize VN disconnections by any post-disaster single-physical-link failure. We model the problem as an integer linear program (ILP). Numerical examples show that our approach reduces VN disconnections and the expected capacity loss after a disaster.**

***Index Terms*—optical network, disaster resiliency, post-disaster survivability, virtual-network mapping**

I. Introduction

Virtualization is a new Internet paradigm that allows multiple applications and services from different organization to coexist on a common physical infrastructure, which typically is an optical network, interconnecting servers or data-centers. Two main virtualization services –grid and cloud computing– are implemented by using virtual networks (VNs) to interconnect virtual machines and/or servers. Service providers can map VNs over a physical infrastructure by providing fractions of resources (e.g., bandwidth and processing capacity) for a specific service [1], [2]. Because a single failure in the physical infrastructure may disconnect one or more VNs, many studies have focused on the survivable virtual-network mapping (SVNM) problem that aims at keeping the VN connected during failures in the physical infrastructure [3-7].

However, a disaster may cause multiple failures in the physical infrastructure [8], [9], disconnecting and/or degrading many VNs. Considering that disaster recovery may take days or even weeks, VNs can become vulnerable to post-disaster correlated cascading failures for a relatively long recovery period. Some examples of disasters include: the 2008 Shichuan earthquake which damaged 30,000 kilometers of fiber optic cables and 4,000 telecommunication offices [10]; the 2012 hurricane Sandy that shut down most data-centers in New York area [11] and disconnected most of the communication services in the northeastern of US [12]. Given the scale of their impact, network operators should protect network services from such disasters, despite their rare occurrences.

The SVNM problem for a single-physical-link failure was studied in [7], and an extension for IP-over-WDM optical networks for multiple-link failures was presented in [3]. SVNM, in the context of grid- and cloud-computing survivability over optical networks, was studied in [4], [6], suggesting server capacity relocation and lightpath re-provisioning. A recent survey [13] summarized works on disaster survivability but only a few considered VN mapping. For a regional failure, Yu et al [5] proposed a virtual-node restoration approach, and Habib et al [8] presented a model to design a disaster-resilient optical data-center network.

Most SVNM approaches are based on deterministic failure models with over-provisioning of physical capacity, which are economically unsustainable for disaster-resiliency and post-disaster survivability, because they demand huge capacity over-provisioning and investment for backup resources. We study a disaster-resilient and post-disaster survivable VN mapping by using a probabilistic model based on risk assessment with adaptation to reduce the risk of VN disconnections and capacity loss. Our approach maps an additional virtual-backup node by exploiting the excess processing capacity of physical nodes (e.g., physical node used by other VNs) to mitigate the processing capacity loss and to recover VNs after a disaster. To reduce VN disconnections in a post-disaster single-physical-link failure, our approach implements a post-disaster survivable mapping.

The physical infrastructure used in our example is based on a wavelength-division multiplexing (WDM) optical network, but our approach is also applicable for general mesh networks. We conduct numerical examples for two disaster models: earthquake and weapons of mass destruction (WMD) [9]. Numerical results show that our approach significantly reduces risk of VN disconnection in a disaster and provides survivability for post-disaster single-physical-link failures.

II. Problem Statement and Model

single-link, multiple-link and node failures in optical networks have been widely studied in the past. The concept of shared-risk-group (SRG) has been also introduced to represent a generic set of links/nodes that fails together. In particular the problem of survivable virtual network mapping (SVNM) has been investigated under the assumption of single-link, single-node and SRG failure cases [3-7]. However, a disaster may cause not only multiple failures (i.e.,SRG failure) in the physical network, but it is also followed by post-disaster correlated cascading failures that can cause even more damage and VN disconnections.

In this study, we investigate a disaster-resilient and post-disaster survivable VN mapping model (DRM-PDS) that combines four protection approaches; survivable VN mapping (SVNM) for single-physical-link failure; disaster resilient by risk-aware VN mapping (DRM); virtual-backup-node selection and mapping (VBNM); and post-disaster survivability (PDS). In PDS approach we focus on survivability to post-disaster single-link failures. We describe each approach in the following.

A. Survivable VN Mapping (SVNM)

As a first approach of our model we deploy SVNM protection for any single-physical-link failure. SVNM ensures that virtual links of the same cut do not share the same physical link [3]. A cut is the set of virtual links whose failures can disconnect the VN. SVNM approach consider all the cuts of each VN to provide survivability. Fig. 1 shows an example of two VNs: VN1 = { 2, 3, 4, 5} and VN2 = {1, 2, 3} mapped over an optical network {A, B, C, D, E, F, G}, where every virtual link is mapped over a lightpath. Fig. 1(a) shows a non-survivable mapping where, if any physical link in circles fails, one or both VNs will be disconnected. Fig. 1(b) shows an example of SVNM where any single-physical-link failure will not disconnect any VN.

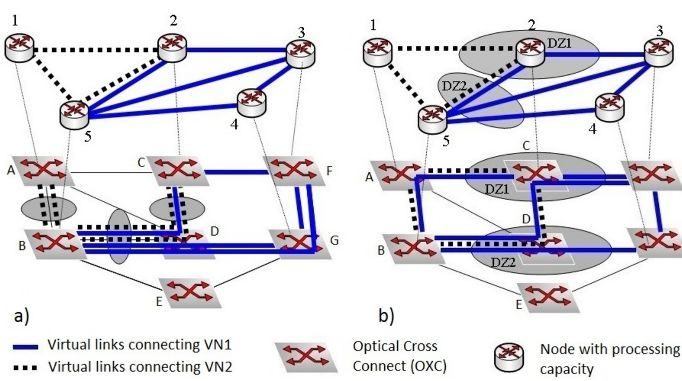

Fig. 1. Non-survivable and survivable VN mapping (SVNM) over a WDM optical network.

B. Disaster Resiliency by Risk-Aware VN Mapping (DRM)

SRG-disjoint VN mapping is difficult to implement and economically unsustainable, because it cannot map a VN, if a disaster affects a virtual node, without increasing the physical network resources for backup. For instance, in Fig. 1(b), for any of two possible disasters (DZ1 and DZ2), SRG-disjoint approach is not feasible. Hence, we implement a disaster-resilient VN mapping using a probabilistic model based on the risk assessment introduced in [9] (e.g., risk-aware VN mapping) complementing the SVNM introduced above.

Our objective is to minimize the risk (i.e., expected loss):

$$min \sum_{n \in N} \sum_{\gamma \in \Gamma} (\text{Loss of } \gamma \text{ with disaster } n)\, p_n \qquad (1)$$

where the expected loss is the sum of the capacity that can be lost if a disaster n occurs and disconnects virtual links and VNs, N is the set of disaster zones (DZ), Γ is the set of VNs, and p_n is the probability that disaster n will cause a damage.

From the example in Fig. 1, Fig. 2 is obtained by implementing DRM and SNVM. In this example, both VNs are resilient in case of single-physical-link failure, and have lower risk of VN disconnections in case of any disaster occurs, compared to the VN mapping in Fig. 1(b).

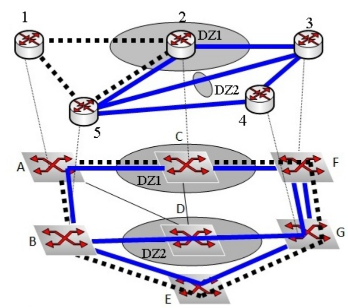

Fig. 2. Disaster-resilient VN mapping with two DZs.

However, in Fig. 2, DZ1 can still disconnect both VNs, because it affects the physical node C and the virtual node 2 used by both VNs. To overcome this problem, we suggest to map a virtual-backup node for each VN.

C. Virtual-Backup-Node Selection and Mapping (VBNM)

We develop VBNM approach that maps an additional virtual-backup node for each VN. The selection of the virtual-backup node is among the physical nodes that have enough processing capacity to share and can be used by other VNs (e.g., excess processing capacity). The node selected must be not only more available but also safer in case of a disaster. The virtual-backup node can replace any virtual node in its own VN (including virtual nodes not affected by DZs) and can be shared as a backup node with another VN. Every virtual-backup node is connected using one virtual link to each virtual node in its own VN (Fig. 3(a)).

A virtual-backup node not only reduces VN disconnection during a disaster, but also offers additional processing capacity to relocate, recover, and replicate virtual machines or servers. Yu et al [5] suggested backup nodes to protect against physical node failures, but DRM-PDS differs in the way it selects, maps, and shares the virtual-backup node among each VN. The combination of these three approaches of DRM-PDS presented so far makes it a powerful tool to map disaster-resilient VNs and useful for grid and cloud computing.

D. Post-Disaster Survivable Virtual-Network Mapping (PDS)

After a disaster, a single-physical-link failure may disconnect more VNs, because the remaining physical network and VNs are more vulnerable to correlated cascading failures during the recovery period, which may take several days [10].

For this reason, we develop PDS to ensure post-disaster survivability of the VNs. PDS takes all post-disaster cuts into account by considering all possible virtual node replacements by the virtual-backup node. Figs. 3(b) to 3(d) show all possible replacements by the virtual-backup node in the VN in Fig. 3(a). The extended cuts are calculated and added to the problem in addition to the basic cuts used by SVNM.

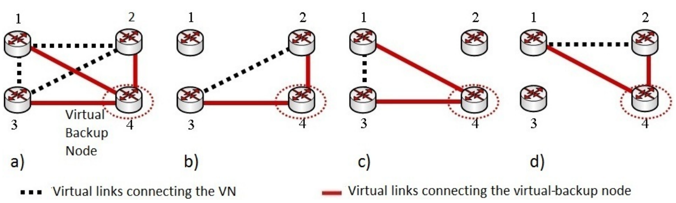

Fig. 3. Post-disaster cuts including virtual-backup-node replacement.

Fig. 4(a) presents a VN mapped without PDS. In this example, if a disaster in DZ1 occurs, the physical node C and its physical links will fail, but the VN will not be disconnected, because the virtual-backup node 4 will replace the failed virtual node 2. However, after the disaster, some single-physical-link failures may disconnect the VN. For example, after the disaster in DZ1, a post-disaster failure in physical link {A, B} will disconnect the VN, because virtual links {1, 2} and {1, 4} will be disconnected.

By implementing DRM-PDS, we obtain the mapping in Fig. 4(b), where the VN will not be disconnected by *any* single-physical-link failure, disaster failure, or post-disaster single-physical-link failure, and the expected loss of bandwidth and processing capacity will be reduced.

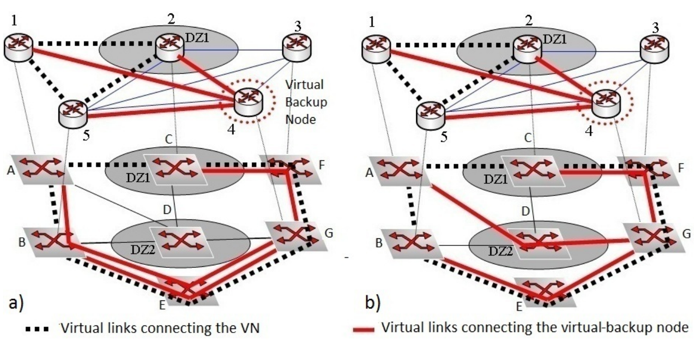

Fig. 4. Disaster-resilient virtual-network mapping with virtual-backup-node and post-disaster survivability.

E. ILP Formulation

We formulate the problem into a mathematical model which turns out to be an ILP given below.

1) Given:

- $G(V, E)$: Physical topology, where V is the set of physical nodes and E is the set of physical links.
- $\hat{V}$: Set of virtual node locations.
- $\Gamma = \left\{\gamma =< V_\gamma, E_\gamma, C_\gamma, \hat{E}_\gamma, \hat{C}_\gamma, \alpha_\gamma >\right\}$: Set of virtual networks (VNs), where V_γ, E_γ, and C_γ are the set of virtual nodes, virtual links, and cuts of the virtual network γ; $\hat{E}_\gamma$ is set of links including the links in E_γ and links from each node in V_γ to each node in $\left\{\hat{V} - V_\gamma\right\}$; $\hat{C}_\gamma = \bigcup_{b\in\{\hat{V}-V_\gamma\}} \hat{C}_b^\gamma$, where $\hat{C}_b^\gamma$ is the set of cuts of the virtual networks formed by replacing a node in V_γ by a virtual node b (i.e., nodes in $\left\{\hat{V} - V_\gamma\right\}$ are candidate virtual-backup nodes).
- $N = \{n =< S_n, p_n >\}$: Set of possible disasters with $S_n, \{|S_n| = |E|\}$, set of binary valuables s_{ij}^n (which is 1 if the physical link $\{i, j\}$ is disconnected by disaster n), and p_n is the probability of disconnection of a link with disaster n.
- P'_u: Maximum processing capacity of physical node u to allocate a virtual-backup node.
- P_v: Processing capacity required for virtual node $v \in \hat{V}$.
- P_{free}^u: Excess processing capacity in physical node u.
- L_u^γ: 1 when physical node u is used by topology γ.

$$P_{free}^u = P'_u - \sum_{\gamma\in\Gamma} P_u L_u^\gamma, \ \forall u \in E, \gamma \in \Gamma \tag{2}$$

- F_{ij}: Physical link (i, j)'s free capacity in number of wavelengths.
- d: Penalty coefficient for VN disconnection ($d \geq 1$).
- b_e: Bandwidth requirement of virtual link e.
- b_c: Total bandwidth in cut c.
- m_c: Number of virtual links in cut c.
- I: Number of virtual-backup nodes available for mapping.

2) Binary variables:

- D_e^n: 1 if virtual link e is disconnected by disaster n.
- M_{ij}^e: 1 if virtual link e is mapped on physical link (i, j).
- $K_{u,v}^\gamma$: 1 if virtual link exists from node u to v in γ.
- Y_b^γ: 1 if b is assigned as a backup virtual node to γ.
- Q_c^n: 1 if all the virtual links of cut c are disconnected by disaster n.
- X_γ^n: 1 if virtual network γ is disconnected by disaster n.
- $T_{g,h}^n$: is an auxiliary variable.
- Z_b: 1 if node b is used as a backup node.

3) Objective function: The objective function is:

$$\begin{aligned} \min \sum_{n\in N}\sum_{\gamma\in\Gamma}\left(\sum_{c\in C_\gamma} dQ_c^n b_c + \sum_{e\in\hat{E}_\gamma} D_e^n b_e\right) p_n \\ + \epsilon \times \sum_{(i,j)\in E}\sum_{\gamma\in\Gamma}\sum_{e\in\hat{E}_\gamma} M_{ij}^e \end{aligned} \tag{3}$$

where the expected loss of γ is the sum of capacity in terms of bandwidth that can be lost if VN is disconnected by disaster n with probability p_n in cut c, $\sum_{c\in C_\gamma} Q_c^n b_c$. The disconnections of all links in a cut result in a VN disconnection because the VN is divided into two isolated parts. Expected loss also includes the capacity loss due to virtual-link failures with disaster n, $\sum_{e \in \hat{E}_\gamma} D_e^n b_e$ regardless of their effect on VN disconnection. Note that VN disconnection by a cut failure damages VN more than virtual-link failure, so we multiply loss by cut failure by a penalty coefficient d. The second part of the equation tries to avoid mapping virtual links onto long lightpaths.

4) Constraint to determine if virtual links are affected by a disaster:

$$D_e^n \geq \frac{1}{M} \sum_{(i,j) \in E} s_{ij}^n M_{ij}^e, \ \forall e \in \hat{E}_\gamma, \gamma \in \Gamma, n \in N \quad (4a)$$

$$D_e^n \leq \sum_{(i,j) \in E} s_{ij}^n M_{ij}^e, \ \forall e \in \hat{E}_\gamma, \gamma \in \Gamma, n \in N \quad (4b)$$

where M is a large number. This constraint captures the possible disconnection of every virtual link e by disaster n.

5) Constraint to determine a cut failure by a disaster:

$$Q_c^n \leq \frac{\sum_{e \in E_c} D_e^n}{m_c}, \ \forall c \in C_\gamma, \gamma \in \Gamma, n \in N \quad (5a)$$

$$Q_c^n \geq \sum_{e \in E_c} D_e^n - m_c + 1, \ \forall c \in C_\gamma, \gamma \in \Gamma, n \in N \quad (5b)$$

Eq. (5) captures the VN disconnections if a disaster disconnects all links in a cut c.

6) Constraint to determine VN disconnection caused by a disaster:

$$X_\gamma^n \geq \frac{1}{M} \sum_{c \in C_\gamma} Q_c^n, \ \forall \gamma \in \Gamma, n \in N \quad (6a)$$

$$X_\gamma^n \leq \sum_{c \in C_\gamma} Q_c^n, \ \forall \gamma \in \Gamma, n \in N \quad (6b)$$

This constraint chooses the virtual-backup node outside a region with high risk of disaster.

7) Survivability constraint:

$$\sum_{e \in E_c} M_{ij}^e \leq m_c - 1, \quad \forall c \in (\hat{C}_b^\gamma + C_\gamma), b \in (\hat{V} - V_\gamma), \gamma \in \Gamma, (i,j) \in E \quad (7)$$

This constraint implements SVNM and PDS. It uses the basic cuts of the VN and the post-disaster cuts that include all possible virtual node replacements by the virtual-backup node.

8) Flow-conservation constraints:

$$\sum_{(i,s_e) \in E} M_{is_e}^e - \sum_{(s_e,j) \in E} M_{s_e j}^e = -K_{s_e,d_e}^\gamma, \ \forall e \in \hat{E}_\gamma, \gamma \in \Gamma \quad (8a)$$

$$\sum_{(i,d_e) \in E} M_{id_e}^e - \sum_{(d_e,j) \in E} M_{d_e j}^e = K_{s_e,d_e}^\gamma, \ \forall e \in \hat{E}_\gamma, \gamma \in \Gamma \quad (8b)$$

$$\sum_{(k,j) \in E} M_{kj}^e - \sum_{(i,k) \in E} M_{ik}^e = 0, \ \forall e \in \hat{E}_\gamma, \gamma \in \Gamma, \quad k \in \hat{V} - \{s_e, d_e\} \quad (8c)$$

These constraints ensure that each lightpath is mapped on a virtual link, and it does not pass the same physical node more than once.

9) Physical-link-capacity constraint:

$$\sum_{e \in \hat{E}_\gamma} M_{ij}^e \leq F_{ij}, \ \forall (i,j) \in E, \gamma \in \Gamma \quad (9)$$

The next four constraints implement the virtual-backup-node selection and mapping.

10) Links between virtual nodes and virtual-backup node constraint:

$$K_{u,v}^\gamma = 1, \ \forall u, v \in V_\gamma, u \neq v, \gamma \in \Gamma \quad (10a)$$

$$K_{u,b}^\gamma = Y_b^\gamma, \ \forall u \in V_\gamma, b \in (\hat{V} - V_\gamma), \gamma \in \Gamma \quad (10b)$$

This constraint ensures the connectivity to the selected virtual-backup node of VN.

11) Virtual-backup-node selection constraint:

$$\sum_{b \in (\hat{V} - V_\gamma)} Y_b^\gamma = 1, \ \forall \gamma \in \Gamma, Y_b^\gamma = 0, \ \forall b \in V_\gamma, \gamma \in \Gamma \quad (11)$$

12) Virtual-backup-node sharing constraint:

$$T_{g,h}^n \leq X_g^n, \ \forall g, h \in \Gamma, g \neq h, n \in N \quad (12a)$$

$$T_{g,h}^n \leq X_h^n, \ \forall g, h \in \Gamma, g \neq h, n \in N \quad (12b)$$

$$T_{g,h}^n \geq X_g^n + X_h^n - 1, \ \forall g, h \in \Gamma, g \neq h, n \in N \quad (12c)$$

$$Y_b^g + Y_b^h \leq 2 - T_{g,h}^n, \ \forall g, h \in \Gamma, g \neq h, n \in N, \quad b \in \left[\hat{V} - (V_g \cup V_h)\right] \quad (12d)$$

This set of constraints is very important for DRM-PDS, because they ensure that a virtual-backup node cannot be shared among VNs that may be disconnected by the same disaster.

13) Constraint of virtual-backup node:

$$Z_b \geq \frac{\sum_{\gamma \in \Gamma} Y_b^\gamma}{M}, \ \forall b \in \hat{V} \quad (13a)$$

$$Z_b \leq \sum_{\gamma \in \Gamma} Y_b^\gamma, \ \forall b \in \hat{V} \quad (13b)$$

14) Processing capacity of virtual-backup node constraint:

$$\sum_{b \in \hat{V}} Z_b \leq I, \ \forall b \in \hat{V} \quad (14)$$

where I = 1 means one virtual-backup node is forced to be shared by all the VNs. The maximum value of I is the number of VNs to be mapped (e.g., one virtual-backup node per VN).

III. Illustrative Examples

A. Experimental Setup

We study our methods on a 24-node US mesh network (Fig. 5(b)) with 32 wavelengths per link and wavelength conversion. Two types of disasters: one natural disaster (earthquake), and one human-made disaster (weapon of mass destruction (WMD) attacks) were introduced and modeled in [9] and shown in Fig. 5(b). We consider five full-mesh virtual networks, each consisting of four virtual nodes distributed over 16 physical nodes which have processing capacity (Fig. 5(a))[1]. We assume that each virtual link requires full lightpath.

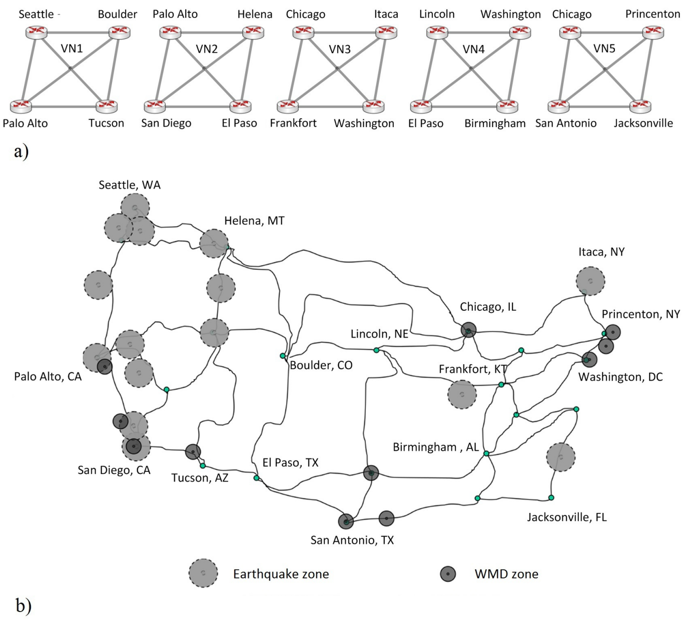

Fig. 5. (a)VNs implemented and (b)physical topology with disaster zones for earthquake and potential WMD attacks [9].

B. Compared approaches

We compare our approach (e.g., DRM-PDS) with the following approaches:

- Resource-aware mapping with fixed virtual-backup-node approach (RAM-Fixed), in which one virtual-backup node is chosen in advance for each VN.
- Resource-aware VN mapping with VBNM (RAM), which differs from the previous approach in the way to select each virtual-backup node for each VN.
- Disaster-resilient VN mapping with VBNM (DRM), is similar to DRM-PDS but without PDS.
- Resource-aware mapping with VBNM and PDS (RAM-PDS).

Resource-aware approaches (RAM-Fixed, RAM, and RAM-PDS) use following objective function:

$$min \sum_{(i,j)\in E} \sum_{\gamma\in\Gamma} \sum_{e\in\hat{E}_\gamma} M^e_{ij} \tag{15}$$

These approaches are summarized in Table I.

C. Evaluation Metrics

To compare the five approaches, we use four metrics:

[2]Note that, for larger VNs with sub-wavelength granularity requirements, ILP becomes intractable.

TABLE I
DETAILS OF IMPLEMENTED APPROACHES

	Approach	RAM-Fixed	RAM	DRM	RAM-PDS	DRM-PDS (our approach)
Objective	Min-Res. (Eq. (15))	X	X		X	
Objective	Min-Risk (Eq. (3))			X		X
Methods used	SVNM	X	X	X	X	X
Methods used	DRM			X		X
Methods used	VBNM	Fixed	Select	Select	Select	Select
Methods used	PDS				X	X

1) Risk of VN disconnection:

$$\sum_{n\in N} \sum_{\gamma\in\Gamma} \left(\sum_{e\in\hat{E}_\gamma} D^n_e b_e + \sum_{c\in C_\gamma} dQ^n_c b_c \right) p^n_d \tag{16}$$

2) Penalty for capacity loss:

$$\sum_{e\in\hat{E}_\gamma} D^n_e b_e + \sum_{c\in C_\gamma} dQ^n_c b_c \tag{17}$$

3) Post-disaster VN disconnection: Number of VN disconnections by single-physical-link failure after any of possible disasters.

4) Resources used: Number of wavelengths provisioned to map VNs:

$$\sum_{(i,j)\in E} \sum_{\gamma\in\Gamma} \sum_{e\in\hat{E}_\gamma} M^e_{ij} \tag{18}$$

D. Results

We divide our analysis into three parts: disaster resiliency, post-disaster survivability, and resource consumption.

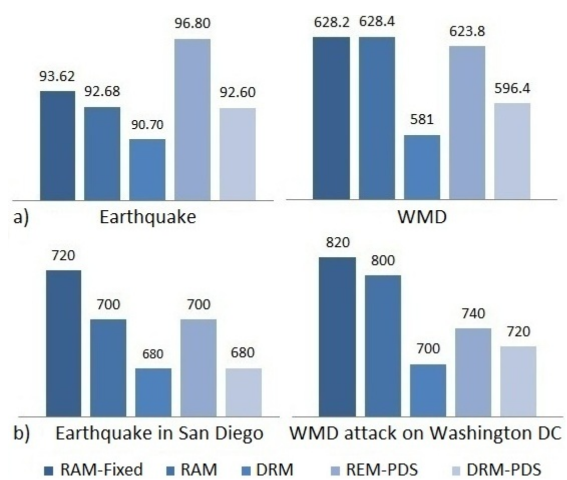

Fig. 6. Risk of disconnection and penalty for capacity loss.

1) Disaster resiliency: We compare the approaches based on risk of VN disconnection and penalty for capacity loss. Fig. 6(a) shows the results for the risk of VN disconnection:

- Risk-aware approaches (DRM and DRM-PDS) have lower risk of disconnection compared to resources-aware (RAM-Fixed, RAM, and RAM-PDS) approaches.

- Implementation of post-disaster survivability constraint slightly increases the risk for DRM-PDS vs. DRM, because some of the virtual links traverse additional DZs to ensure survivability in a post-disaster failure.

Fig. 6(b) presents the penalty for capacity loss of two DZs as examples, an earthquake in San Diego and of WMD attack on Washington DC.

- Note that risk-aware approaches have the lowest penalty.
- In case of a WMD attack on Washington DC, DRM-PDS will have a little higher penalty compared to DRM because it is offering post-disaster survivability.

Thus, the superiority of risk-aware approaches (DRM and DRM-PDS) is demonstrated in terms of disaster resiliency.

2) Post-disaster survivability: From Fig. 7, we note that:

- Both post-disaster survivable approaches (DRM-PDS and RAM-PDS) have the lowest number of VN disconnections in case of a single-physical-link failure.
- In case of earthquake, RAM-PDS still has high number of disconnections compared to DRM-PDS that has no disconnection.

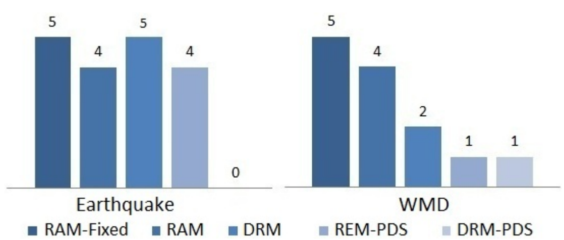

Fig. 7. Number of VN disconnections in any post-disaster single-physical-link failure.

This evaluation confirms that the combination of four components implemented in DRM-PDS that include risk-assessment and post-disaster survivability constraint decreases the post-disaster VN disconnections.

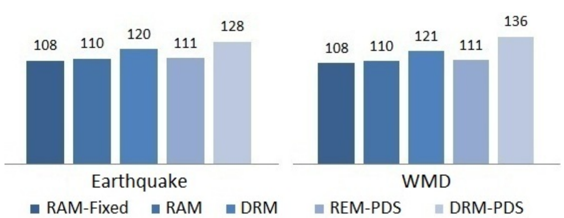

Fig. 8. Resources used by the mapping in wavelength.

3) Resource consumption: Fig. 8 shows that risk-aware approaches use fewer additional wavelengths to deal with disaster and post-disaster failures compared to resources-aware approaches.

IV. Conclusion

We studied the disaster-resilient and post-disaster survivable virtual-network mapping and adaptation problem. Our approach implements a probabilistic model based on risk assessment to offer an economically-sustainable disaster-resilient and post-disaster survivable virtual-network mapping with virtual-backup-node selection (DRM-PDS).

Our model was formulated as an ILP and compared with four different approaches: resource-aware mapping (RAM-Fixed, RAM, and RAM-PDS) and disaster-resilient mapping (DRM). Results showed that DRM-PDS (our approach) reduces the risk of VN disconnections and capacity loss, and decreases the number of post-disaster VN disconnections due to any single-link failure in the physical infrastructure (e.g., correlated cascading failures). Thus, our model is suitable for multiple-VN services in cloud and grid computing, because they require protection against disaster and survivability after disasters.

By building upon the findings of this study, we can further explore the problem for larger VNs with sub-wavelength granularity requirements.

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